THE EFFECT OF SURFACE ROUGHNESS UPON 25 ST ALUMINUM ALLOY SUBJECTED TO REPEATED TENSILE STRESSES ABOVE THE PROPORTIONAL LIMIT

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The research was carried out in collaboration with Lieutenant Commander W. M. Ringness, U. S. Navy.

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SUMMARY

Fatigue tests were conducted on 54 specimens of 25 ST aluminum alloy for the purpose of determining the effect of surface roughness on the fatigue life of the material when subjected to constant repeated tensile stresses above the proportional limit. In addition, the basic stress vs. cycle curve for 25 ST aluminum alloy was extended to include the range of cycles below 100,000.

A machine capable of applying repeated pure tension loads at the rate of 52 cycles per minute, without shock but with a high rate of loading, was used to obtain the data.

It was found that the rate of build-up and the duration of the impulse created an equivalent static load equal to the peak of the impulse loading.

For the material tested, it was found that as the surface roughness increased from 5 μ to 200 μ, the life expectancy of the alloy in general was reduced. However, the experimental results revealed a larger degree of scatter in the cyclic range below 40,000 cycles as opposed to the relatively consistent data obtained at the higher cycles. Therefore, no general conclusions could be ascertained as to the effect of roughness on the fatigue life of the material in the high stress region.

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

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I. INTRODUCTION

The purpose of this investigation is to determine the effect of roughness on the fatigue strength of 25 ST aluminum alloy in the range of cycles between 500 and 100,000.

Fatigue-strength curves for aluminum alloys ordinarily cover a range of cycles starting at 50,000 to 100,000 and extending to approximately 500,000,000. Since aluminum alloys have wide applications in industry, much useful engineering information would be obtained by extending these curves to include the lower cyclic range. Many aircraft structural members, such as parts of the landing gear assembly, are subjected to tensile stresses in the cyclic ranges considered in this report.

The problem of determining, in its entirety, the effects of repeated loads on aluminum alloys is enormous. Closely allied problems have been investigated during the past few years; however, little experimental data have been made available on the subject.

The design and building of an adequate testing machine for carrying out the tests in the range of cycles considered was accomplished in 1947 by Lieut. Comdrs. Robert L. Mastin and Edward G. Bull, U. S. Navy. The machine was modified slightly by Mr. Chintakindi V. JogaRao and Captain Conrad N. Nelson, U. S. Air Force. The work of Bull and Mastin was carried further as reported in the thesis by Conrad N. Nelson, Captain, U. S. Air Force, "Repeated Loads Aobve the Proportional Limit on 24 ST Aluminum Alloy", C.I.T. 1948.

The above authors' work showed that almost all deformation takes place in the first ten cycles of the applied stress, and that there is no relation between the elongation of a specimen and its life expectancy. They also indicated that aging time, magnitude of overstresses, and initial stresses had an effect on the life expectancy of 24 ST aluminum alloy. However, their test results on the effects of aging time, etc. were not conclusive, as stated by the authors, and they suggested further work on the problem in general.

Since the problem is vast in scope, covering a large number of metals, their alloys, and an infinite number of loadings, only one phase of the subject was considered, i.e. the effect of surface roughness upon 25 ST aluminum alloy subjected to repeated tensile stresses in the cyclic range below 100,000 cycles. Although only one alloy was tested, the effect of surface roughness on other aluminum alloys would probably parallel these results; however, further work is necessary to establish the basic high stress-low cycle curves for the other common aircraft materials. It is to be noted that these results apply only to members with freely-hinged ends.

This investigation was carried out in collaboration with Lt. Comdr. W. M. Ringness, U. S. Navy, at the Daniel Guggenheim Aeronautical Laboratory, California Institute of Technology, Pasadena, California, in 1949.

II. EQUIPMENT

Test Specimens

All specimens were made from a 25 ST forging whose chemical composition was 4.43% Cu, 0.67% Si, 0.016% Mg, 0.45% Fe, 0.73% Mn, 0.25% Zn, 0.02% Cr, and remainder Al. The alloy had the following properties:

Yield Strength - 39,400/41,250 p.s.i.

Tensile Strength - 58,000/61,396 p.s.i.

% Elongation in 2 inches - 16½/17

Each specimen was carefully made with the customary high standards of experimental work by the C.I.T. Machine Shop in accordance with Fig. 1. As recommended by Captain Conrad N. Nelson, U. S. Air Force, (Ref. 1) the fillet radius was doubled. The surface roughness was applied by circumferential grooving giving ridges of 5 μ, 50 μ, 100 μ, and 200 μ.

A round tool, radius 3/16" was used on a Pratt and Whitney 13" Lathe, Model B. The advance used for the grooving was as follows:

Roughness	Advance
5 μ	0.0012 in./rev.
50 μ	0.007 in./rev.
100 μ	0.010 in./rev.
200 μ	0.0143 in./rev.

The roughness was checked on a Profilometer built by Physicists Research Company.

Testing Machine

The testing machine was designed and built in the 1946-47 school year at C.I.T. by Lieutenant Commanders Bull, Mastin, and Soli, and Lieutenant Ditch, all of the U. S. Navy, and subsequently modified by Mr. Chintakindi V. JogaRao and Captain Nelson, U. S. Air Force to strengthen the H-beam base of the platform (Refs. 1 and 2). Additional modifications were made by Lieut. Comdr. W. M. Ringness, U. S. Navy and the author.

The machine consists essentially of an aircraft type hydraulic system which applies a pure tensile load (design maximum of 11,500 lbs.) to the specimen which is anchored at one end and secured at the other to a piston of the hydraulic system (See Figs. 3 and 4).

Hydraulic pressure is supplied by a positive displacement gear pump driven by a five (5) h.p. 220-volt A.C. electric motor rated at 1140 r.p.m. A step-up reduction gear of 3.06 to 1 raises the pump r.p.m. to 3420.

The hydraulic system (Fig. 11) begins at a six and eight-tenths (6.8) gallon reservoir with filler strainer. The fluid passes through an oil strainer to the suction side of the pump, through a pressure relief valve (set to lift at 1250 p.s.i.), an accumulator, a pressure regulating valve, a Vickers solenoid-operated pilot valve, and hence to the cylinder. A Bourdon hydraulic pressure gage, protected from shock by a shut-off valve, is installed in the line just ahead of the pilot valve. Four return lines are provided one each from the low pressure end of the cylinder, the discharge side of the pilot valve, regulating valve, and relief valve.

The reservoir was filled by means of a hand pump located within the main frame of the machine. Although all types of oil were used no failures of the system were attributable to the fluid.

The movement of the piston is controlled by the Vickers solenoid triggered through contact points operated by a circular cam driven by a 1/20 H.P. 110-volt A.C. universal wound motor. This same motor also drives a mechanical counter which indicates exactly one-half of the actual number of piston strokes (Fig. 12).

The entire system (Figs. 5, 6, and 7) except for the specimen, its fittings, the cylinder, the pressure gage, the counter, and the electrical controls, is mounted below the table top.

The test platform consists of two 5" steel H-beams, six feet long bolted together upon which are mounted heavy steel fittings to anchor the cylinder and the fixed end of the test specimen. The 11.5 sq. in. piston is attached to a universal joint which in turn is connected to the load coupon (Fig. 2). The test specimen is secured between the load coupon and 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. The universal joints which remove bending stresses carry counter weights for static balance of the free ends. Lt. Cdr. Ringness and the author installed safety guides for these balances since there was a tendency for them to rotate the universal joints. However, these guides were made very loose to allow for axial movement of the weights as well as a few degrees of rotation.

During the first few tests it was observed by the investigators that the cylinder and fixed end did not have the proper alignment, thereby introducing bending loads in the specimen in spite of the universal joints. To correct this, shims were placed under the hydraulic cylinder until all noticeable effects of bending were eliminated.

Since it was necessary to leave the machine in operation for extended periods of time (the rate of loading was 52 cycles per minute), an additional modification of the testing machine was considered essential. This change consisted of installing a micro-switch in the electrical circuit, the operation of which shut down the entire system. The switch, modified from a "normally closed" to a "normally open" type, was located on the testing platform in such a position whereby upon failure of the test specimen a collar on the piston struck the actuating arm of the micro-switch as the piston returned home upon fracture of the test piece. When the micro-switch was actuated, it opened a three-pole, double-throw relay which controlled the counter circuit, the solenoid circuit, and the main motor cutoff switch (Fig. 12). This modification made by Lt. Cdr. Ringness and the author allowed the investigators to subsequently carry out many more tests than would have been possible had this change not been made.

Load Measuring Coupon

The "load coupon" (Fig. 2), located between the hydraulic piston and the test specimen, is the device used for measuring accurately the actual load being applied to the specimen. Mounted at ninety degree spacing on the steel coupon were four (4) SR-4 resistance wire strain gages. These gages were connected in series to increase the sensitivity and to remove bending effects of the coupon. This was the only means of accurately measuring the stresses as the pressure gage, having once been calibrated against the load in the cylinder, proved to be only a rough check on the applied load.

Electrical Load Measuring Equipment

The electrical load measuring equipment consists of the "load coupon" with its four strain gages connected in series, an amplifier, a control panel, a Heiland Recording Oscilloscope, and associated power supplies consisting of 110-volts A.C. and 6-volt batteries as necessary (Fig. 13).

A Wheatstone Bridge circuit measures the change of resistance of the gages with changes in load. This signal is sent through the amplifier, hence on to the Heiland Recording Oscilloscope which in turn makes a photographic record of the load applied, automatically plotting this load against a time axis. Thus the rate of loading is also recorded.

Incorporated within this electrical system is a method of applying known electrical loads of 1000, 2000, 3000, and 4000 pounds. This electrical feature provided a means of comparing the applied load with a known standard during testing. This was accomplished as follows:

After the strain gages were cemented onto the coupon and checked separately, the coupon was placed in a Riehle Bros. Tensile Testing

Machine. The gages were connected in series and a record of e.m.f. drop across the gage (in millivolts) vs. load on the coupon was made (Fig. 15). During this strain gage calibration, the amount of resistance was determined which, when connected in parallel with the SR-4 gages, would give electrically the same effect as applying corresponding static loads of 1000, 2000, 3000, and 4000 pounds to the load coupon. These known resistances were installed in the control panel and then connected to the electrical circuit through a selector switch. Then it was possible to select any one or all of the four known electric loads while the test was in progress and thus place a standard calibrating line on the recording paper in the Heiland Recorder. Hence with each actual load that was recorded there was associated with it a known standard calibration Load vs. Time curve. This calibration method eliminated errors due to voltage and temperature changes inherent in the power supply.

The sensitivity of the strain gages could be controlled by controlling the voltage applied across them. However, after a few trials, it was ascertained that two six-volt direct current batteries connected in series gave the best results in that the full width of the recording paper was then utilized.

The Heiland was powered by ten volts of direct current.

Fig. 8 shows an oscilloscope recording which is typical of those obtained on all tests. The information as taken from Fig. 8 is tabulated below:

Duration of Zero Load	0.63 sec.
Duration of Maximum Load	0.33 sec.
Time - No Load to Full Load	0.14 sec.
Time - Full Load to No Load	0.025 sec.
Time for one complete cycle	1.125 sec.
Number of cycles per minute	52
Maximum Rate of Loading	41,700 lbs./sec.
Maximum Rate of Unloading	184,000 lbs./sec.

Since the rate of loading of the specimen had been established as being satisfactory by Bull and Mastin (Ref. 2) the Heiland Recording Oscilloscope was used only to obtain the magnitude of the applied load.

The possibility of utilizing other load measuring and recording devices such as a large oscilloscope with a retentive screen was investigated by Nelson (Ref. 1). However, he found that the low frequency of the testing machine precluded the use of such devices.

III. PROCEDURE

Tables III through LVI tabulate the data obtained during this investigation.

After all preliminary calibrations were made, a series of fatigue tests were made on 25 ST aluminum alloy. For record purposes all tests are listed in this report even though in some cases useful data were not obtained. Each test was run until the specimen failed. Fig. 10 is an example of a complete typical data sheet.

The actual loads applied during any one test were determined in the following manner:

Three calibration lines were established by recording the equivalent 1000, 2000, and 3000, or 2000, 3000, and 4000 pound electric loads on the Heiland Recorder. The applied load was recorded immediately afterward. This procedure was continued throughout the test. A typical set of such readings are shown in Fig. 9.

The heights of the calibration and load lines are measured after the film is developed and dried. For example, from Fig. 9 it appears that 0.32" corresponds to a 1000 pound load. The load line is 0.84" in height. Thus by simple arithmetic the load is computed:

$$\frac{0.84}{0.32} \times 1000 = 2625 \text{ pounds}$$

The corresponding stress (cross-section area being 0.0707 sq. in.)

$$\frac{2625}{0.0707} = 37{,}130 \text{ p.s.i.}$$

No effort was made to calibrate the hydraulic pressure gage, as was done by the previous investigators, since the first few tests showed that the relation between the hydraulic pressure gage setting and the actual load applied would change from day to day. However, the pressure gage was used to determine the initial load setting.

Although the hydraulic system does not keep a perfectly constant load, the load variations were not over excessive during any complete test.

IV. RESULTS AND DISCUSSION

As mentioned previously in this report, the frequency of load application is 0.867 cycles per second. Since the load application is non-steady in nature, it seemed desirable to investigate the effect of any longitudinal vibrations that might be set up.

From Den Hartog, Appendix II, (Ref. 3)

$$f = \frac{1}{2}\sqrt{\frac{E}{m'l^2}} \qquad \text{where}$$

$f =$ fundamental natural frequency, cycles/sec.

$m' =$ mass/unit vol. $0.101/386$ lb. sec^2/in^4

$l =$ length, 2"

$E = 10{,}300{,}000$ p.s.i.

The natural period is then $T = \frac{1}{f} = 2.02 \times 10^{-5}$ sec. Thus all vibration will be damped out between cycles since $\frac{0.63}{2.02 \times 10^{-5}} = 3{,}115{,}000$ natural periods are completed (Rest periods $= 0.63$ seconds). Therefore, there is no effect on this system due to the periodicity of loading.

In order to determine a dynamic load factor for this elastic system, as outlined by Dr. J. M. Frankland (Ref. 4), certain assumptions must be fulfilled to allow treatment as a one degree of freedom system.

1. The impulse should be at least one tenth of the duration of the natural period.

2. The impact load should be distributed fairly uniformly over the structure.

3. The fundamental mode should be uncoupled with higher modes. All three conditions are fulfilled by this system idealized to the extent

that the fundamental mode considered is longitudinal and may be assumed uncoupled with higher modes (Condition 3). The other two conditions or assumptions are obviously met.

Where the duration of impulse is long compared to the natural period of the system, as in this case, Dr. Frankland states that the important parameter is the rate of buildup of the impulse. Thus

$$n = 1 + \frac{2}{pt_o} \sin \frac{pt_o}{2} \quad \text{where}$$

n = dynamic load factor $\frac{\text{e.s.l.}}{\text{impulse peak load}}$

e.s.l. = equivalent static load

p = circular natural frequency

t_o = time required for buildup = 0.14 sec.

$$pt_o = 2\pi(49,500)(.14) = 43,600$$

Since $\frac{2}{pt_o} \sin \frac{pt_o}{2} << 1$, the equivalent static load is approximately equal to the peak of the impulse loading. Therefore, the system can be considered subjected to the loads as determined by the load measuring equipment described on page 7.

It must be pointed out that if the buildup time is in the neighborhood of the natural period of the system, equivalent static loads equal to twice the peak loading may be expected. Also, not only equivalent static loading but rate of buildup must be considered when comparing these results to similar investigations.

Figs. 16, 17, 18, 19, and 20 are the plots of the test data compiled in Tables III through LVI inclusive. Since it has been determined that vibration in this system has negligible effect on the resulting loading, the loads listed in the Tables can be considered as the actual loads applied.

An examination of the data reveals the accuracy achieved in attempting to hold a constant load throughout a complete test. All results, where sufficient information was obtained, were plotted. Although no definite reading interval was established between runs, it can be assumed that where long periods of time existed between readings, the load remained constant. The test data substantiates this.

The basic curve, specimens tested with a 5μ roughness, is shown in Fig. 16. The results for roughness factors of 50μ, 100μ, and 200μ are plotted and represented in Figs. 17, 18, and 19 respectively. Fig. 20 is a compilation of all results. The type of break was also recorded on each Figure, but the type (normal or fillet) had little or no effect on the general trend of the curves.

The scatter is that which is to be expected in compiling experimental data of this type. However, as a result it was difficult to ascertain the precise location of the curves. But it is felt that increasing roughness has a definite tendency, however small, toward decreasing the fatigue strength of 25 ST aluminum alloy. Time prevented further investigation of the portion of the 50μ curve in the cyclic range between 5,000 and 45,000 cycles.

Upon closer investigation of Fig. 20 it appears that roughness has more effect upon the cyclic life of this material in the range of 40,000 cycles and upwards than in the region below 40,000 cycles. The data were also more consistent in this range. Although negative in nature, it appears that the different surface roughnesses have very little effect on 25 ST when failure occurs at stresses corresponding to cycles lower than 40,000. It is felt that further investigation along these lines of the other important aluminum alloys is needed.

V. CONCLUSIONS

For the material tested, 25 ST aluminum alloy, surface roughness reduced the life expectancy of the alloy when subjected to constant repeated tensile stresses which were above the proportional limit. As the surface roughness increased from 5μ to 200μ, the number of cycles to cause failure of the test specimen for a given load decreased. The results were more pronounced in the range from 40,000 to 100,000 cycles.

In the regions below 40,000 cycles the amount of scatter increased. It was therefore impossible to draw accurate conclusions as to the effect of surface roughness on the cyclic life of 25 ST aluminum alloy in this region except that this indicated the convergence of all curves on the point, $N = 1$ cycle, σ = ultimate tensile strength.

VI. RECOMMENDATIONS

As a result of this investigation the following recommendations are made:

1. That similar tests be carried out for other aluminum alloys common to the aircraft industry.

2. That the direct current supply be replaced by alternating current in the applicable circuits of the electrical load measuring equipment.

3. That the rate of loading be increased from 52 cycles per minute to two or three times this value, thus reducing the time required to complete a single test.

4. That a precision type pressure control valve be installed along with a more stable pressure gage so that after the machine is once calibrated, the entire system would be independent of any load measuring equipment other than the pressure gage itself.

VII. REFERENCES

1. "Repeated Loads Above the Proportional Limit on 24 ST Aluminum Alloy", C.I.T. Thesis by Captain Conrad N. Nelson, U.S. Air Force.
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3. "Mechanical Vibrations", Den Hartog, McGraw-Hill, 1949
4. "Effects of Impact upon Single Elastic Structures", J. M. Frankland, Proc. Soc. Experimental Stress Analysis, Vol. VI, No. 2
5. "The Direct-Stress Fatigue Strength of 17 ST Aluminum Alloy Throughout the Range From 1/2 to 500,000,000 Cycles of Stress, E. E. Hartman and G. W. Stickley, NACA Tech. Note No. 865

TABLE 1

Calibration of Strain Gages

(Connected in Series)

Reading	Load (lbs.)	Millivolts
1	100	.310
2	200	.615
3	300	.930
4	400	1.22
5	500	1.55
6	600	1.85
7	700	2.15
8	800	2.49
9	900	2.78
10	1000	3.10
11	1100	3.41
12	1200	3.73
13	1300	4.03
14	1400	4.35
15	1500	4.68
16	1600	4.98
17	1700	5.29
18	1800	5.62
19	1900	5.93
20	2000	6.21
21	2100	6.56
22	2200	6.83

TABLE I (Cont'd)

Reading	Load (lbs.)	Millivolts
23	2300	7.19
24	2400	7.50
25	2500	7.82
26	2600	8.13
27	2700	8.44
28	2800	8.76
29	2900	9.09
30	3000	9.36

TABLE II

Static Tensile Test

25 ST 5μ Surface Roughness

Throop Hall--Materials Testing Lab.

Specimen Diameter 0.3" Area: 0.0707 sq. in.

Load lbs.	#79 Gage Rdg.	#79 Strain Rdg.	#80 Gage Rdg.	#80 Strain in/in	Average Strain in/in	Stress p.s.i.
0	0	0	0	0	0	0
300	2.0	3.05x10^{-4}	2.5	3.905x10^{-4}	3.477x10^{-4}	4243
600	5.3	8.082	4.5	7.029	7.555	8486
900	8.0	12.2	7.6	11.871	12.035	12729
1200	10.4	15.86	10.6	16.557	16.208	16972
1500	13.0	19.825	13.3	20.775	20.300	21215
1800	15.8	24.095	16.3	25.460	24.777	25460
2100	19.6	29.89	20.0	31.240	30.565	29701
2400	28.2	43.00	28.3	44.205	43.602	33945
2560	42.0	64.05	42.0	65.604	64.827	36209
2700	45.2	68.93	46.0	71.852	70.391	38189
2800	75.0	114.37	78.0	121.84	118.11	39604
2930	85.2	129.93	88.6	138.39	134.16	41442
3000	92.3	140.76	95.0	148.39	144.58	42430
3100	102.9	156.92	98.5	153.86	155.39	43847

#79 --- 1.525 x 10^{-4} in/in/division

#80 --- 1.562 x 10^{-4} in/in/division

TABLE III

Test 1 Approx. Gage Setting 200 p.s.i.

Reading	Cycles	Load (lbs)
1	30	2285
2	100	2357
3	1500	2143
4	2000	2571
5	2400	2500
6	2600	2571
7	2800	2500
8	3000	2571
9	4000	2340
10	4500	2270
11	5000	2360
12	5500	2285
13	6900	2350
14	8240	2410
15	10000	2571
16	70000	2350
17	74200	2515
18	76200	2570
19	262204	Failure

Roughness - 5μ

Break - Fillet

Ave. Load - 2350 lbs.

Stress - 33,000 p.s.i.

TABLE IV

Test 2 Approx. Gage Setting 220 p.s.i.

Reading	Cycles	Load (lbs.)
1	100	2670
2	1000	2610
3	2520	2880
4	3000	2720
5	71050	2620
6	71200	2760
7	75000	2760
8	83600	No reading
9	105000	Failure

Roughness - 5μ

Break - Fillet

Ave. Load - 2700 lbs.

Stress - 38200 p.s.i.

TABLE V

Test 3 Approx. Gage Setting 240 p.s.i.

Reading	Cycles	Load (lbs.)
1	40	2960
2	3000	2950
3	8000	2970
4	12400	2750
5	16900	2850
6	56008	Failure

Roughness - 5μ

Break - Fillet

Ave. Load - 2900 lbs.

Stress - 41,000 p.s.i.

TABLE VI

Test 4

Approx. Gage Setting 260 p.s.i.

Reading	Cycles	Load (lbs.)
1	40	3110
2	2500	3160
3	7600	2960
4	11760	No reading
5	13800	3170
6	20850	3100
7	21720	3020
8	22972	Failure

Roughness - 5 μ

Break - Normal

Ave. Load - 3100 lbs.

Stress - 43,800 p.s.i.

TABLE VII

Test 24

Approx. Gage Setting 260 p.s.i.

Reading	Cycles	Load (lbs.)
1	3000	3240
2	7900	3280
3	7920	3250
4	13100	3250
5	13200	3250
6	18000	3330
7	18060	3270
8	18374	Failure

Roughness - 5 μ

Break - Fillet

Ave. Load - 3250 lbs.

Stress - 46,000 p.s.i.

TABLE VIII

Test 26 Approx. Gage Setting 270 p.s.i.

Reading	Cycles	Load (lbs.)
1	3000	3480
2	7680	3500
3	7700	3470
4	9900	3500
5	9920	3500
6	21002	Failure

Roughness - 5μ

Break - Fillet

Ave. Load - 3485 lbs.

Stress - 49,300 p.s.i.

TABLE IX

Test 5 Approx. Gage Setting 280 p.s.i.

Reading	Cycles	Load (lbs.)
1	10	3240
2	7780	No reading
3	7812	3420
4	9220	3390
5	11600	No reading
6	11660	3360
7	17660	3380
8	Machine broke down	

Roughness - 5μ

TABLE X

Test 6 Approx. Gage Setting 280 p.s.i.

Reading	Cycles	Load (lbs.)
1	20	3260
2	1060	3470
3	1120	3560
4	1620	3520
5	1650	3440
6	Machine broke down at 4000 cycles	

Roughness - 5μ

TABLE XI

Test 22 Approx. Gage Setting 280 p.s.i.

Reading	Cycles	Load (lbs.)
1	30	3260
2	1930	3560
3	5420	3500
4	9820	3620
5	13020	3560
6	16280	3580
7	18870	Failure

Roughness - 5μ

Break - Fillet

Ave. Load - 3360 lbs.

Stress - 47,500 p.s.i.

TABLE XII

Test 13

Approx. Gage Setting 280 p.s.i.

Reading	Cycles	Load (lbs.)
1	20	3460
2	7540	3390
3	7560	3570
4	9400	3570
5	9440	3500
6	13460	3570
7	13490	3570
8	14564	Failure

Roughness - 5μ

Break - Normal

Ave. Load - 3520 lbs.

Stress - 49,780 p.s.i.

TABLE XIII

Test 25

Approx. Gage Setting 290 p.s.i.

Reading	Cycles	Load (lbs.)
1	80	No reading
2	600	3550
3	3420	3590
4	7500	3580
5	10340	No reading
6	10540	No reading
7	11240	3510
8	11260	3590
9	13700	Failure

Roughness - 5μ

Break - Normal

Ave. Load - 3560 lbs.

Stress - 50,300 p.s.i.

TABLE XIV

Test 7

Approx. Gage Setting 300 p.s.i.

Reading	Cycles	Load (lbs.)
1	10	3440
2	3280	3540
3	3320	3540
4	3400	3540
5	10750	3660
6	10800	3730
7	12750	No reading
8	12800	No reading
9	12980	No reading
10	13430	3670
11	19326	Failure

Roughness - 5 μ

Ave. Load - 3590 lbs.

Break - Normal

Stress - 50,700 p.s.i.

TABLE XV

Test 23

Approx. Gage Setting 300 p.s.i.

Reading	Cycles	Load (lbs.)
1	3000	3640
2	7300	3830
3	9580	3450
4	9600	3610
5	13832	Failure

Roughness - 5 μ

Ave. Load - 3630 lbs.

Break - Normal

Stress - 51,300 p.s.i.

TABLE XVI

Test 9 Approx. Gage Setting 320 p.s.i.

Reading	Cycles	Load (lbs.)
1	10	No reading
2	50	3630
3	6740	3680
4	6760	No reading
5	7000	3870
6	7060	3870
7	9316	Failure

Roughness - 5μ

Break - Normal

Ave. Load - 3760 lbs.

Stress - 53,100 p.s.i.

TABLE XVII

Test 10 Approx. Gage Setting 340 p.s.i.

Reading	Cycles	Load (lbs.)
1	30	3920
2	1080	4015
3	2080	4120
4	3240	Failure

Roughness - 5μ

Break - Normal

Ave. Load - 4020 lbs.

Stress - 56,800 p.s.i.

TABLE XVIII

Test 11 Approx. Gage Setting 360 p.s.i.

Reading	Cycles	Load (lbs.)
1	50	4450
2	100	4510
3	400	4390
4	550	Failure

Roughness - 5μ

Break - Normal

Ave. Load - 4450 lbs.

Stress - 63,000 p.s.i.

TABLE XIX

Test 8 Approx. Gage Setting 220 p.s.i.

Reading	Cycles	Load (lbs.)
1	10	2670
2	4650	2620
3	4800	2730
4	5400	2800
5	9320	2690
6	13400	2710
7	17200	2680
8	77380	Failure

Roughness - 50μ

Break - Fillet

Ave. Load - 2700 lbs.

Stress - 38,200 p.s.i.

TABLE XX

Test 28 Approx. Gage Setting 230 p.s.i.

Reading	Cycles	Load (lbs.)
1	10	No reading
2	4260	No reading
3	4500	No reading
4	6420	2700
5	6440	2870
6	8072	2930
7	8080	2880
8	9460	2890
9	16180	2970
10	16200	2730
11	21860	3000
12	21800	2950
13	23660	2870
14	48892	Failure

Roughness - 50μ

Break - Fillet

Ave. Load - 2880 lbs.

Stress - 40,700 p.s.i.

TABLE XXI

Test 12 — Approx. Gage Setting 240 p.s.i.

Reading	Cycles	Load (lbs.)
1	5	3000
2	30	3000
3	660	2780
4	680	3050
5	1600	3090
6	1630	3170
7	7000	3000
8	11200	3050
9	16830	2950
10	36840	Failure

Roughness = 50μ

Break = Normal

Ave. Load = 3000 lbs.

Stress = 42,400 p.s.i.

TABLE XXII

Test 27 Approx. Gage Setting 250 p.s.i.

Reading	Cycles	Load (lbs.)
1	2980	3120
2	7540	3160
3	7560	3280
4	9560	3150
5	9600	3090
6	10650	3140
7	10670	3170
8	16200	3010
9	23740	Failure

Roughness = 50μ

Break = Fillet

Ave. Load = 3140 lbs.

Stress = 44,400 p.s.i.

TABLE XXIII

Test 15 Approx. Gage Setting 260 p.s.i.

Reading	Cycles	Load (lbs.)
1	10	3300
2	175	3470
3	5010	3350
4	11100	3460
5	14600	3250
6	17400	3290
7	20534	Failure

Roughness = 50 μ

Break = Fillet

Ave. Load = 3350 lbs.

Stress = 47,400 p.s.i.

TABLE XXIV

Test 29 | Approx. Gage Setting 270 p.s.i.

Reading	Cycles	Load (lbs.)
1	3810	3570
2	3830	3570
3	7280	3440
4	7300	3470
5	9710	3450
6	9730	3390
7	19300	3290
8	19310	3290
9	20970	3490
10	21000	3440
11	27370	Failure

Roughness - 50μ

Break - Normal

Ave. Load - 3430 lbs.

Stress - 48,500 p.s.i.

TABLE XXV

Test 14 Approx. Gage Setting 280 p.s.i.

Reading	Cycles	Load (lbs.)
1	10	3410
2	40	3410
3	3760	3390
4	4000	3560
5	8840	3540
6	12860	3430
7	20280	3570
8	24612	Failure

Roughness = 50 μ

Break = Normal

Ave. Load = 3470 lbs.

Stress = 49,000 p.s.i.

TABLE XXVI

Test 16 Approx. Gage Setting 300 p.s.i.

Reading	Cycles	Load (lbs.)
1	520	3630
2	3280	3520
3	8320	3650
4	11832	Failure

Roughness = 50 μ

Break = Fillet

Ave. Load = 3600 lbs.

Stress = 50,900 p.s.i.

TABLE XXVII

Test 19 Approx. Gage Setting 320 p.s.i.

Reading	Cycles	Load (lbs.)
1	10	3860
2	200	3860
3	1020	3860
4	2497	Failure

Roughness = 50μ

Break - Normal

Ave. Load = 3860 lbs.

Stress - 54,600 p.s.i.

TABLE XXVIII

Test 18 Approx. Gage Setting 340 p.s.i.

Reading	Cycles	Load (lbs.)
1	10	4170
2	100	4170
3	850	4170
4	880	4170
5	1900	4080
6	2218	Failure

Roughness - 50μ

Break - Normal

Ave. Load - 4150 lbs.

Stress = 58,600 p.s.i.

TABLE XXIX

Test 17 Approx. Gage Setting 360 p.s.i.

Reading	Cycles	Load (lbs.)
1	10	4160
2	18	Failure

Roughness - 50 μ

Break - Normal

Ave. Load - 4160 lbs.

Stress - 58,800 p.s.i.

TABLE XXX

Test 38 Approx. Gage Setting 210 p.s.i.

Reading	Cycles	Load (lbs.)
1	44	2630
2	72	2570
3	550	2600
4	570	2550
5	2980	2550
6	3000	2580
7	3650	2550
8	3660	2550
9	7250	2640
10	7260	2550
11	11200	2440
12	14600	2520
13	21450	2610
14	56830	2520
15	56840	2630
16	60125	2670
17	64300	2550
18	64310	2620
19	68080	2600
20	68100	2600
21	73890	2660
22	73900	2660
23	81090	2500
24	81100	2500
25	91378	Failure

Roughness - 100μ

Break - Normal

Ave. Load - 2580 lbs.

Stress - 36,500 p.s.i.

TABLE XXXI

Test 35 Approx. Gage Setting 230 p.s.i.

Reading	Cycles	Load (lbs.)
1	868	2780
2	3140	2810
3	4320	2790
4	8100	2760
5	11200	2670
6	14100	2760
7	18500	2850
8	22650	2710
9	23945	Failure

Roughness - 100 μ

Break - Fillet

Ave. Load - 2760 lbs.

Stress - 39,000 p.s.i.

TABLE XXXII

Test 34 Approx. Gage Setting 250 p.s.i.

Reading	Cycles	Load (lbs.)
1	1670	3020
2	3380	3000
3	8190	3000
4	10260	3000
5	10800	3070
6	10820	3090
7	14710	3070
8	18640	3090
9	18680	3150
10	20100	3180
11	23060	3070
12	23080	3130
13	25100	3180
14	27492	Failure

Roughness = 100μ

Break = Fillet

Ave. Load = 3080 lbs.

Stress = 43,600 p.s.i.

TABLE XXXIII

Test 30 Approx. Gage Setting 260 p.s.i.

Reading	Cycles	Load (lbs.)
1	1780	3305
2	4590	3370
3	4600	3300
4	7930	3320
5	11360	3270
6	13200	3350
7	16800	3290
8	22338	Failure

Roughness - 100 μ

Break - Fillet

Ave. Load - 3300 lbs.

Stress - 46,700 p.s.i.

TABLE XXXIV

Test 32 Approx. Gage Setting 280 p.s.i.

Reading	Cycles	Load (lbs.)
1	1720	3420
2	4510	3610
3	4530	3530
4	5570	3440
5	5590	3310
6	11430	3440
7	11450	3370
8	12754	Failure

Roughness = 100μ

Break = Normal

Ave. Load - 3420 lbs.

Stress - 48,300 p.s.i.

TABLE XXXV

Test 31 Approx. Gage Setting 300 p.s.i.

Reading	Cycles	Load (lbs.)
1	80	3330
2	110	3350
3	3850	3540
4	3880	3720
5	8570	3460
6	8600	3640
7	8680	Failure

Roughness - 100 μ

Break - Fillet

Ave. Load - 3505 lbs.

Stress - 49,500 p.s.i.

TABLE XXXVI

Test 33 Approx. Gage Setting 310 p.s.i.

Reading	Cycles	Load (lbs.)
1	80	3660
2	100	3600
3	3906	3630
4	4000	No reading
5	4924	Failure

Roughness - 100 μ

Break - Fillet

Ave. Load - 3630 lbs.

Stress - 51,300 p.s.i.

TABLE XXXVII

Test 20 Approx. Gage Setting 320 p.s.i.

Reading	Cycles	Load (lbs.)
1	66	3720
2	500	3890
3	7700	3950
4	8310	Failure

Roughness = 100μ

Break = Fillet

Ave. Load = 3850 lbs.

Stress = 54,500 p.s.i.

TABLE XXXVIII

Test 37 Approx. Gage Setting 320 p.s.i.

Reading	Cycles	Load (lbs.)
1	30	3680
2	50	3680
3	1620	3940
4	2640	4060
5	2916	Failure

Roughness = 100μ

Break = Normal

Ave. Load - 3840 lbs.

Stress = 54,300 p.s.i.

TABLE XXXIX

Test 21 Approx. Gage Setting 340 p.s.i.

No readings. Machine broke down after 20 cycles.

Roughness - 100μ

TABLE XL

Test 36 Approx. Gage Setting 340 p.s.i.

Reading	Cycles	Load (lbs.)
1	30	3820
2	140	3880
3	200	3940
4	540	4100
5	560	4120
6	724	Failure

Roughness - 100μ

Break - Normal

Ave. Load - 3970 lbs.

Stress - 56,100 p.s.i.

TABLE XLI

Test 51 Approx. Gage Setting 210 p.s.i.

Reading	Cycles	Load (lbs.)
1	20	2520
2	1390	2600
3	3790	2540
4	5060	2600
5	5260	2720
6	8300	2650
7	11700	2500
8	17400	2520
9	24250	2630
10	29600	2520
11	34850	2500
12	42096	Failure

Roughness - 200 μ

Break - Fillet

Ave. Load - 2580 lbs.

Stress - 36,500 p.s.i.

TABLE XLII

Test 45 Approx. Gage Setting 220 p.s.i.

Reading	Cycles	Load (lbs.)
1	70	2460
2	700	2570
3	3400	2660
4	6750	2670
5	10610	2690
6	12030	2670
7	15790	2720
8	18250	2700
9	22800	2720
10	30140	2720
11	37662	Failure

Roughness - 200 μ

Break - Fillet

Ave. Load - 2660 lbs.

Stress - 37,600 p.s.i.

TABLE XLIII

Test 48 Approx. Gage Setting 240 p.s.i.

Reading	Cycles	Load (lbs.)
1	40	2820
2	1180	2910
3	3220	2930
4	6420	2880
5	8310	2880
6	11450	2910
7	14160	2930
8	17700	3010
9	20200	2980
10	23430	2920
11	26432	Failure

Roughness - 200 μ

Break - Fillet

Ave. Load - 2920 lbs.

Stress - 41,300 p.s.i.

TABLE XLIV

Test 54 Approx. Gage Setting 250 p.s.i.

Reading	Cycles	Load (lbs.)
1	230	2950
2	5216	3000
3	7220	2950
4	7530	2990
5	12480	3010
6	16270	3030
7	19450	3080
8	22840	3070
9	25972	Failure

Roughness - 200 μ

Break - Normal

Ave. Load - 3010 lbs.

Stress - 42,600 p.s.i.

TABLE XLV

Test 42 Approx. Gage Setting 260 p.s.i.

Reading	Cycles	Load (lbs.)
1	40	3400
2	1160	3470
3	3180	3100
4	4170	3200
5	5220	3160
6	7350	3220
7	8160	3290
8	9250	3230
9	10100	3230
10	11374	Failure

Roughness - 200 μ

Break - Fillet

Ave. Load - 3255 lbs.

Stress - 46,000 p.s.i.

TABLE XLVI

Test 41 Approx. Gage Setting 280 p.s.i.

No readings. Machine broke down

Roughness - 200μ

TABLE XLVII

Test 49 Approx. Gage Setting 280 p.s.i.

Reading	Cycles	Load (lbs.)
1	40	3540
2	2520	3420
3	4090	3440
4	6940	3440
5	8210	3420
6	10810	3530
7	10830	3460
8	12550	3450
9	14476	Failure

Roughness - 200μ

Break - Fillet

Ave. Load - 3460 lbs.

Stress - 49,000 p.s.i.

TABLE XLVIII

Test 44 Approx. Gage Setting 290 p.s.i.

Reading	Cycles	Load (lbs.)
1	40	3630
2	2010	3630
3	4360	3650
4	6820	3590
5	8150	3630
6	9058	Failure

Roughness - 200 μ

Break - Normal

Ave. Load - 3625 lbs.

Stress - 51,200 p.s.i.

TABLE XLIX

Test 39 Approx. Gage Setting 300 p.s.i.

Reading	Cycles	Load (lbs.)
1	40	3312
2	500	No reading
3	Machine failed	

Roughness - 200 μ

TABLE L

Test 46 Approx. Gage Setting 300 p.s.i.

Reading	Cycles	Load (lbs.)
1	46	3580
2	7680	No reading
3	2640	No reading
4	3690	No reading
5	Electrical failure	

Roughness - 200μ

TABLE Ll

Test 43 Approx. Gage Setting 310 p.s.i.

Reading	Cycles	Load (lbs.)
1	10	3500
2	36	3660
3	50	3690
4	720	3770
5	730	3710
6	1230	3790
7	1250	3670
8	1770	3730
9	1800	3730
10	2680	3640
11	2700	3690
12	3150	3810
13	4670	3810
14	5390	3690
15	6280	3690
16	7850	Failure

Roughness - 200μ

Break - Normal

Ave. Load - 3705 lbs.

Stress - 52,400 p.s.i.

TABLE 111

Test 40 Approx. Gage Setting 310 p.s.i.

Reading	Cycles	Load (lbs.)
1	30	3610
2	40	3640
3	810	3710
4	820	3740
5	1120	3740
6	1140	3710
7	2380	3640
8	2400	3700
9	3150	3710
10	3170	3710
11	3710	3660
12	3720	3800
13	5000	3620
14	5010	3570
15	6440	3590
16	6940	Failure

Roughness - 200 μ

Break - Fillet

Ave. Load - 3680 lbs.

Stress - 52,000 p.s.i.

TABLE LIII

Test 47 Approx. Gage Setting 320 p.s.i.

Reading	Cycles	Load (lbs.)
1	88	3550
2	100	3670
3	640	3790
4	650	3820
5	2420	3770
6	2450	3820
7	4140	3810
8	5270	3810
9	7556	Failure

Roughness - 200 μ

Break - Fillet

Ave. Load - 3755 lbs.

Stress - 53,100 p.s.i.

TABLE LlV

Test 52 Approx. Gage Setting 320 p.s.i.

Reading	Cycles	Load (lbs.)
1	30	3650
2	390	3610
3	800	3720
4	820	3550
5	1260	3570
6	1280	3540
7	2050	3740
8	2870	3740
9	3200	3830
10	3420	3830
11	4960	3850
12	6210	3730
13	7234	Failure

Roughness - 200μ

Break - Fillet

Ave. Load - 3710 lbs.

Stress - 52,500 p.s.i.

TABLE LV

Test 53 Approx. Gage Setting 330 p.s.i.

Reading	Cycles	Load (lbs.)
1	24	3830
2	40	3870
3	540	3830
4	780	3850
5	1016	Failure

Roughness - 200μ

Break - Normal

Ave. Load - 3845 lbs.

Stress - 54,300 p.s.i.

TABLE LV1

Test 50 Approx. Gage Setting 340 p.s.i.

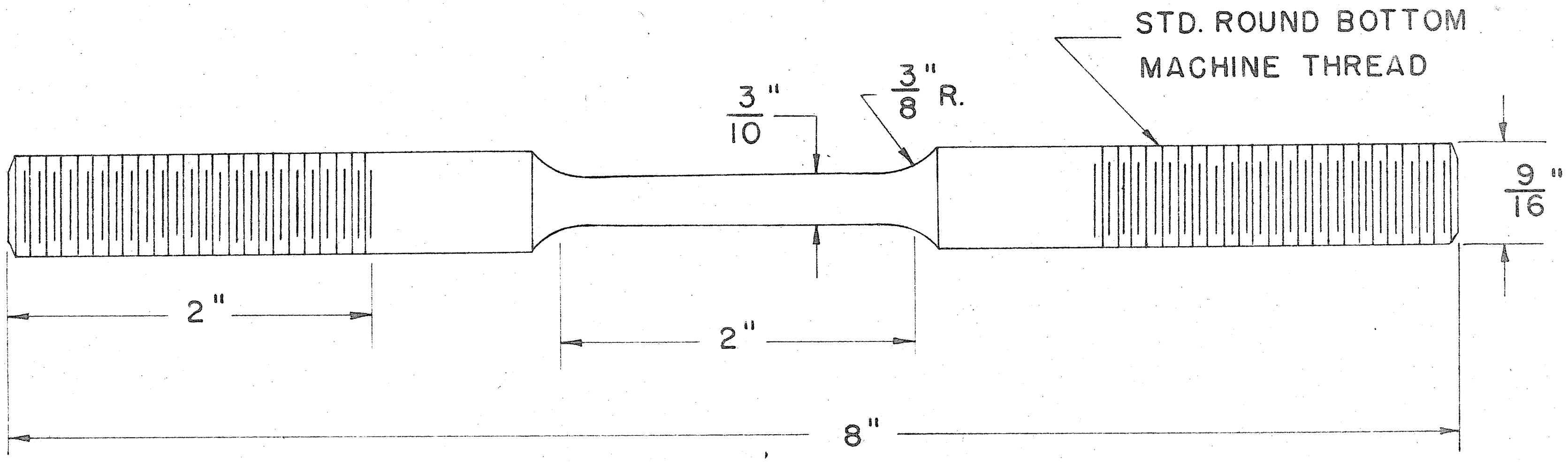
Reading	Cycles	Load (lbs.)
1	20	3660
2	75	3725
3	150	3800
4	300	Failure

Roughness - 200μ

Break - Normal

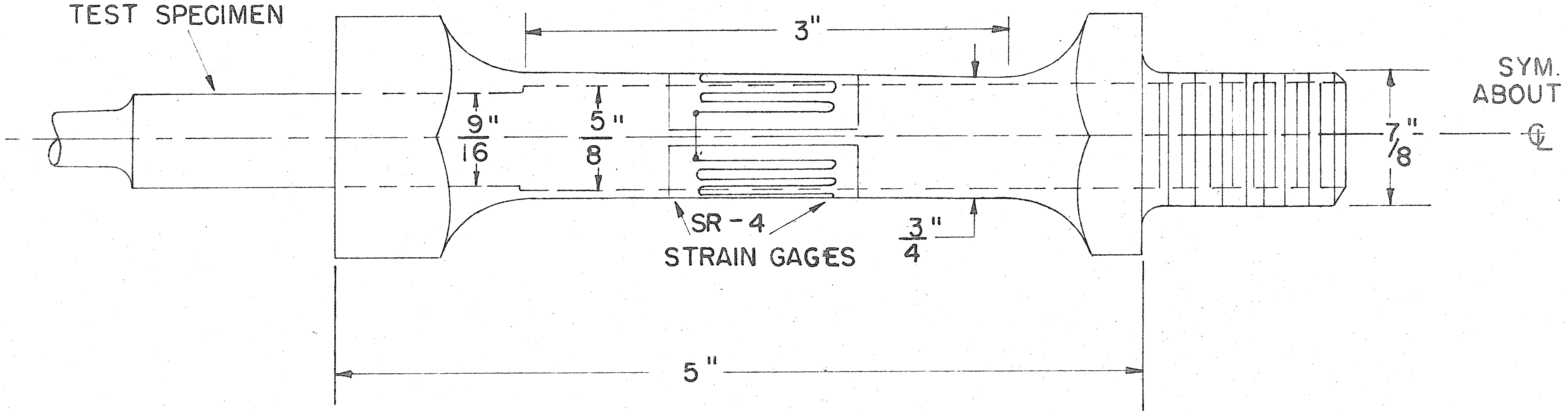
Ave. Load - 3730 lbs.

Stress - 52,750 p.s.i.



TEST SPECIMEN

FIG. 1



LOAD MEASURING COUPON

FIG. 2

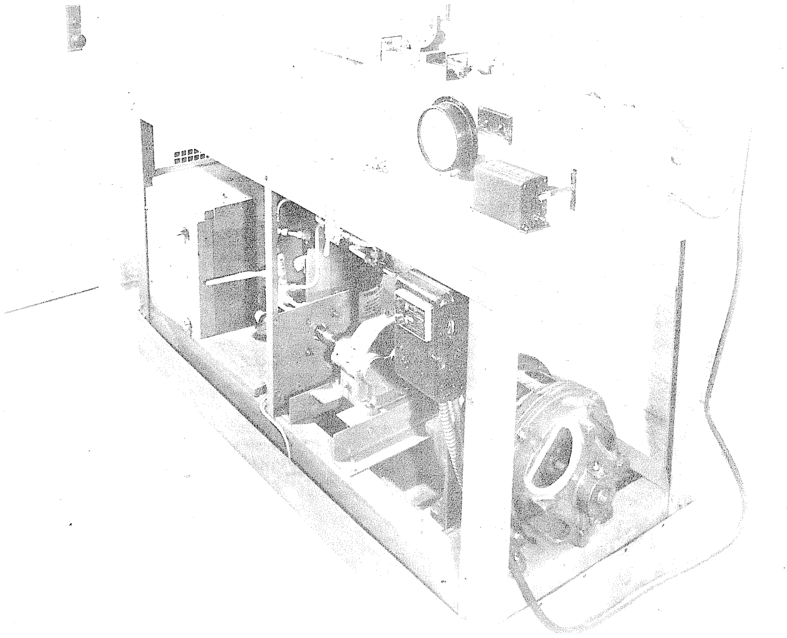


Fig. 3

General View of Machine

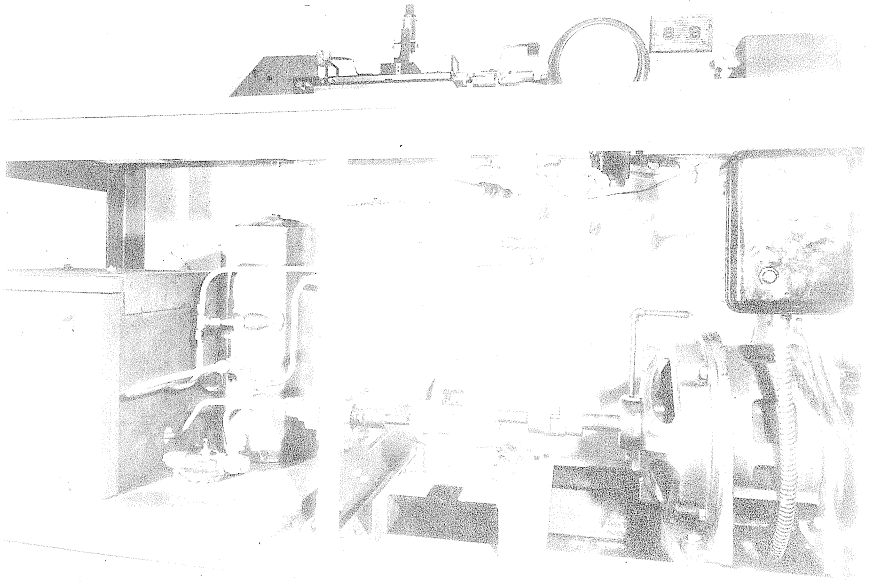


Fig. 4

Hydraulic Section

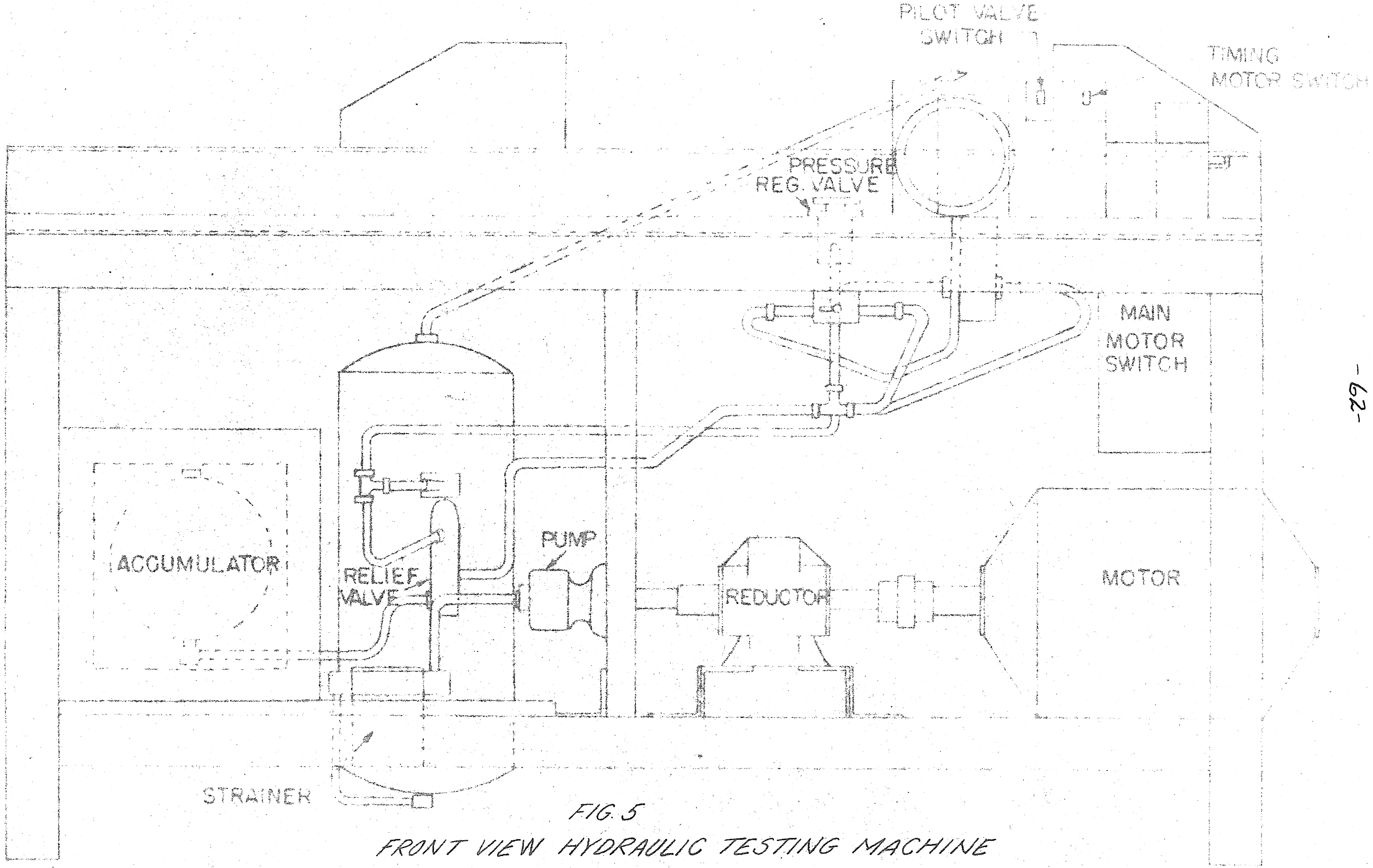


FIG. 5
FRONT VIEW HYDRAULIC TESTING MACHINE

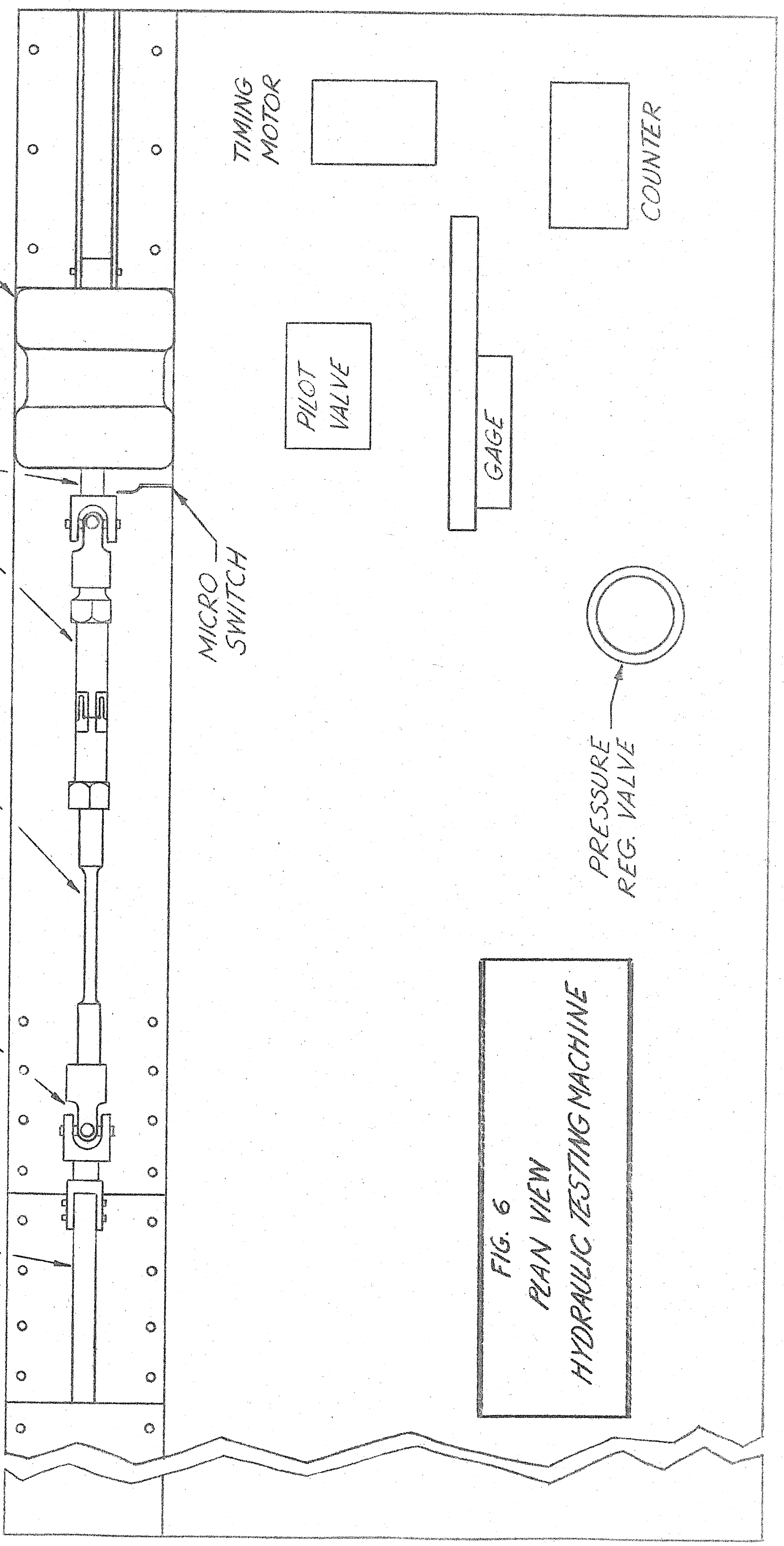


FIG. 6
PLAN VIEW
HYDRAULIC TESTING MACHINE

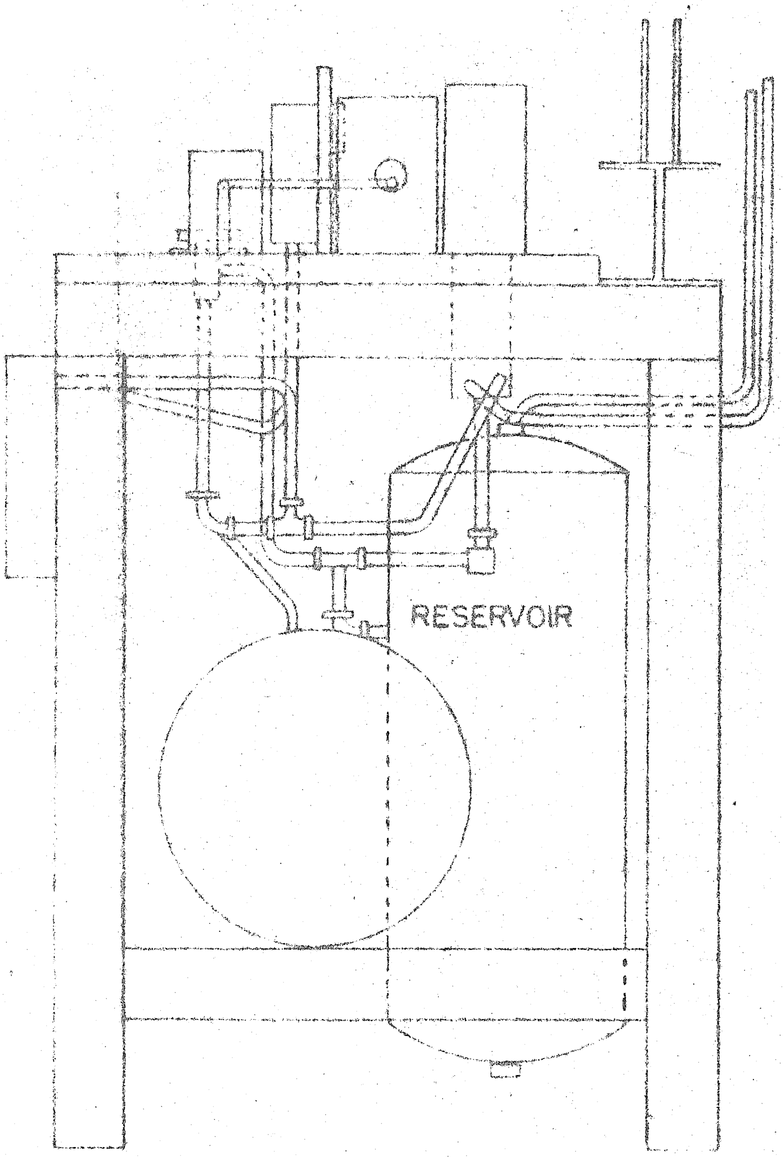


FIG. 7
END VIEW HYDRAULIC TESTING MACHINE

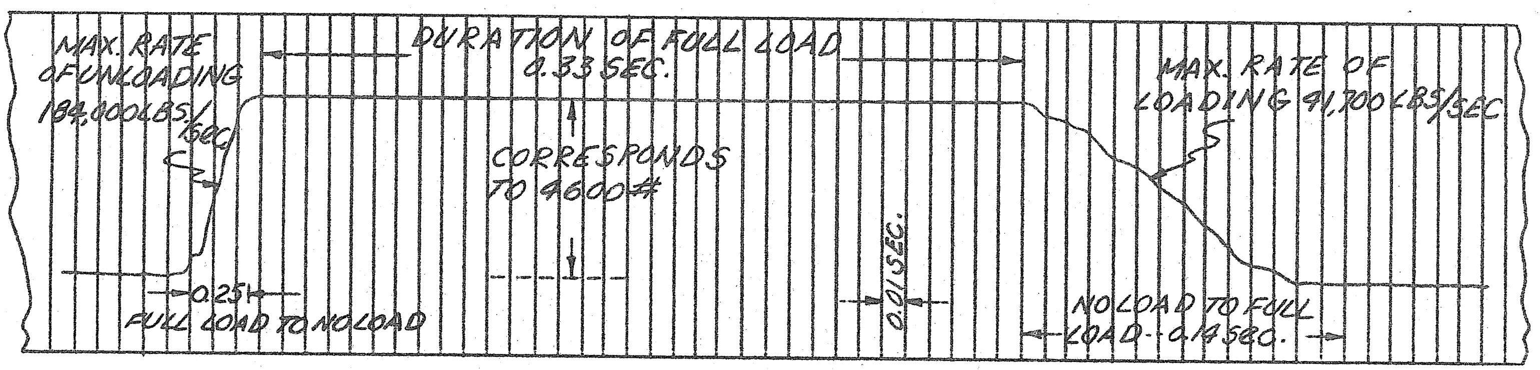


FIG. 8

STUDY OF LOAD APPLICATION

(FROM OSCILLOGRAPH PHOTOGRAPH)

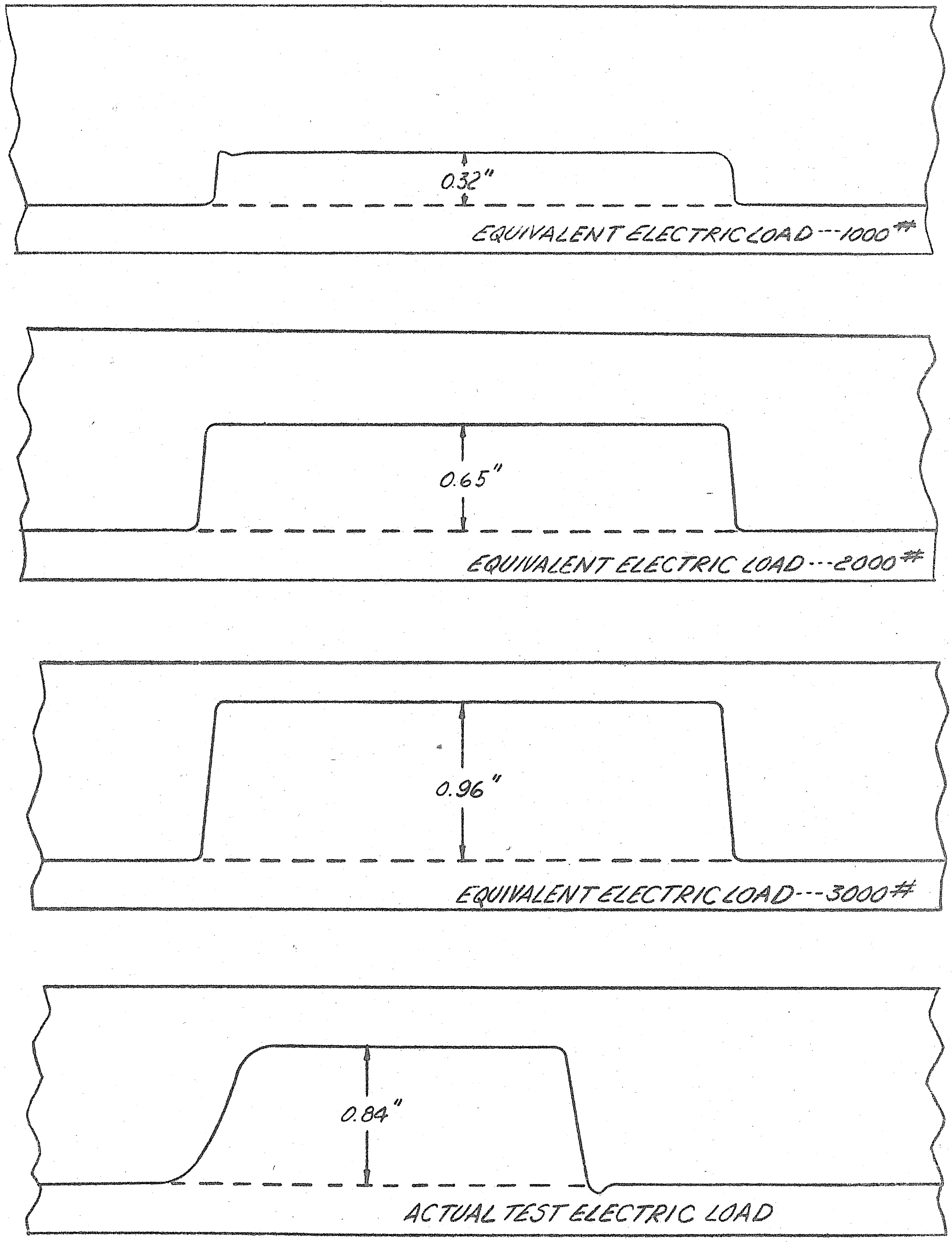


FIG. 9

TYPICAL TEST RESULT AS FILMED

Sample Test
Date________

G.A.L.C.I.T.

Gage

Structures Laboratory

Roughness

Reading No.	Electric Load	Cycles	Height Inches	Actual Load lbs.	Tensile Load p.s.i.
1	1000	4	0.27		
2	2000	4	0.55		
3	3000	4	0.81		
4	4000	4	1.08		
		Ave.	0.27		
5		4	0.70	2590	36600
6		4	0.70	2590	36600
7		4	0.70	2590	36600
8	2000	4000	0.60		
9	3000	4000	0.91		
10	4000	4000	1.19		
		Ave.	0.30		
11		4000	0.78	2600	36800
12		4000	0.78	2600	36800
13		4000	0.78	2600	36800
14	1000	8000	0.20		
15	2000	8000	0.40		
16	3000	8000	0.61		
		Ave.	0.20		
17		8000	0.52	2590	36600
18		8000	0.52	2590	36600
19		8000	0.51	2550	36000

Reading No.	Electric Load	Cycles	Height Inches	Actual Load lbs.	Tensile Load p.s.i.
61	2000	76000	0.44		
62	3000	76000	0.67		
63	4000	76000	0.80		
		Ave.	0.22		
64		76000	0.57	2590	36600
65		76000	0.57	2590	36600
66		76000	0.57	2590	36600
Failure		77380	Fillet Break		

Fig. 10

Typical Data Sheet

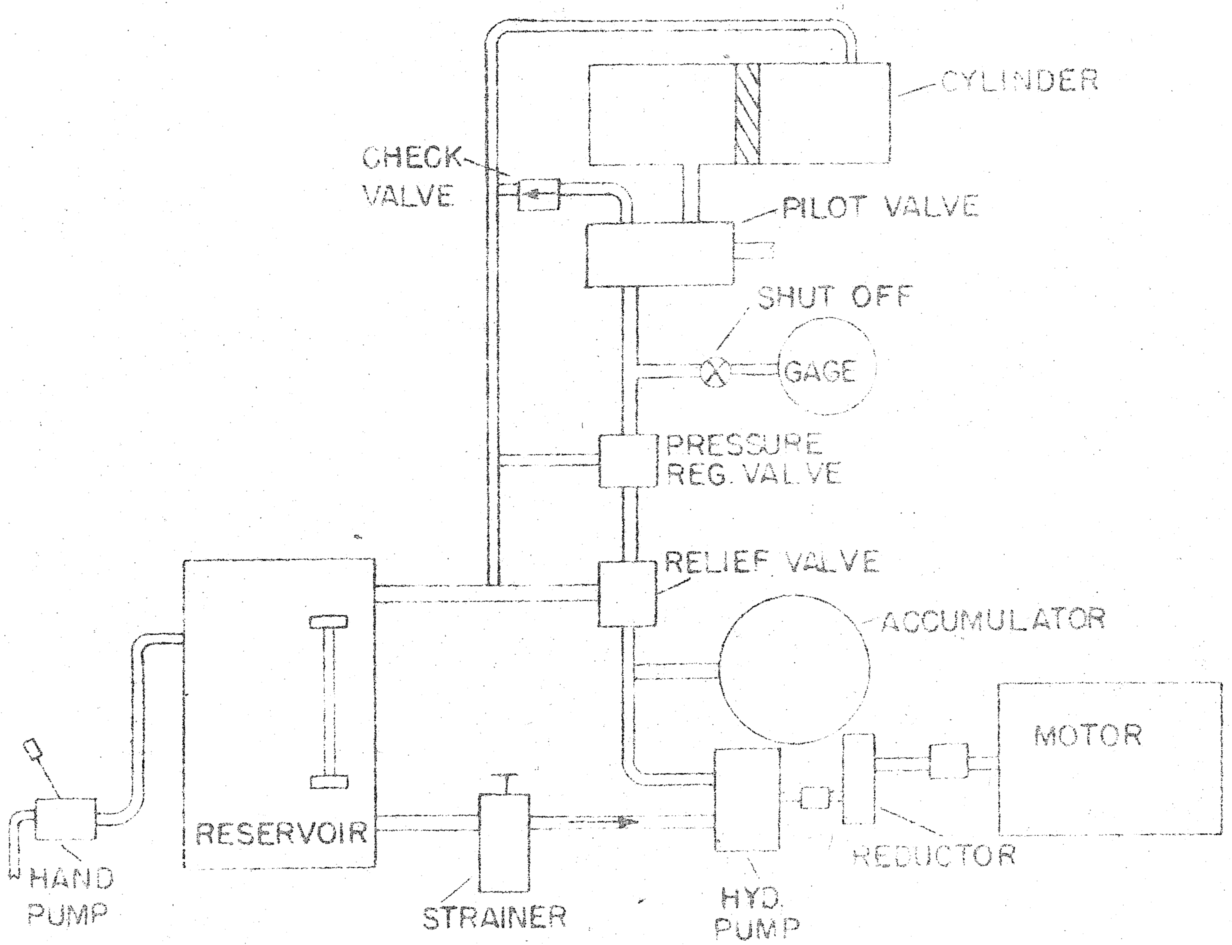


FIG. 11

SCHEMATIC DRAWING OF HYDRAULIC SYSTEM

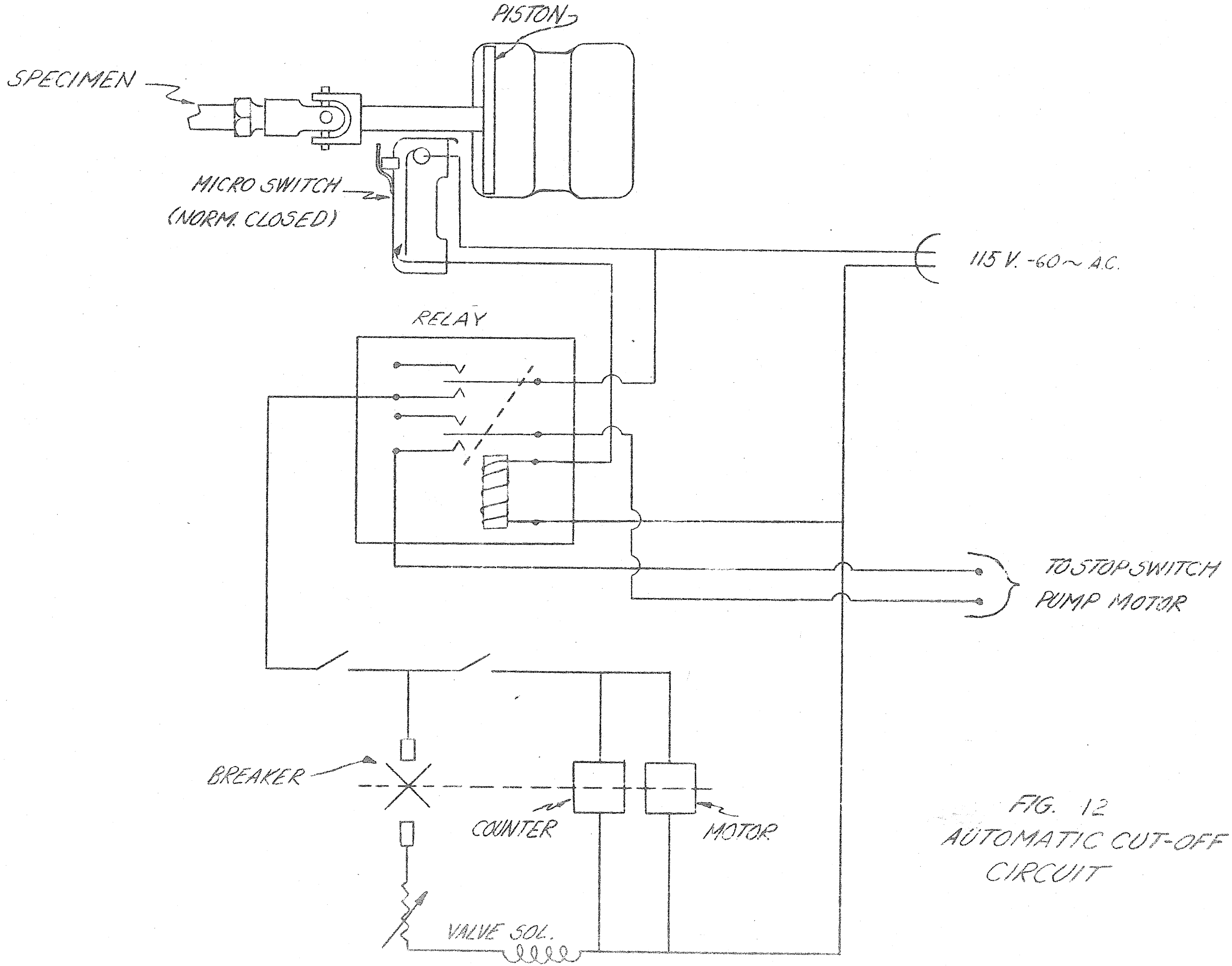
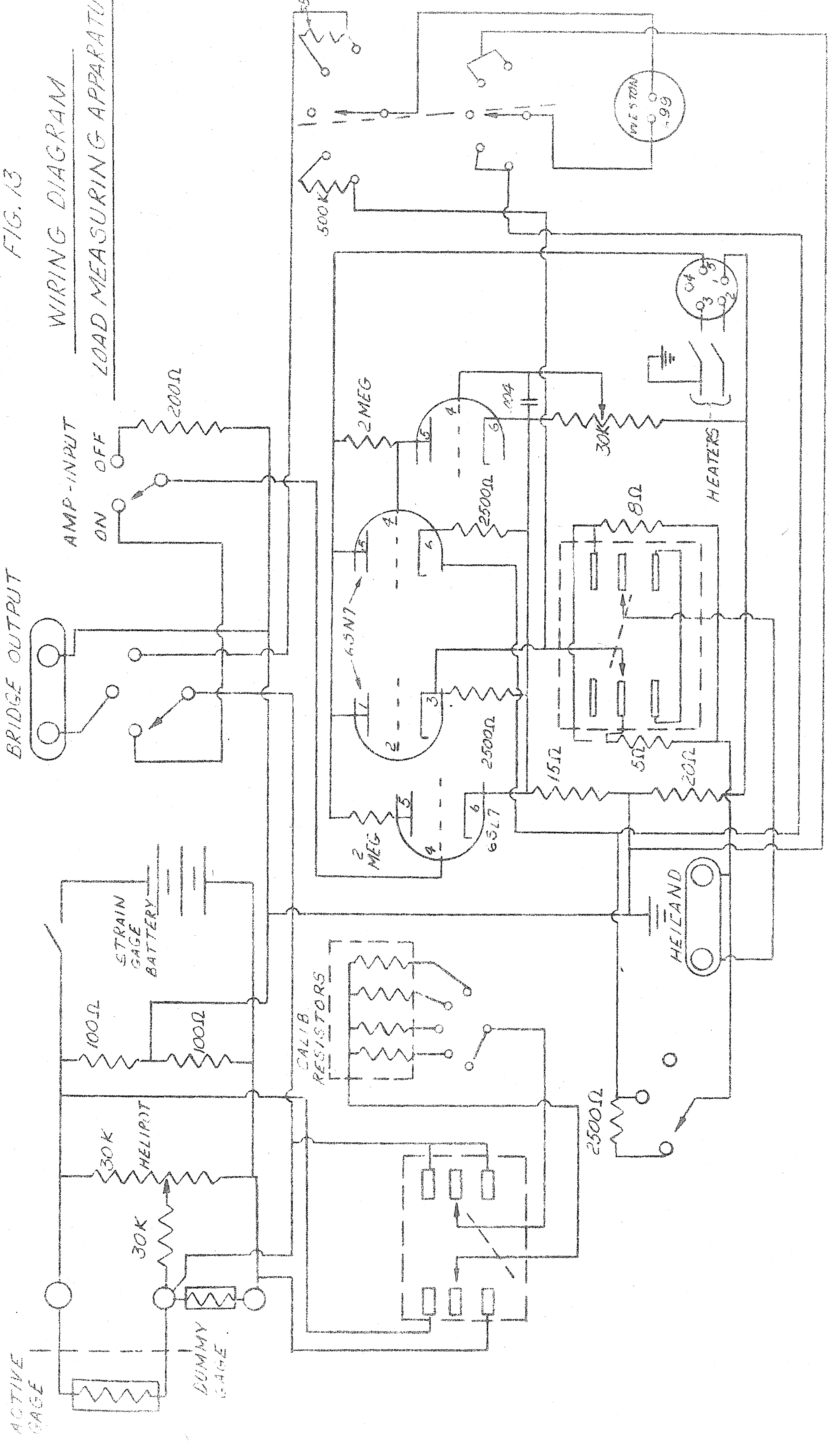


FIG. 12
AUTOMATIC CUT-OFF
CIRCUIT

FIG. 13

WIRING DIAGRAM

LOAD MEASURING APPARATUS



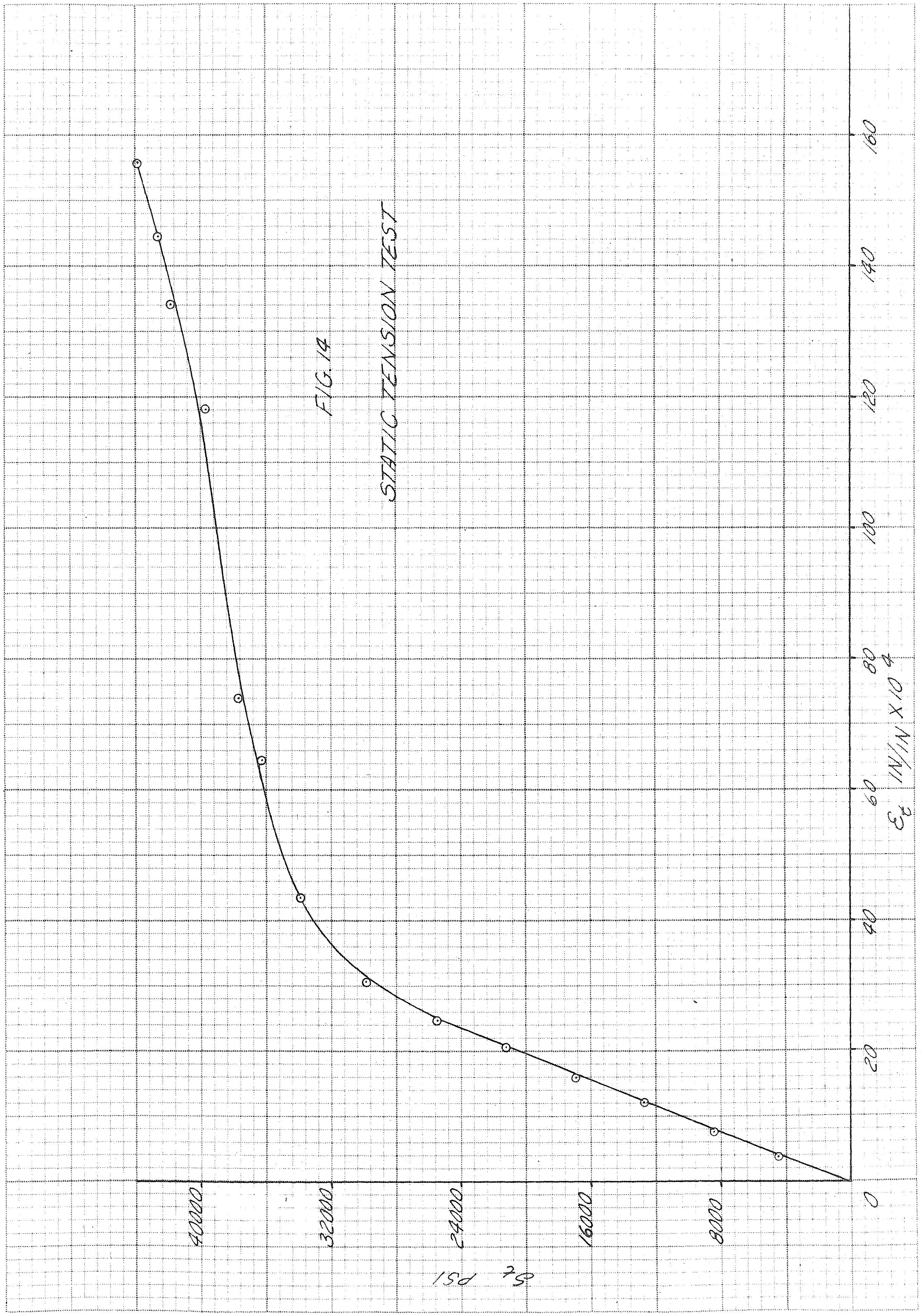


FIG. 14

STATIC TENSION TEST

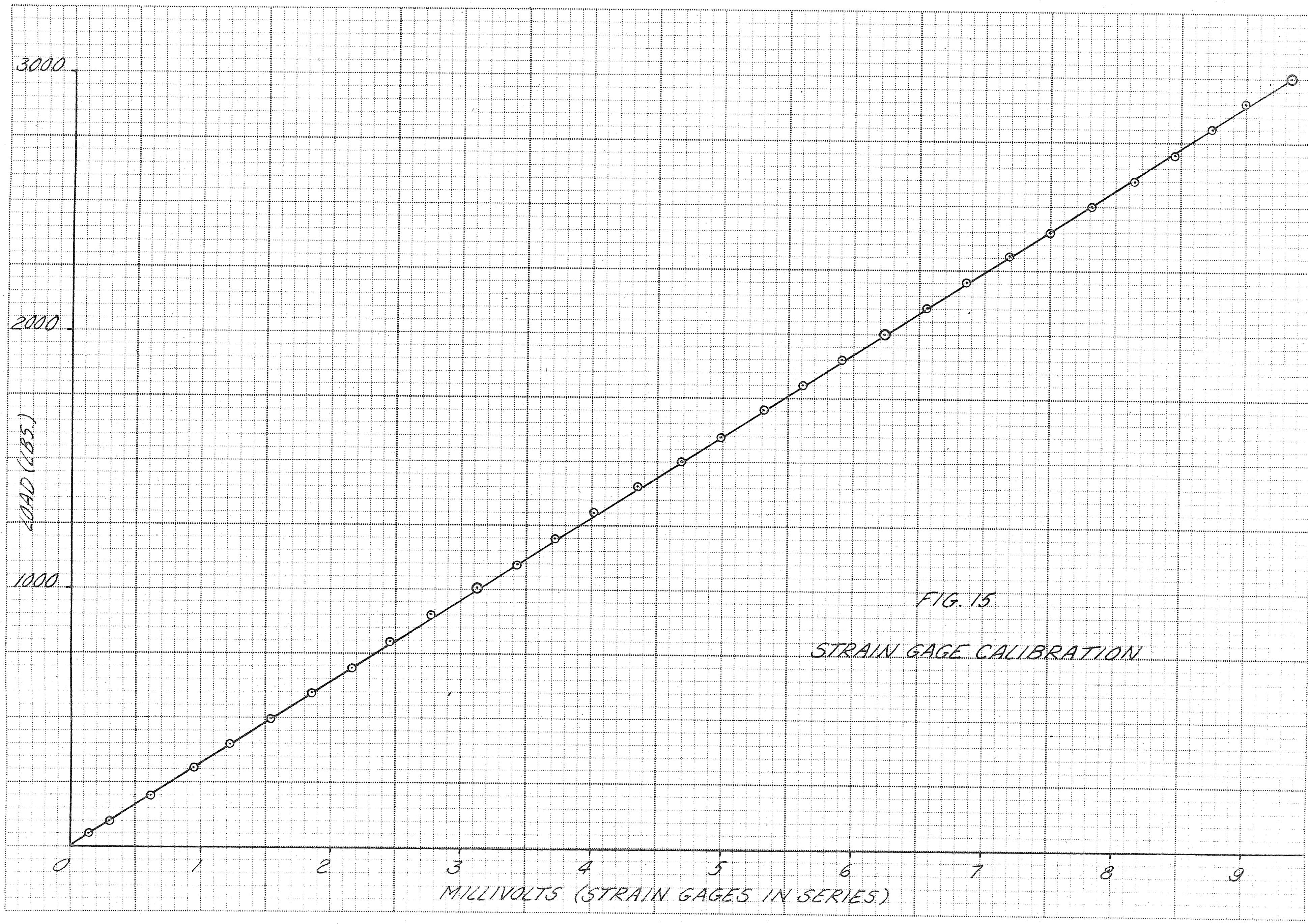


FIG. 15

STRAIN GAGE CALIBRATION

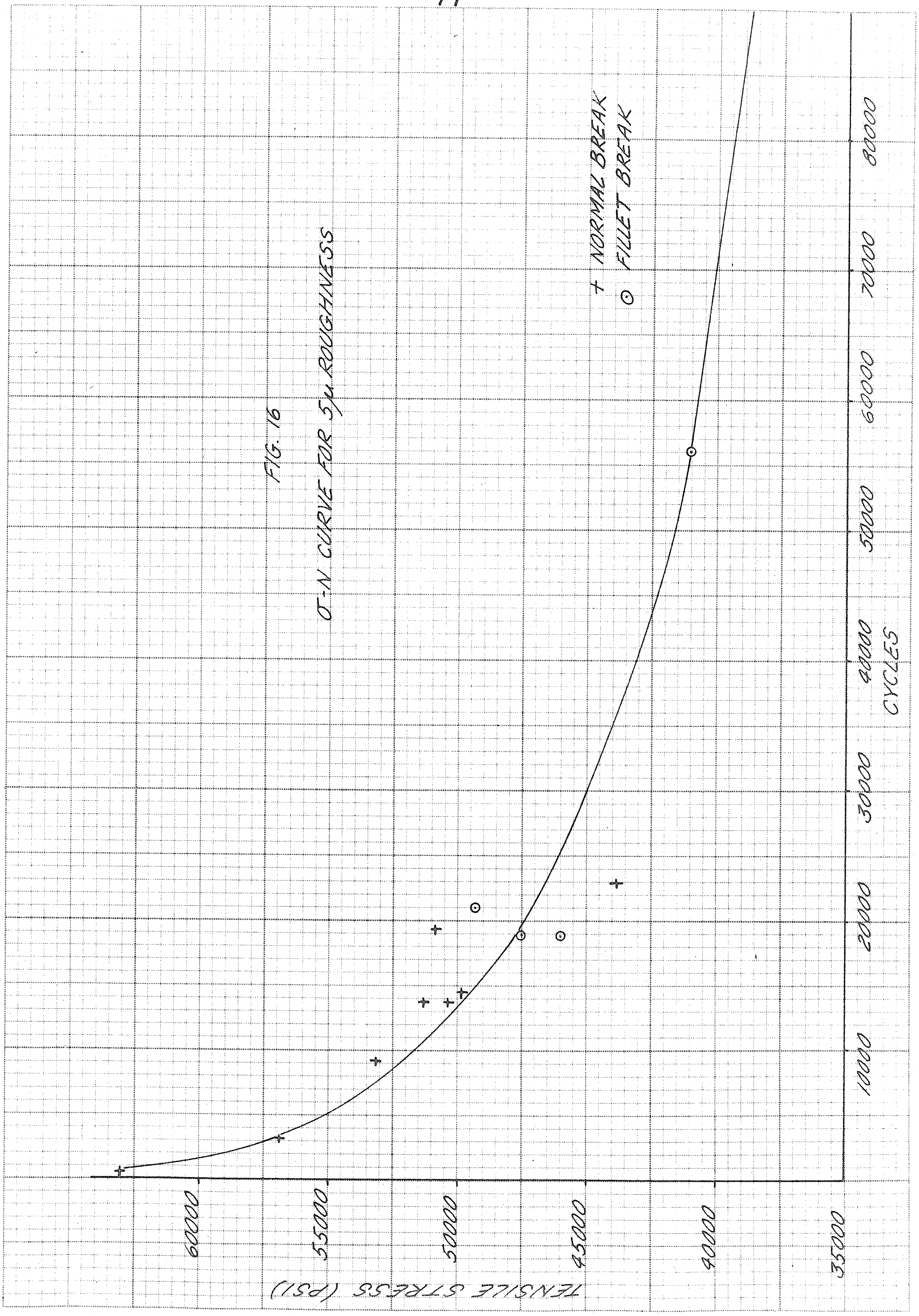


FIG. 16

σ-N CURVE FOR 5μ ROUGHNESS

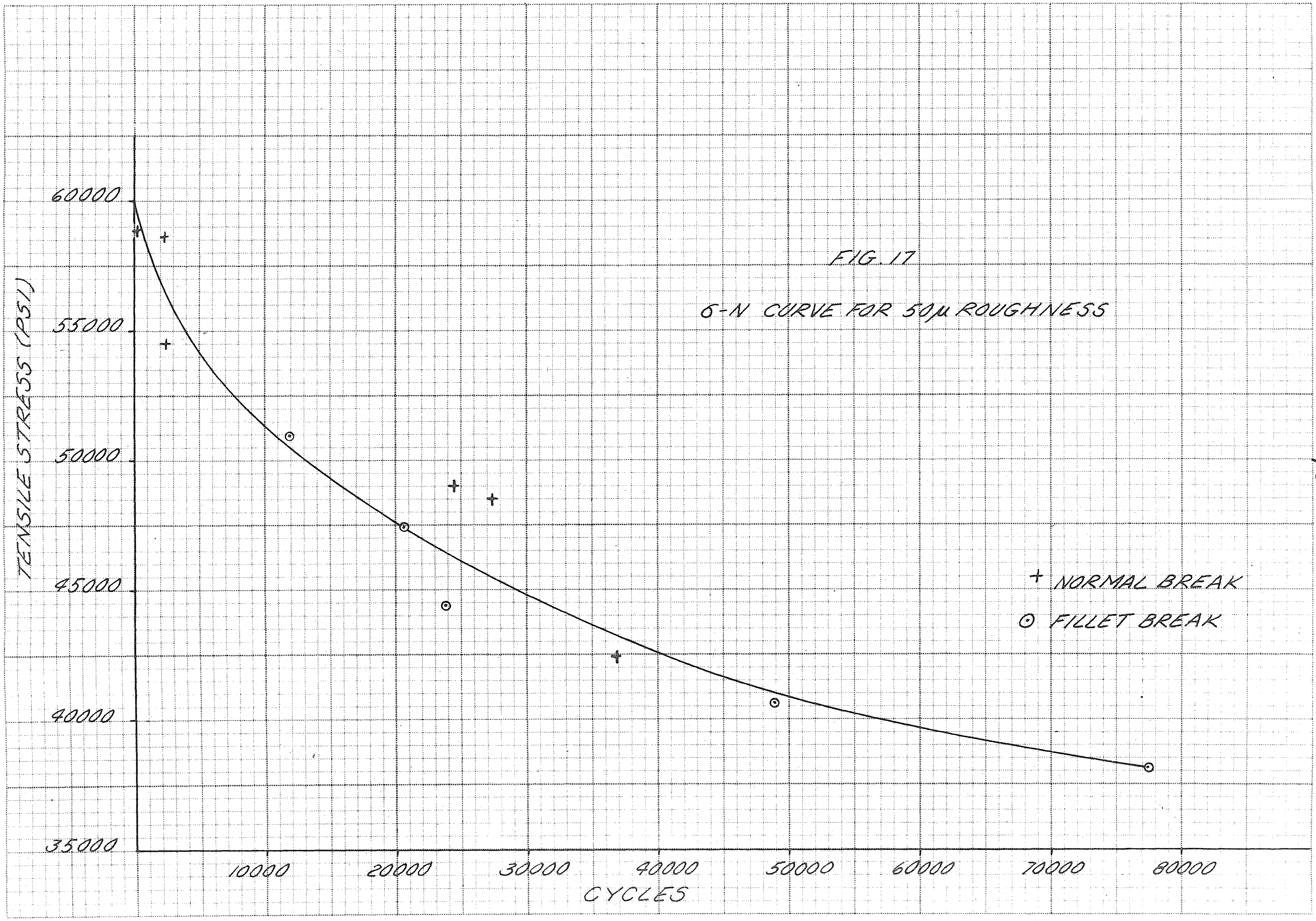


FIG. 17

σ-N CURVE FOR 50μ ROUGHNESS

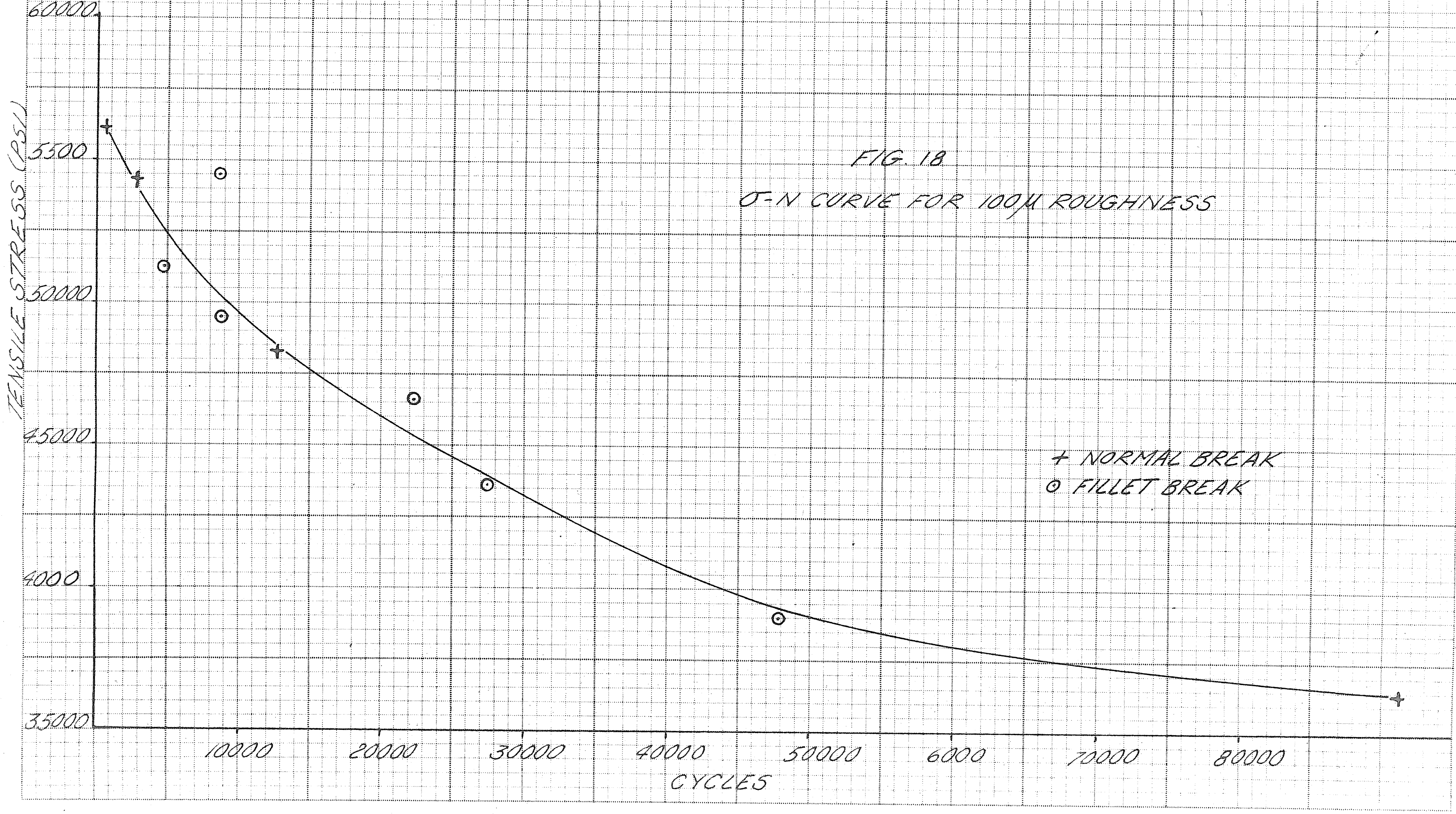


FIG. 18

σ-N CURVE FOR 100μ ROUGHNESS

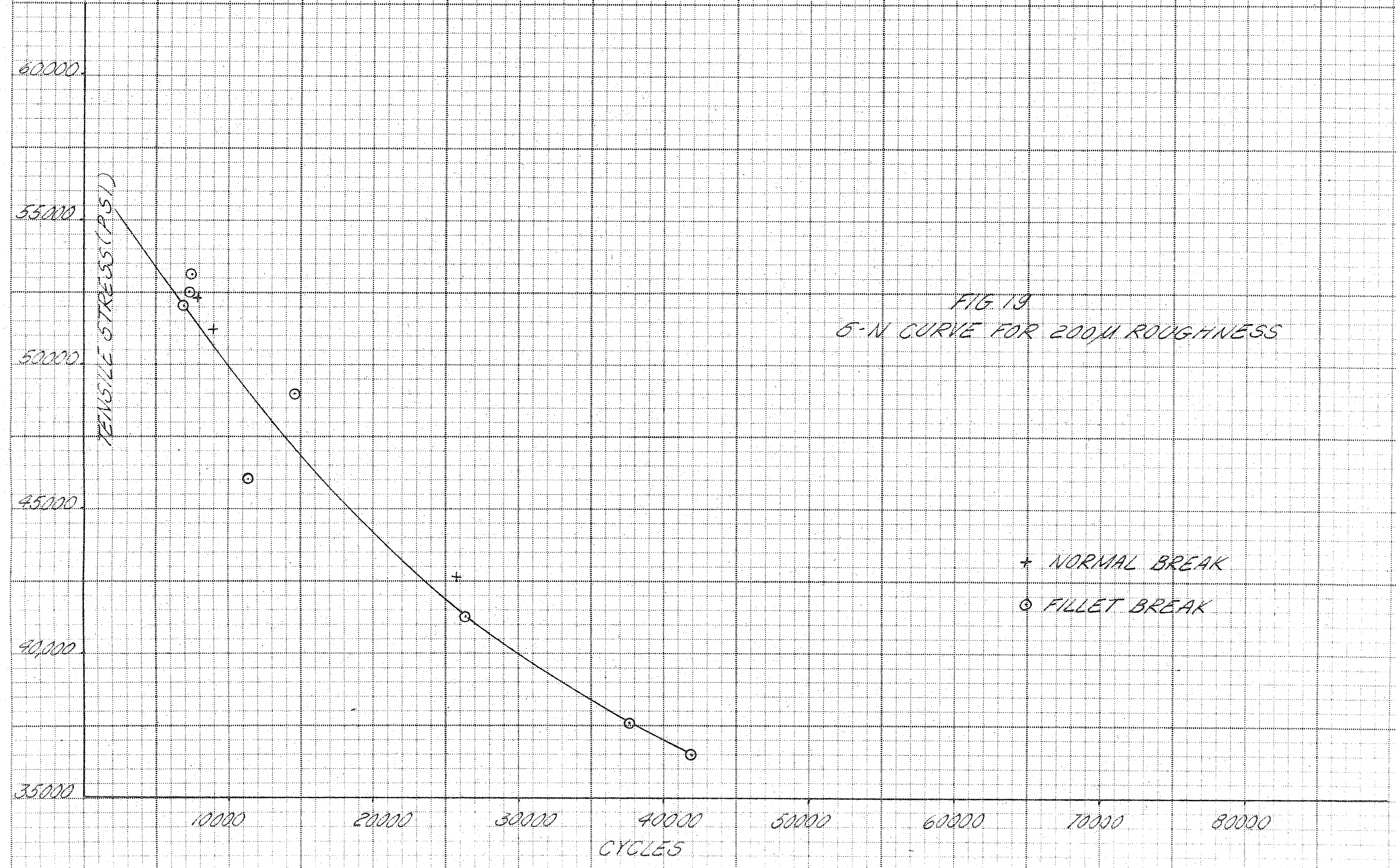


FIG 19
σ-N CURVE FOR 200μ ROUGHNESS

FIG. 20 COMPOSITE PLOT