N8300R:72-106

(NASA-CR-132218) STRESS RELAXATION OF HIGH STRENGTH A-286 BOLTS IN SIMULATED STORAGE AT ROOM TEMPERATURE (Aerojet-General Corp., Sacramento, Calif.) 45 p HC $4.25 CSCL 13I G3/15

N73-24527

Unclas 17725

ENGINEERING OPERATIONS REPORT

FLUID DYNAMICS COMPUTER PROGRAMS FOR NERVA TURBOPUMP

DRA

PROJECT 121

MAY 1972

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N8120R:72-029

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STRESS RELAXATION OF HIGH STRENGTH A-286 BOLTS IN SIMULATED STORAGE AT ROOM TEMPERATURE

I. INTRODUCTION

Possible relaxation of stress in preloaded structural elements of NERVA engines during storage was established as a subject of practical concern in Reference (1)*. Subsequently, a review of the published information relating to this problem, Reference (2), disclosed that there was not then available sufficient data to permit reliable conclusions to be reached. It was generally concluded that thermally activated relaxation of the type customarily encountered at high temperatures was not expected to occur at the low temperatures ($\leq$ 300°F) where long time NERVA storage conditions will prevail. Nevertheless, instances where relaxation occurred by a different mechanism at such moderate temperatures were also reported in Reference (2). Accordingly, testing of the specific materials employed in NERVA were recommended.

In order to first establish the seriousness of the problem at a moderate cost, a Phase I testing program was proposed, Reference (3), which was to be followed by a Phase II effort as required. A test program, Reference (4), was proposed and adopted to guide the conduct of Phase I testing. This is the investigation, with some revisions, that is reported here. It is concerned solely with the room temperature stress relaxation behavior of typical bolted flange components of the NERVA engine. Specifically these are the high strength material A-286 used for bolts, nuts and insert type threaded fasteners and the aluminum alloy 7075 T6 employed widely in the NERVA pressure vessel flanges. It was not considered necessary in this phase of investigation to include the titanium flange material used extensively in the NERVA TPA. Instead, control specimens of high strength steel were employed.

II. SUMMARY/CONCLUSIONS

Twelve simulated bolted flange test specimens were prepared. Parameters that were varied among the twelve specimens were the flange material, the bolt

*References are listed at the end of this report.

shank diameter and the bolt loading in terms of percent of yield strength.

An effort was made to closely control each of the parameters of the tests, with particular attention to the bolt materials properties and the bolt load measurement technique. Bolt materials properties were established by correlating hardness measurements of the test samples with the yield strength properties that were determined from tensile tests of bolts taken at random from the same lot. Control and measurement of bolt tension was established by incorporating a lightly stressed high strength steel thrust collar in the simulated flange assembly. Foil resistance strain gages, arranged in a four arm bridge configuration, provided a strain indication directly proportional to the bolt load that was exerted upon the flange. Creep and drift of the instrumented thrust collar were minimized by employing very high strength materials at relatively low stress. Strain gages and their bonding materials were also selected so as to minimize creep. The materials are rated for use at temperatures up to 300°F, the maximum test temperature anticipated even in Phase II follow-on testing. Standard instrumentation for static strain measurement was employed, including a strain indicator and a 20-channel switching and balancing unit. Repeatability of constant strain readings with this instrumentation over a long term test period is estimated at $\pm$ 10 μ-in/in. This corresponds to about $\pm$ 0.6% of full load on a typical bolt specimen. Thus, very small relaxation of bolt load, less than say 1/2%, could be obscured by drift and noise in the measurement system. This limitation was considered acceptable in view of the fact that stress relaxation of that amount is structurally insignificant.

The test results showed that stress relaxation effects in typical simulated NERVA bolted flanges are very small. Although ambient temperature changes and instrumentation drift somewhat obscured the precision of the test results, it was shown that the most probable relaxation was less than one percent in the first 1000 hour period. This conclusion was based on the averages for all specimens, with straight line projections of the data on semi-log charts beyond the completion of testing (500 hours).

Although the tests were planned so as to incorporate test specimens with different bolt stress, bolt configuration, terminal fastener type and flange material, these differences produced insufficient difference in bolt load relaxation to permit any further conclusions to be drawn.

In addition to the primary conclusion stated above, some other data of interest in bolted flange design were obtained. Among these data are:

(1) Curves showing bolt tension versus torque (Figure 16)

(2) Curves showing bolt tension versus bolt elongation (Figures 14, 15, 19 and 20)

(3) Materials properties for high strength A-286 bolts (Figures 7, 8, 9 and 10)

III. TECHNICAL DISCUSSION

A. DESIGN OF TEST SPECIMENS

The requirements of the relaxation test specimen are that it be structurally related to a typical NERVA bolted flange, while allowing the accurate measurement of bolting tensile forces over a long time-span. The test specimens should include sufficient variation of typical bolted flange parameters so that the parameters contributing most to bolt load relaxation can be readily identified and evaluated.

These requirements were met by a dozen of the specimens shown in Figure 1 (Drawing No. 113995). Two types are indicated, the one at the left incorporating a nut, Item 11, and the other an insert, Item 10, to engage the bolt threads, Item 12. Each specimen incorporates two simulated flange members, Items 5 or 8, made from high strength steel or aluminum, respectively. A short hollow steel tube (thrust collar, Item 9) separates the two flange components. The purpose of this collar is to serve as a bolt tension force transducer. As described later, foil strain gages were bonded to the outer surface of the collar. Since the bolt tension force is always reacted through it, measurement of the thrust force in the collar provides a direct measure of the bolt tension. In contrast, the attachment of a strain gage to the bolt would only give the bolt strain, which is not convertible to stress and load under non-steady creep or relaxation conditions. Therefore the instrumented collar is an indispensable element in the test apparatus.

The objective of these Phase I experiments was to determine the degree of stress relaxation occurring in flange bolts that are stressed near the maximum permitted by the design criteria of SNPO-C-1. Only those parameters of significance to stress relaxation during engine storage were to be considered. Engine temperature was not one of these parameters since terrestrial storage is normally anticipated at ordinary room conditions.

Typical bolted flange designs in the NERVA engine may differ from one another in respect to the applied stress, the flange material, the bolt size, the bolt shank configuration and the terminal fastener. Two variations of all these parameters (except bolt size) were included in these Phase I tests.

The typical test sample is shown in exploded view in Figure 2. It consists of:

(a) A high strength A-286 bolt (EWB-0420-8-46) with 1/2-20 rolled threads and having either a plain shank (0.4995 dia.) or reduced diameter shank (.4340 dia.), and with a hardened steel beveled washer (WCL22-8).

(b) A two-part simulated flange machined from either 4340 steel (Mil-S-500 Cond. F) or 7075 aluminum alloy (QQA-250/12 temper T-6).

(c) A strain gage instrumented collar machined from 4340 steel and with the four linear foil gages connected in an external bridge configuration for measurement of the thrust exerted by the bolt upon the flange.

(d) A terminal fastener with silver-plated threads. The type shown in Figure 1 is the 61170-820 nut. The alternate fastener is an insert (KNH820 T-SP) installed in an aluminum block (7075 alloy).

Component dimensions are shown in Figure 3, and the materials specification list in Figure 4. Twenty four bolts were purchased in one lot for these test preparations.

B. MATERIALS CHARACTERIZATION

Stress relaxation in a given metal is a function of time, temperature and stress. If the relaxation of stress in a test specimen is to be related in a quantitative way to another sample, say a bolt in a NERVA engine flange, there must be some common characterization of the two specimens with regard to a significant property of the materials. In this case the 0.2 percent offset yield strength was chosen as the significant (reference) material property. It is assumed that the relaxation observed in the test sample when it is initially stressed to, say, 85 percent of its yield strength* will be the same in a NERVA bolt made to the same specifications and initially loaded to 85 percent of its yield strength. The two yield strengths are not necessarily equal, nor are they likely to be. To establish this reference, tensile tests were performed on three each standard shank and reduced shank bolts. The test method is indicated schematically in Figure 5, which is the list of instructions to the test laboratory. Typical bolts are shown at the left in Figure 6 and a full-shank bolt pulled to fracture is shown at the right. The stress-strain curves derived from the pair of bonded strain gages placed diametrically opposite on each side of the 6 bolt test specimens are shown in Figures 7 and 8. Yield strengths (.2% offset) are shown plotted on probability paper in Figure 9. The data for one of the reduced diameter bolts was discarded, since it did not fit the normal distribution indicated by the other five. This was attributed to machining effects, since this bolt was the first one machined. Cutting techniques were improved before the others were machined.

Rockwell C hardness measurements were also made on the remaining 18 bolts in this lot, and the normal distribution established. By assuming correlation of the $\pm$ 3σ values of both the hardness and the yield strength, the curve of Figure 10 was obtained. The solid line terminates at the $\pm$ 3σ values of hardness measurements on the 18 bolt test samples. Pairs of bolts were as closely matched as possible by this means so that differences in material properties would not distort their comparison. The mean yield stress for this bolt sample is considerably greater than the published 160 ksi minimum property for high strength A-286 bolts. The vendor data sheet for these bolts specifies 200 ksi minimum ultimate tensile strength.

The tensile properties of other test specimen components were not explicitly determined. Materials specifications and standard quality control procedures were implicitly relied upon to provide the required typical properties.

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*The limit imposed by SNPO-C-1 design criteria

C. INSTRUMENTATION

The instrumented thrust collar (Item 9, Figure 1) is the heart of the bolt stress measurement system. Both the torque and the tension carried by the bolt are reacted through this collar, and thus it can be utilized as a transducer for measurement of both these quantities when properly instrumented. Four bonded metal foil resistance strain gages arranged electrically in a Wheatstone bridge configuration were installed. A separate bridge was installed to measure each of the two loads carried by the bolt, i.e., tension and torque.

The bolt tension force is reacted by an equal and opposite compressive force applied to the collar. Two strain gages with the axes oriented axially and two oriented tangentially on the collar outer surface formed this bridge. The indicated strain output of the bridge is the integrated sum of the four gage strains. The calculated calibration constant for this compression bridge was

$$K_c = \sum_{i=1}^{4} \frac{1}{E} (\sigma_1 - \nu\sigma_2)_i = 88.5 \ \mu\text{-in/in per Kip}$$

where σ_1 is the stress along the strain gage axis and σ_2 the transverse stress. Similarly, the calibration constant for the torque bridge consisting of four gages aligned with the $\pm$ 45° diagonal directions was calculated to be

$$K_t = 251 \ \mu\text{-in/in per Kip-inch}$$

One instrumented collar was prepared for each of the twelve test specimens planned. Two of these were electrically defective and could not be used. The remaining ten were tested in compression in a calibrated hydraulic laboratory testing machine, and with the bridge output measured using the same instruments that were later used in the relaxation tests. Several cycles of load to 40 Kips were first applied so as to eliminate plasticity and creep effects from the transducer unit. Then, calibration curves in compression were obtained as shown in Figures 11 and 12. In general, each unit showed an initial adjustment period up to at least 5 Kips load, followed by linear behavior thereafter. The experimental calibration constants based on the 24 Kips force data are given in Table I.

TABLE I

LOAD CELL COMPRESSION
CALIBRATION CONSTANTS, K_c
(μ-in/in indicated strain
per Kip compressive force)

Load Cell No.	K_c	Load Cell No.	K_c
1	55.1	7	71.2
2	73.0	8	70.0
3	X	9	68.9
4	66.5	10	71.8
5	76.0	11	X
6	70.0	12	75.9

It is seen that the measured compression response is generally less than that which was predicted, averaging 69.8 experimentally as compared to 88.5 predicted. Presumably this is due to lateral confinement of the collar that was not included in the calculation. The response of the load cells is adequate for accurate measurement of bolt tensile forces. Torque calibration of the load cells was not accomplished due to lack of time prior to the program termination. These torque bridges were later found to exhibit no torque response, indicating that electrical defects existed in the gage circuits.

Measurement of the load cell output under test conditions was accomplished with a BLH Model N strain indicator and a BLH 20-channel switching and balancing unit. This is a manual, null balance system that required operator presence for all readings.

D. TESTING - INITIAL PHASE

A typical test setup is shown at (a) in Figure 13. The test specimen is held by its lower flange component only, in a heavy machinists vise.

A calibrated torque wrench with socket engages the bolt head. Strain gage readout instrumentation units are shown at the right. Bolt over-all length measurements were made with a .001 inch-per-division micrometer caliper of 4"-5" capacity, having a spherical adapter in place on one of the anvils. These measurements were taken at intervals of torque during the bolt torquing operation. Figure 13(b) shows a typical test specimen with the strain gage leads proceeding from the load cell.

The test plan parameters are shown in Table II. This table defines all the components of each specimen, gives the significant material properties, the planned loading conditions and the corresponding load cell indicated strain and instrumentation channel. As shown, no instrumentation was available for Specimen Nos. 11 and 12, and testing was not performed on them.

In each case, bolt torque was applied in increments of 200 μ-in/in load cell output. The applied bolt torque, the measured bolt elongation and the measured bolt tension are tabulated for the initial loading of each specimen in Table III. The data are plotted as bolt elongation versus bolt tension in Figures 14 and 15, for the plain and reduced shank specimens respectively. The estimated linear mean curves indicate that bolt elongations of 505×10^{-6} and 660×10^{-6} inches per kip bolt tension are produced in the two types of bolt, respectively. These relative elongations are nearly in the same relation that one would predict solely on the basis of the bolt shank cross sectional areas.

The bolt torque vs. tension data are plotted in Figure 16, showing the large variation of torque required to produce a given tension, about ± 30 percent from the mean. The envelope of the data indicates a nonlinear relationship between bolt tension and applied torque.

Following the initial loading described in Table III, the load cell strain indicated was recorded intermittently for a period of about 140 hours. Typical test records of bolt tension (load cell strain readout) as a function of time are shown in Figure 17. Fluctuations of load seen there are almost entirely a consequence of differential thermal stress induced by ambient temperature fluctuation. Steel flange specimens (Nos. 2, 3 and 4) exhibit virtually no change because of the minor thermal expansion differences in their components. Aluminum flange specimens on the other hand (Nos. 6, 7 and 8 in Figure 17) show

TABLE II

BOLT RELAXATION TEST PARAMETERS* - INITIAL LOAD APPLICATION

Spec. No.	Bolt No.	Flange Mat'l	Fastener Type	Bolt Shank Hardness (R_c)	Bolt Min. Area (in^2)	Thread Root Area (in^2)	Bolt .2%YS (ksi)	Bolt Tension (%YS)	Bolt Tension (kips)	Load Cell (#)	Max. $\Delta\varepsilon_c$ (μ-in/in)
1	B	Stl.	Nut	44.0	.1515	.1515	196.2	85	25.26	1	1390
2	Q	Stl.	Nut	44.0	.1491	"	196.2	85	24.87	2	1810
3	H	Stl.	Ins.	44.3	.1515	"	198.6	85	25.57	4	1720
4	M	Stl.	Ins.	44.3	.1479	"	198.6	85	24.97	5	1675
5	C	Al.	Nut	44.6	.1515	"	201.1	85	25.90	6	1810
6	E	Al.	"	44.6	.1515	"	201.1	75	22.85	7	1640
7	N	Al.	"	44.3	.1488	"	198.6	85	25.12	8	1750
8	R	Al.	"	44.3	.1480	"	198.6	75	22.04	9	1540
9	G	Al.	Ins.	44.4	.1515	"	199.5	85	25.69	10	1825
10	I	Al.	"	44.4	.1515	"	199.5	75	22.67	12	1740
11	J	Al.	"	44.2	.1485	"	197.8	85	24.96	-	
12	L	Al.	"	44.3	.1485	"	198.6	75	22.12	-	

*Molykote No. 321 Applied to Bolt Threads and to Bolt Head Bearing Surfaces

TABLE III

BOLT TORQUE TEST DATA*
- INITIAL LOAD APPLICATION

TEST NO. 1

T	ΔL	P
0	0	0
10	.0017	4.9
20	.0037	8.3
28	.0059	11.7
40	.0080	15.5
55	.0097	18.7
65	.0117	22.1
80	.0139	25.7

TEST NO. 2

T	ΔL	P
0	0	0
9	.0016	3.8
15	.0036	5.8
20	.0055	7.7
27	.0075	10.5
40	.0093	13.4
50	.0112	16.2
60	.0125	19.0
70	.0145	21.8
78	.0167	24.9

TEST NO. 3

T	ΔL	P
0	0	0
8	.0024	4.5
19	.0044	7.3
28	.0057	10.1
36	.0066	12.8
46	.0081	15.7
57	.0099	18.5
69	.0113	21.3
80	.0134	24.0
88	.0144	25.9

TEST NO. 4

T	ΔL	P
0	0	0
6	.0015	2.7
15	.0034	5.3
22	.0051	7.7
30	.0071	10.2
41	.0088	12.9
51	.0110	15.6
64	.0135	18.3
76	.0165	22.0

* T = Torque Wrench Reading, LB-FT
ΔL = Growth of Over-all Bolt Length, Inches
P = Bolt Tension, Kips

TABLE III (Cont.)

TEST NO. 5

T	ΔL	P
0	0	0
3	.0028	2.2
10	.0040	4.8
17	.0040	7.7
25	.0048	10.8
30	.0060	13.7
37	.0085	16.7
44	.0090	19.7
50	.0100	22.7
59	.0128	25.9

TEST NO. 6

T	ΔL	P
0	0	0
9	.0019	2.3
13	.0033	4.7
22	.0051	7.5
30	.0065	10.4
37	.0077	13.3
45	.0085	16.3
53	.0098	19.3
61	.0116	23.1

TEST NO. 7

T	ΔL	P
0	0	0
7	.0017	3.9
11	.0031	6.5
17	.0048	9.0
24	.0065	11.7
31	.0083	14.5
40	.0099	17.3
49	.0117	20.0
58	.0137	23.0
64	.0147	25.1

TEST NO. 8

T	ΔL	P
0	0	0
8	.0016	3.9
15	.0034	6.5
21	.0049	9.0
29	.0067	11.7
36	.0086	14.5
45	.0110	17.3
51	.0125	20.0
58	.0133	22.2

TABLE III (Cont.)

TEST NO. 9

T	ΔL	P
0	0	0
5.5	.0007	2.3
13	.0012	4.7
21	.0030	7.5
29	.0045	10.4
37	.0051	13.3
44	.0066	16.3
50	.0083	19.3
60	.0102	22.3
70	.0119	25.7

TEST NO. 10

T	ΔL	P
0	0	0
6	.0021	2.1
15	.0030	4.2
20	.0042	6.8
28	.0060	9.5
35	.0071	12.3
41	.0083	15.1
49	.0091	17.9
57	.0105	20.8
61	.0120	22.6

marked changes of load with every temperature change. Temperature is noted in Figure 17 at several data points. The effect of temperature on load in the steel specimens was opposite in sign and much lower in magnitude than for the aluminum specimens. The coefficients of load cell output change with temperature, λ, was determined for several temperature fluctuations in each test specimen. The averages are noted in Table IV below. It should be emphasized that these coefficients reflect changes of bolt load with temperature. Temperature change alone would not result in any change of load cell output.

TABLE IV

LOAD CELL TEMPERATURE COEFFICIENTS

Test Specimen No.	Coefficient, λ (μ-in/in per °C)
1	- 3.5
2	- 3.1
3	- 3.2
4	- 2.8
5	+ 10.2
6	+ 11.5
7	+ 10.5
8	+ 11.5
9	+ 12.9
10	+ 14.1

Corrections to the load cell output for temperature fluctuation were made to a good approximation according to the linear equation

$$\varepsilon_{true} = \varepsilon_{gage} - \varepsilon_o - \lambda(T - T_{ref.})$$

where ε_{true} is the corrected load cell output, μ-in/in.
ε_{gage} is the load cell scale reading
ε_o is the initial value of the load cell reading prior to load application
λ is the correction coefficient for thermally induced bolt load changes, Table IV
T is the observed temperature at the time of gage reading, °C
and T_{ref} is the temperature at the beginning of the test.

Upon applying the appropriate corrections, the fluctuating of load cell output was greatly reduced, Figure 18. The remaining fluctuation appeared to be largely the result of instrumentation reference shifts, and evidence of significant bolt stress relaxation did not appear. As a result, it was concluded that continuation of the tests according to the original schedule offered little promise of further information.

E. TESTING - REVISED PLAN

In order to explore the range of stress where relaxation at room temperature might conceivably occur, a revised bolt loading plan, Table V, was adopted. Each specimen that had been loaded for approximately 140 hours according to the schedule of Table II was now treated as a virgin specimen in regard to observations of stress relaxation. This was considered justified on the basis of the absence of any prior significant relaxation of bolt stress. As noted in Table V, five pairs of bolt specimens were stressed from 85%YS to 105%YS in increments of 5%. The prescribed bolt load in kips and the load cell output in μ-in/in shown in Table V are derived from the bolt and load cell characteristic data previously given in Table II and Figures 11 and 12.

TABLE V

INCREASED BOLT LOAD SCHEDULE

Specimen No.	Bolt Tension (% Y.S.)	Bolt Tension (Kips)	Max. $\Delta\varepsilon_c$ (μ-in/in)
1	90	26.75	1480
2	90	26.33	1920
3	95	28.58	1930
4	95	27.90	2120
5	100	30.47	2120
6	105	31.99	2180
7	100	29.55	2060
8	105	30.86	2170
9	85	25.69	1830
10	85	25.69	1950

Re-loading procedures were much the same as described for the first loading, without returning to zero load. Torque and bolt elongation data fitted the original loading data quite well, as evidenced by the two sets of curves in Figures 19 and 20, although there was a slight overlap. It is evident that the reduced shank Bolt No. 8 in Figure 20 has proceeded well into the plastic phase, but the corresponding Bolt No. 7 in Figure 19 evidently has not. In order to check the possibility that the desired loading had not been achieved (in terms of percent of yield strength) plots similar to Figures 19 and 20 were made for all the specimens. These plots indicated significant traces of plastic elongation only in Bolt Specimen Nos. 4, 8 and 10. This observation was partly contradictory to the expected result.

In order to perform an independent check on the bolt loads indicated by the load cells, a calculation based upon the measured bolt elongations and the measured elastic moduli was performed according to the equation below.

$$P_\Delta = \frac{A_s E \Delta L}{L} \text{ (approximately)}$$

where P_Δ = bolt load, lb., derived from bolt elongation data

A_s = bolt shank cross section area, in^2

ΔL = bolt elongation, in.

L = bolt length, inches ($L = 3$ in)

E = bolt elastic modulus ($E = 31.3 \times 10^6$; See Figures 7 & 8)

For comparison the bolt loads P_ε were also derived from the load cell output recorded, ε_c, and the calibration curves of Figures 11 and 12. Finally, the prescribed bolt load P in the test plan of Table V was tabulated. These significant data and the comparative results are listed in Table VI. The significance of the ratio P_Δ/P is that values very much larger than unity indicate that appreciable plastic deformation probably occurred during the loading of the bolt. Values close to unity indicate that approximately the prescribed load was applied and that little plastic deformation results. On this basis, bolt Nos. 1, 3, 4 and 10 experienced appreciable plastic deformation and bolt Nos. 5 and 7 probably received

TABLE VI

BOLT LOADS DERIVED FROM LOAD CELL AND BOLT ELONGATION DATA, RESPECTIVELY

Test No.	ΔL (in)	A_s (in^2)	Calc. P_Δ (Kips)	Actual ε_c (μ-in/in)	Calibr. P_ε (Kips)	Table V P (Kips)	Ratio P_Δ/P
1	.0150	.196	30.6	1510	27.4	26.8	1.14
2	.0179	.149	27.8	1942	26.6	26.3	1.06
3	.0164	.196	33.5	1920	28.5	28.6	1.17
4	.0254	.148	39.2	2120	28.0	27.9	1.40
5	.0138	.196	28.3	2050	29.5	30.5	.93
6	.0151	.196	30.9	2170	30.8	32.0	.97
7	.0171	.149	26.6	2070	29.6	29.6	.90
8	.0209	.148	32.2	2182	31.1	30.9	1.04
9	.0133	.196	27.2	1835	25.9	25.7	1.06
10	.0143	.196	29.2	1940	25.6	25.7	1.14

less load than had been intended. The remainder apparently were loaded close to the tension that was prescribed, but without much plastic deformation resulting. Fig. 21 is the plot of the bolt loads P_ε derived from the load cell calibration curve as a function of the bolt elongation ΔL measured by micrometer. A straight line "best fit" curve is drawn for both the plain and reduced shank bolts. Considerable scatter is noted, and the two vectors proceeding from each data point to the curves denote the uncertainty as to whether the scatter is due to bolt load calibration error, to plastic elongation of the bolt, or to measurement errors in bolt elongation. In general, the points lying to the right of their respective curves are those bolts in which significant plastic deformation was induced. Points to the left evidently represent those bolts which did not experience loads as large as had been prescribed in Table V. Inconsistencies between Table V and Figure 21 are probably attributable largely to either (a) errors in the specific bolt yield strength derived from Figure 10 and Table II, or (b) failure of the load cells to perform in the actual tests in the same manner as in the calibration tests, Figures 11 and 12. The apparent deviations from the test plan revealed in Figure 21 may aid later in the interpretation of the behavior of each test specimen.

The temperature-corrected test data for the revised loading test plan is shown on a linear time plot in Figure 22. No significance should be attached to the rapid change of load cell output in the first few hours. This was the result of rapid, uncontrolled changes of the ambient temperature, a condition which was rectified only after several hours. A general and abrupt upward shift of nearly all the load cell outputs is noted between 80 and 100 hours. This is almost certinaly a consequence of instrumentation drift. It is clear, in spite of this shift, that there was little if any relaxation of load in any of the bolts in the first 200 hours. Specimen No. 2 is seen to be almost free of any time-dependent change, while No. 1 exhibited a fairly large shift, about $\pm$ 1.5%. The same type of behavior was observed in the first loading, Figure 18, and the effect is believed to be a property of the individual load cell rather than of the imposed loading conditions or the individual test specimen properties.

F. ANALYSIS

The effect of time on the load cell output is more clearly seen in the semi-log plots of Figures 23, 24 and 25. These figures show the slight but abrupt change in each indicated load near the 100 hour mark. In the period between 100 hours and 500 hours, the load cells in Test Specimens No. 1 and 3 showed a continuing erratic drift that must be attributed to the load cell strain gage installations rather than to relaxation of the bolt load. In contrast, Test Specimen Nos. 2 and 4 show a very stable pattern of response in the same time period. The aluminum flange specimens, Nos. 5 to 10 inclusive, show some moderate scatter in the indicated load cell output, intermediate between the two extremes noted in the steel-flange specimens.

Figures 23, 24 and 25 show straight line segments on semi-log plots giving the best possible fit to the data points. These provide the most probable values for the combined effects of load relaxation and the various sources for drift effects in the instrumentation. No such interpretation was attempted for Nos. 1 and 3 due to their erratic behavior. Examination of these data does not lead to any clear-cut conclusion about bolt stress relaxation, due to the masking effect of the instrumentation shifts. Two extreme viewpoints can be taken, however, in evaluating the data; (A) comparison of the load cell output intercepts at 10 hours and when extrapolated to 1000 hours or (B) the slope of the segment from 100 hours to 500 hours is extended from 1 to 1000 hours. Table VII gives the results of these extreme interpretation methods, and the individual and combined average values. It is seen that there is little or no correlation of the individual average percent relaxation with the imposed test conditions listed in Table VII. On this basis it is concluded that the most probable relaxation of bolt tension is less than one percent in the first 1000 hours of storage, when the applied stress is equal to or greater than 85% of the bolt tensile yield strength. The relaxation projected on this basis during the second 1000 hour period would be much less, on the order of 0.1 percent.

TABLE VII

INTERPRETATION OF THE TEST DATA
BY TWO OPPOSITE EXTREME METHODS*

Test Specimen No.	Nominal Load, % Yield	Interpretation Method A (%)	Interpretation Method B (%)	Avg. (%)
1	90	X	X	X
2	90	0	2.00	1.00
3	95	X	X	X
4	95	0	1.10	0.55
5	100	0	1.68	0.84
6	105	-0.18	2.52	1.17
7	100	-0.33	1.50	0.59
8	105	0.36	3.84	2.10
9	85	-0.21	2.65	1.20
10	85	-0.66	0.70	.02
			Average	0.93

*See text for description of interpretation methods A and B

IV. REFERENCES

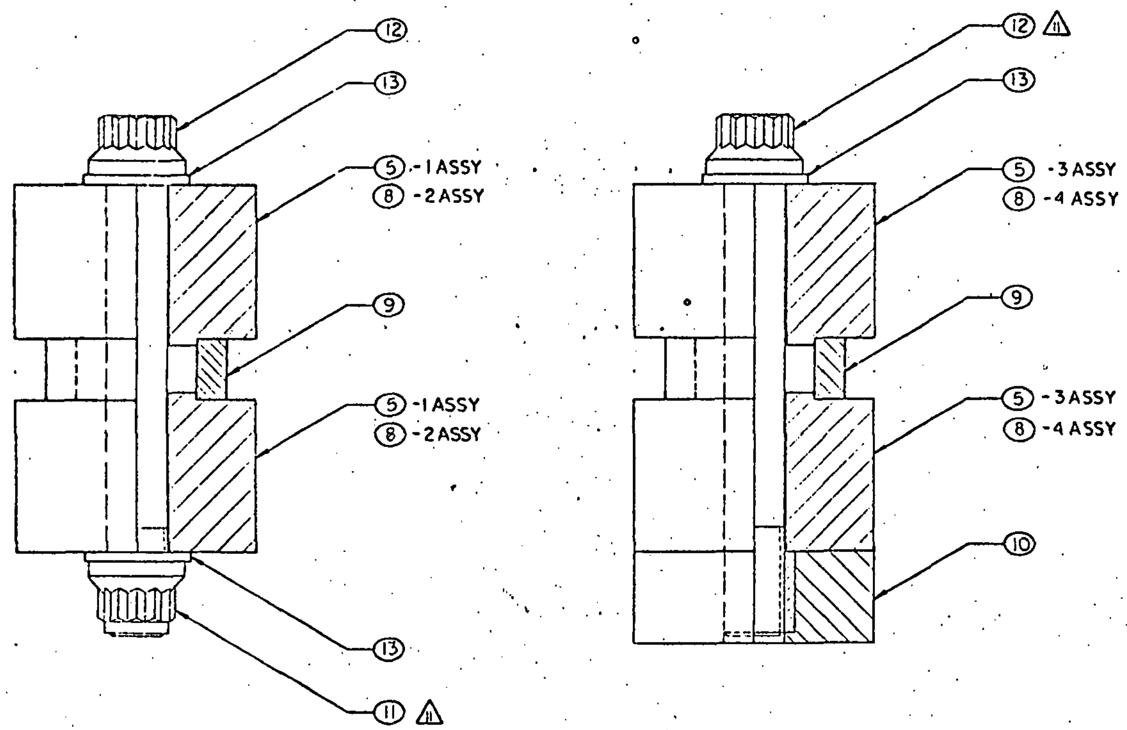
(1) Memorandum N4310:032, U. A. Pineda to I. L. Odgers, "Design Criteria for Storage Conditions", 6 January 1971

(2) Memorandum N4350:MM71-111, H. Derow to T. A. Redfield, "Studies Leading to Design Criteria for Storage Conditions", 17 March 1971

(3) Memorandum N8120:082, R. C. Sampson to H. Derow, "Recommendations for Engine Storage Bolt Relaxation Study", 11 October 1971

(4) Memorandum N8120:113, R. C. Sampson to H. Derow, "Bolt Relaxation Phase I Test Plan", 19 January 1972

... PER MIL-D-1000 FORM 3, MIL-STD-100 AND
... AND SHARP EDGES ... .005-.015 R
... NOTED.
... UNLESS OTHERWISE NOTED.
... PER AGC-STD-9007 LEVEL I
...
... AND APPLICABLE DASH NUMBER.
...CEPTANCE STATUS FOR NON-DESTRUCTIVE TESTING.
...NUFACTURES INSTRUCTIONS.
...R MANUFACTURES INSTRUCTION.
...SETTE GAGES TO BE CONNECTED IN EXTERNAL
...URATION.
...FECT PER MIL-I-6866 TYPE I METHOD A.
...ATERIA PER ANS9032-1.
...NT TO THREADS PER AGC-STD-4351.
...EMENTS TO BE DETERMINED BY COGNIZANT ENGINEER.
...ABRICATION ORDER INSTRUCTIONS.



-1 & -2 ASSY

-3&-4 ASSY

FIG. 1 BOLT TENSION RELAXATION TEST SPECIMENS

		AR	AR	AR	AR	94499	MOLY COTE TYPE 321	LUBRICANT
1						23572	[illegible] 220 T-5P	INSERT
	AR					01083	215058	SOLDER
	AR						216426	ADHESIVE
	AR						217925	PROTECTIVE COATING
	1						216363	TERMINAL
	2						[illegible]	GAGE
	2					[illegible]	[illegible]	GAGE
		1	1	2	2	80539	ACL22-8	WASHER
		1	1	1	1	80539	[illegible]	BOLT
				1	1	80539	6170-820	NUT
		1	1				-10	INSERT ASSY
		1	1	1	1		-9	COLLAR ASSY
		2		2			-8	FLANGE
1							-7	BLOCK
	1						-6	COLLAR
			2		2		-5	FLANGE

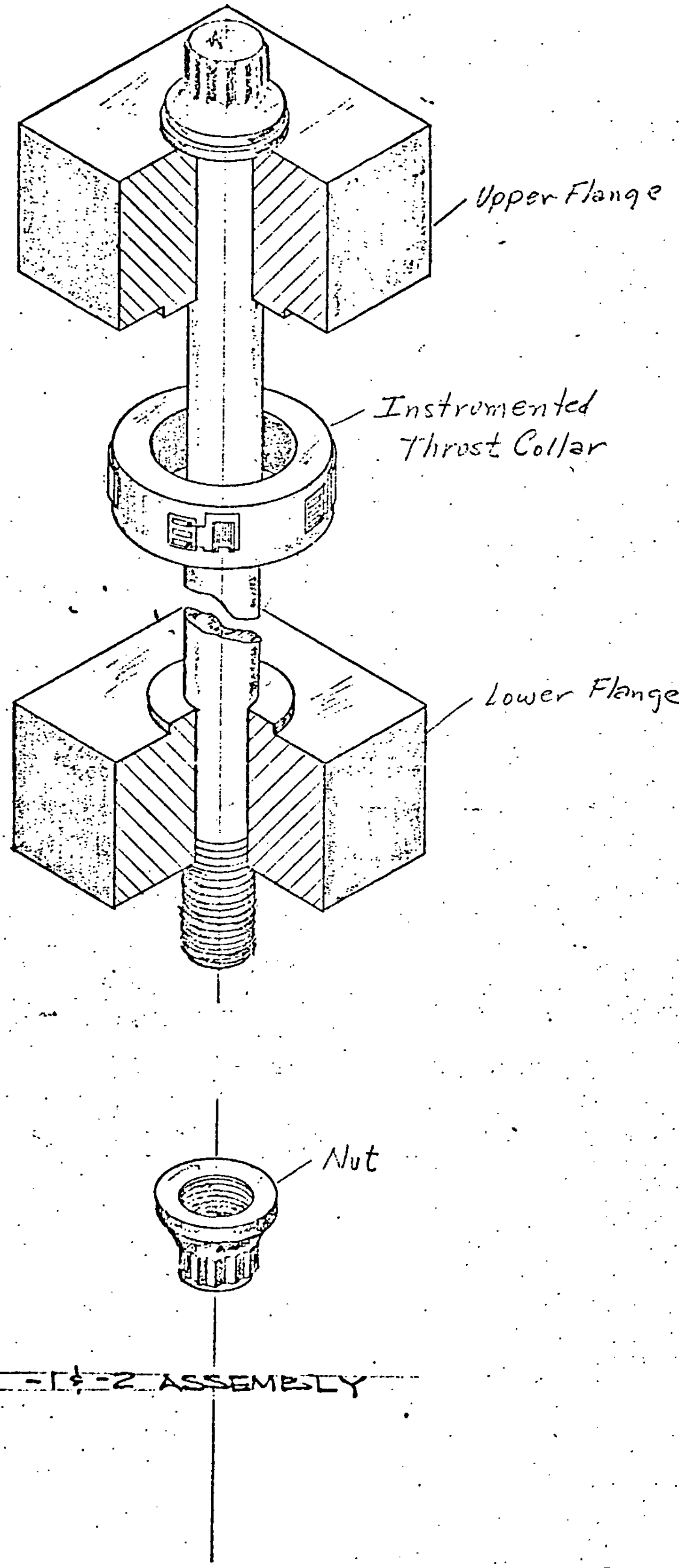


FIG. 2 EXPLODED VIEW

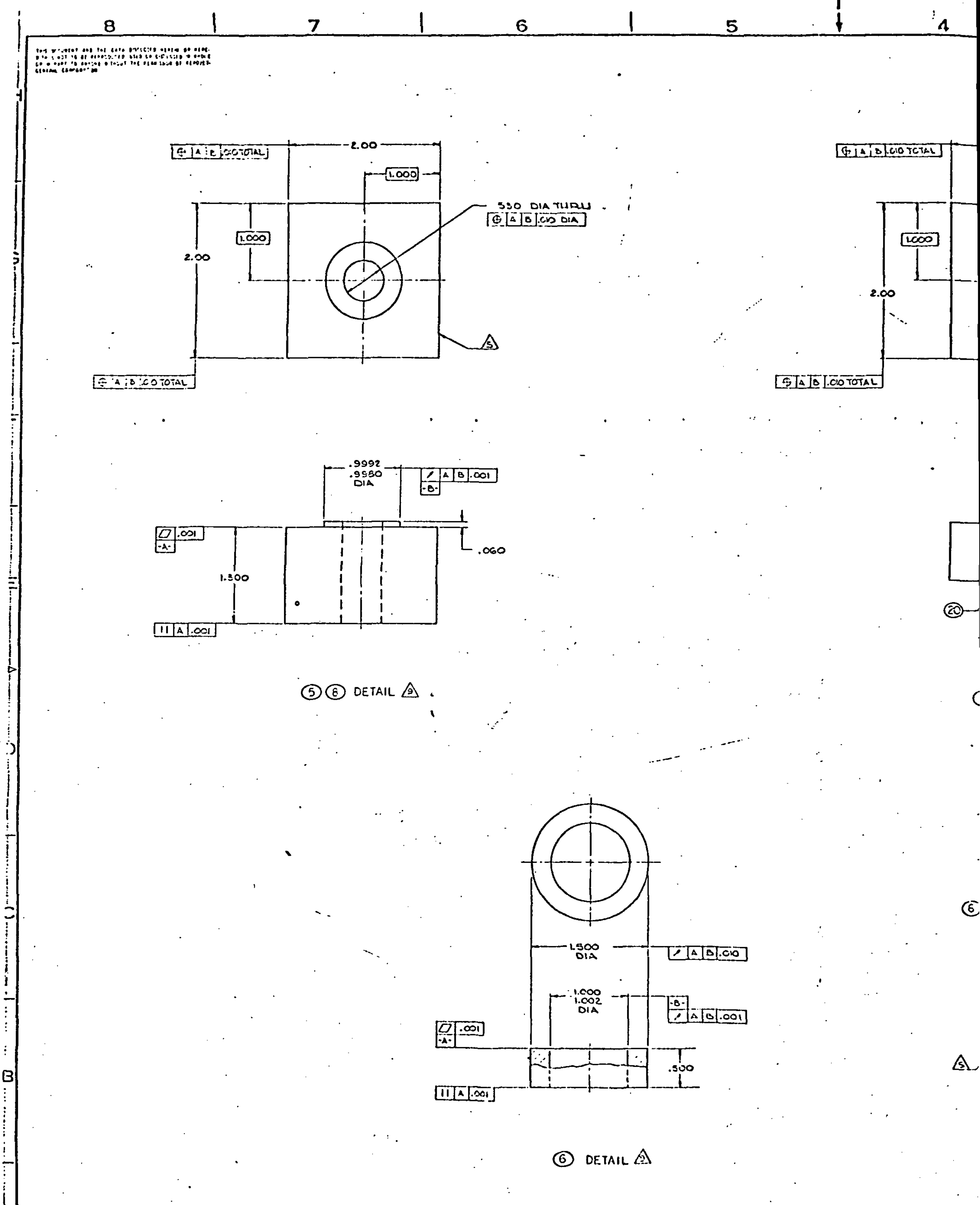


FIG. 3 TEST SPECIMEN COMPONENTS

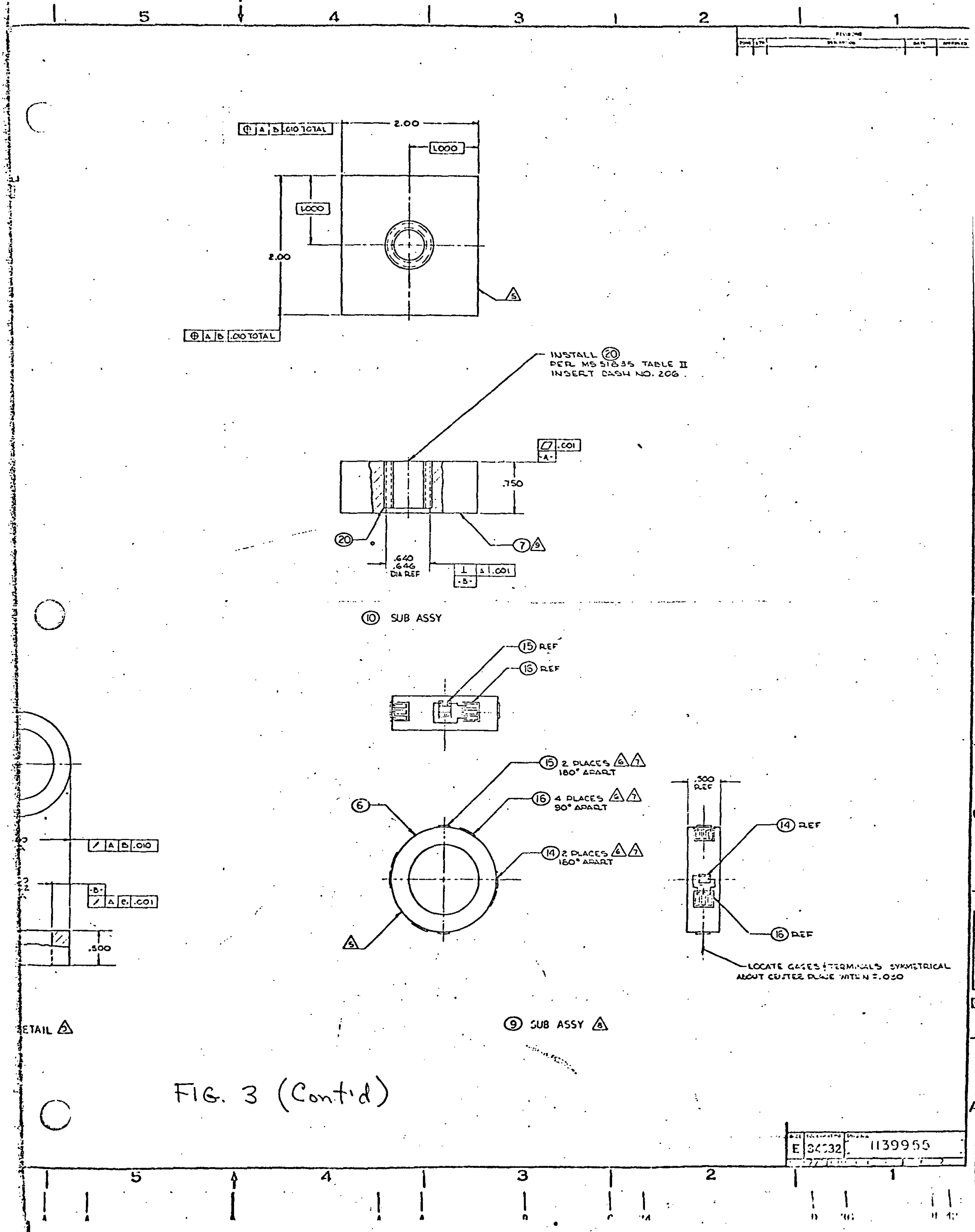

2.00
1.000
1.000
2.00
.010 TOTAL
INSTALL 20
PER MS 51835 TABLE II
INSERT DASH NO. 206
.001
-A-
.750
20
7
.640
.646
DIA REF
.001
-B-
10 SUB ASSY
15 REF
16 REF
15 2 PLACES 180° APART
16 4 PLACES 90° APART
14 2 PLACES 180° APART
6
.500 REF
14 REF
16 REF
LOCATE GAGES & TERMINALS SYMMETRICAL ABOUT CENTER PLANE WITHIN ±.050
9 SUB ASSY
.010
.001
.500
DETAIL
E
1139955

FIG. 3 (Cont'd)

-3&-4 ASSY

FIG. 4 MATERIALS LIST

-10	-9	-4	-3	-2	-1	CODE IDENT	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL / SPECIFICATION		ITEM NO.
		AR	AR	AR	AR	81499	MOLYKOTE TYPE 321	LUBRICANT			21
1						23372	KJH 620 T-5P	INSERT			20
	AR					50599	219058	SOLDER			19
	AR						216626	ADHESIVE	EPY-600		18
	AR						217925	PROTECTIVE COATING			17
	1						216363	TERMINAL	TYPE T-55		16
	2						FAB-12-12-S6-L	GAGE			15
	2					50599	FAED-12-12-S6-L	GAGE			14
		1	1	2	2	50599	WCL22-8	WASHER			13
		1	1	1	1	50599	EWB C420-8-46	BOLT			12
				1	1	50599	61170-820	NUT			11
		1	1				-10	INSERT ASSY			10
		1	1	1	1		-9	COLLAR ASSY			9
		2		2			-8	FLANGE	AL ALLOY 7075	QQ-A-250/12 TEMPER T6	8
1							-7	BLOCK	AL ALLOY 7075	QQ-A-250/12 TEMPER T6	7
	1						-6	COLLAR	STEEL 4340	MIL-S-5000 COND F	6
			2		2		-5	FLANGE	STEEL 4340	MIL-S-5000 COND F	5
											4
											3
											2
											1

PARTS LIST

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES
TOLERANCES
DECIMALS .XX ±.03 .XXX ±.010 ANGULAR ±2°
DO NOT SCALE DRAWING

CONTRACT NO. SNP-1
DRAWN SCHIFINI DATE 11-10-71
CHECK 12-9-71
DESIGN 11-15-71
DESIGN ACTIVITY 11-15-71
CUSTOMER

AEROJET NUCLEAR SYSTEMS COMPANY
A DIVISION OF AEROJET-GENERAL

TITLE BOLT FIXTURE - RELAXATION TEST

SIZE E | CODE IDENT NO. 34632 | DWG NO. 1139955
SCALE 2/1 | SHEET 1 OF 2

APPLICATION: NEXT ASSY FINAL | USED ON

WEIGHTS / STRESS / MATERIALS & PROCESSES / MANUFACTURING ENGRG / QUALITY ASSURANCE / ADDITIONAL APPROVALS / DATE

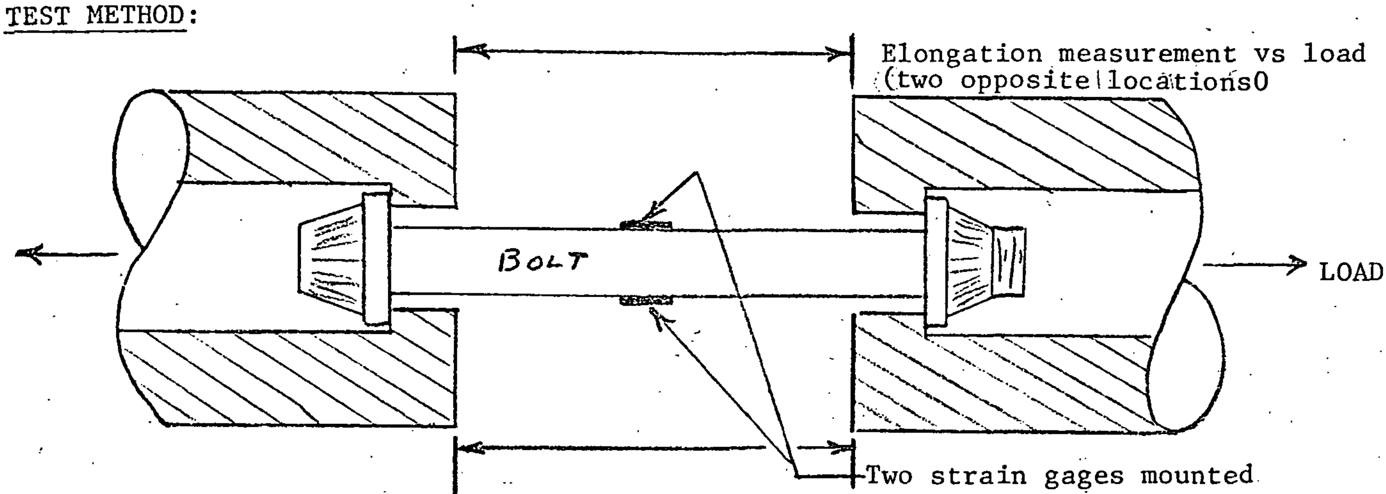
CC-79 PC-2

FIG. 5

BOLT RELAXATION TESTS MATERIALS PROPERTY MEASUREMENT

PURPOSE: To determine continuous record of stress vs strain and load vs elongation in the bolt shanks of 6 each 1/2-20 bolts made from high strength A-286 material. Three of these will have shanks machined to the root diameter of the threads.

TEST METHOD:



TEST RECORDS REQUIRED:

(1) Strain (μ in/in) vs load continuous from zero to 10,000 μ in/in indicated strain, or to fracture, whichever occurs first.

(2) Bolt elongation recorded continuously as a function of load over the same range.

(3) Note the correct bolt number (letter designation is marked on bolt head) on each test record.

(4) Return all bolts and nuts.

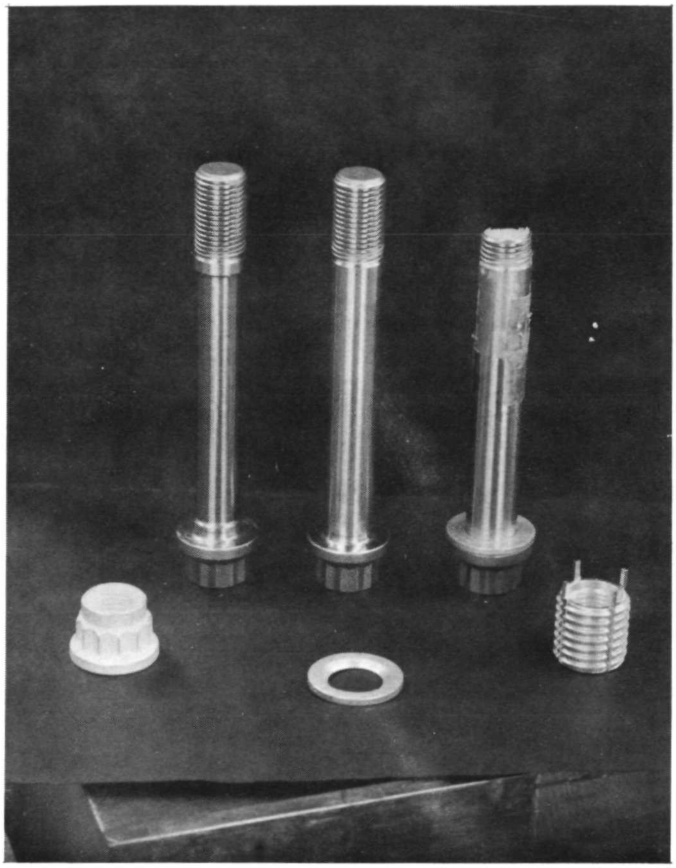


FIG. 6 - Bolting Components

c

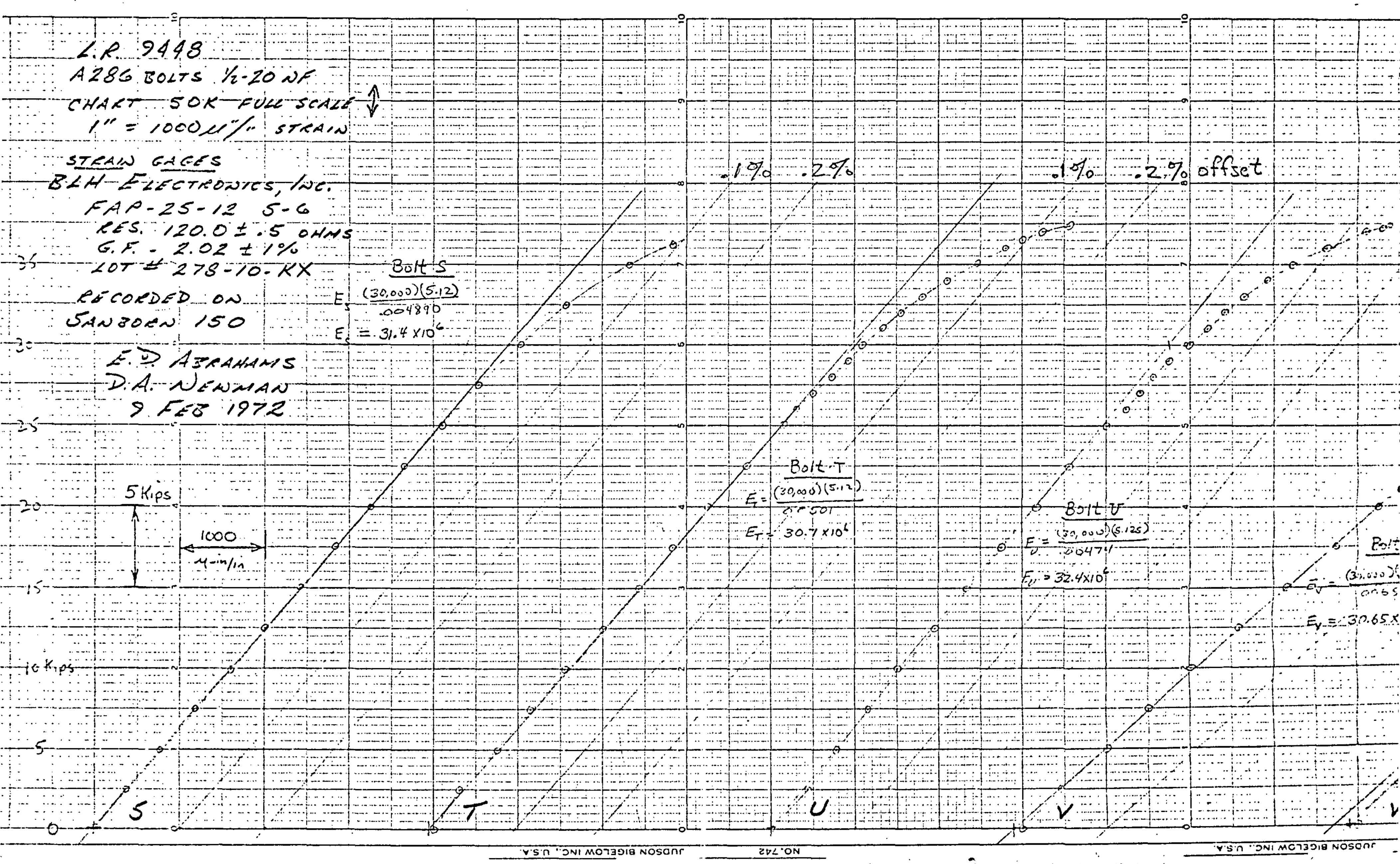


FIG. 7 LOAD-STRAIN CURVES FOR STANDARD SHANK BOLTS

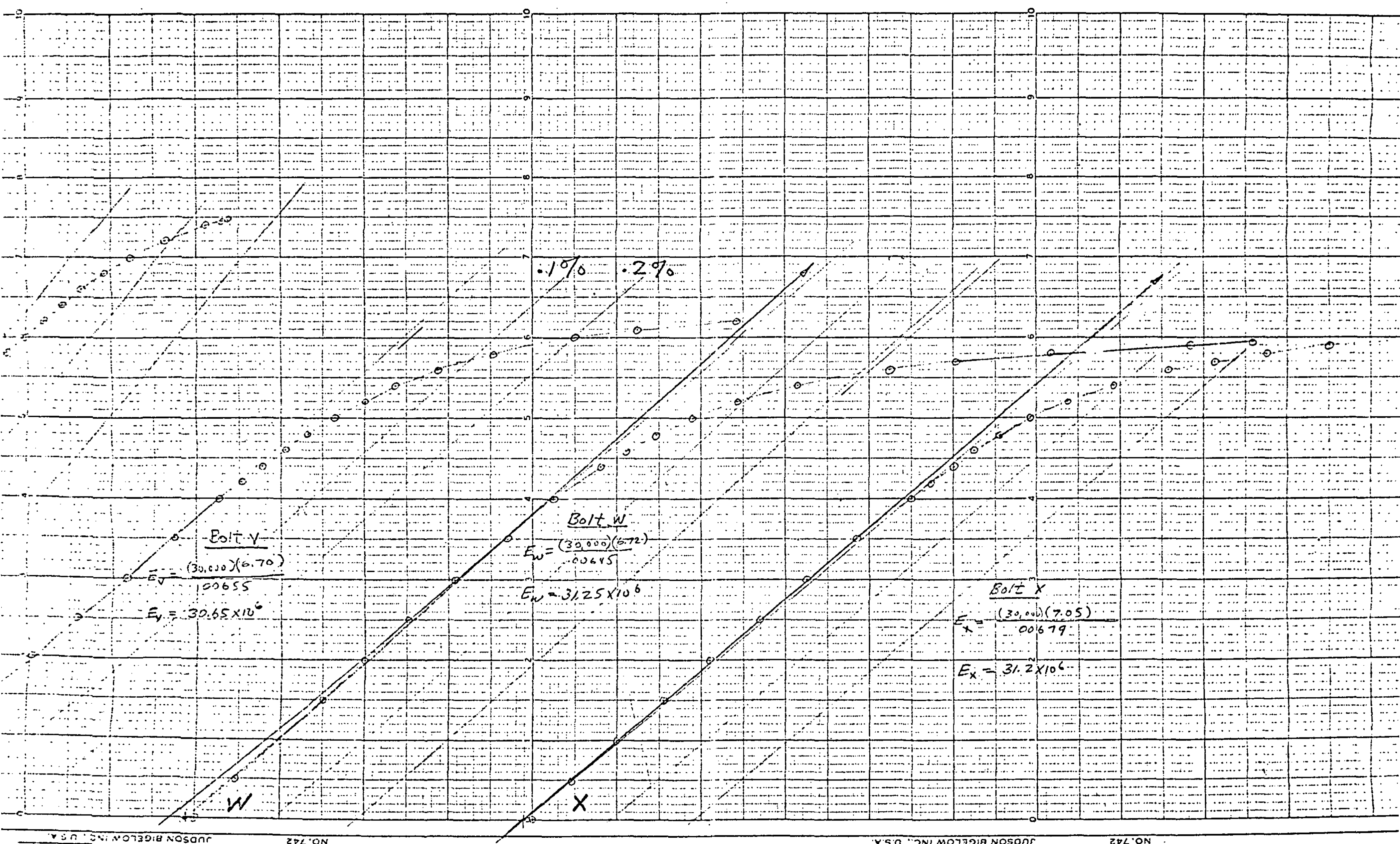


FIG. 8 LOAD - STRAIN CURVES FOR REDUCED SHANK BOLTS

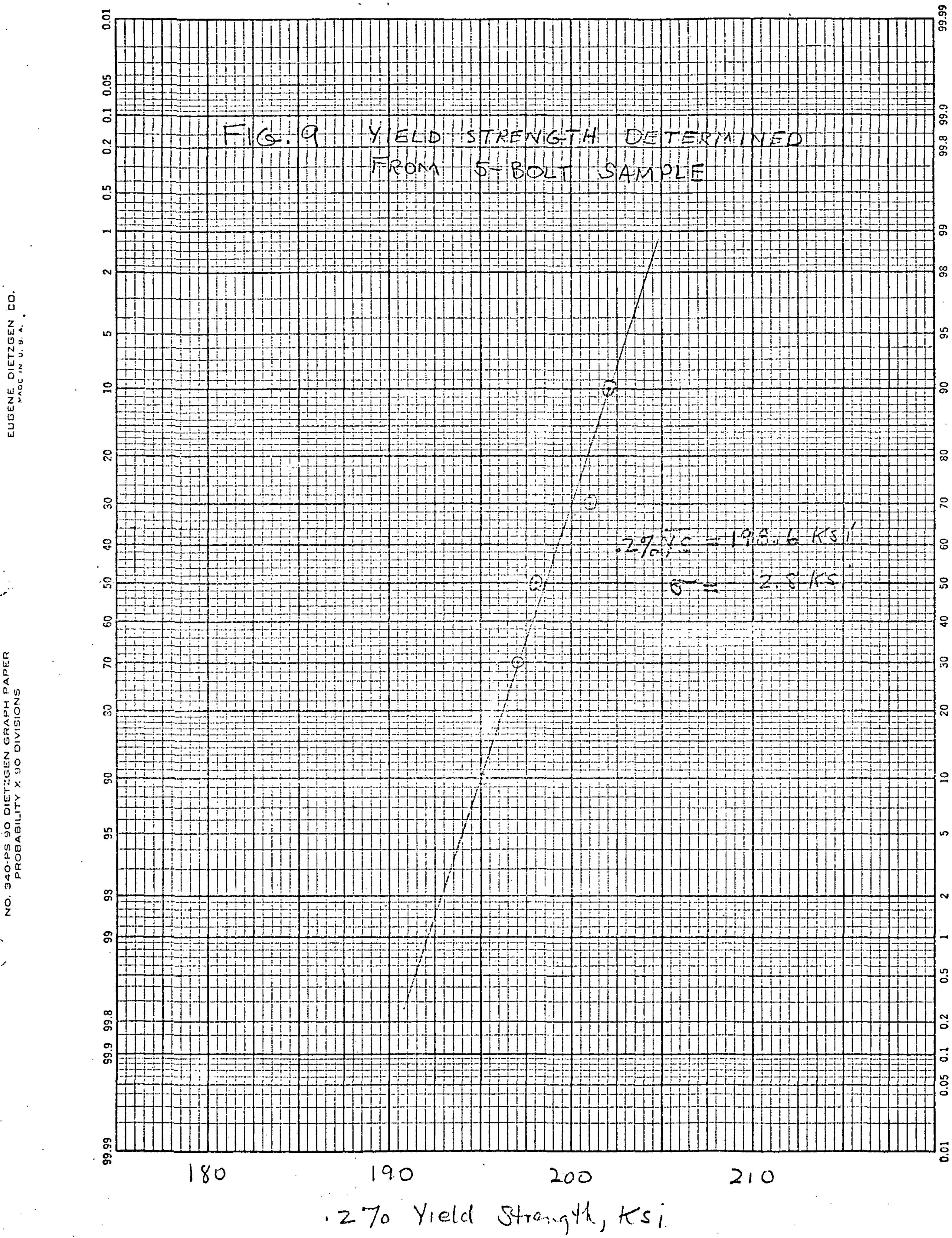


FIG. 9 YIELD STRENGTH DETERMINED FROM 5-BOLT SAMPLE
.2% YS = 198.6 KSI
σ = 2.8 KSI
180
190
200
210
.2% Yield Strength, KSI
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
EUGENE DIETZGEN CO.
MADE IN U. S. A.
NO. 340-PS 90 DIETZGEN GRAPH PAPER
PROBABILITY X 90 DIVISIONS

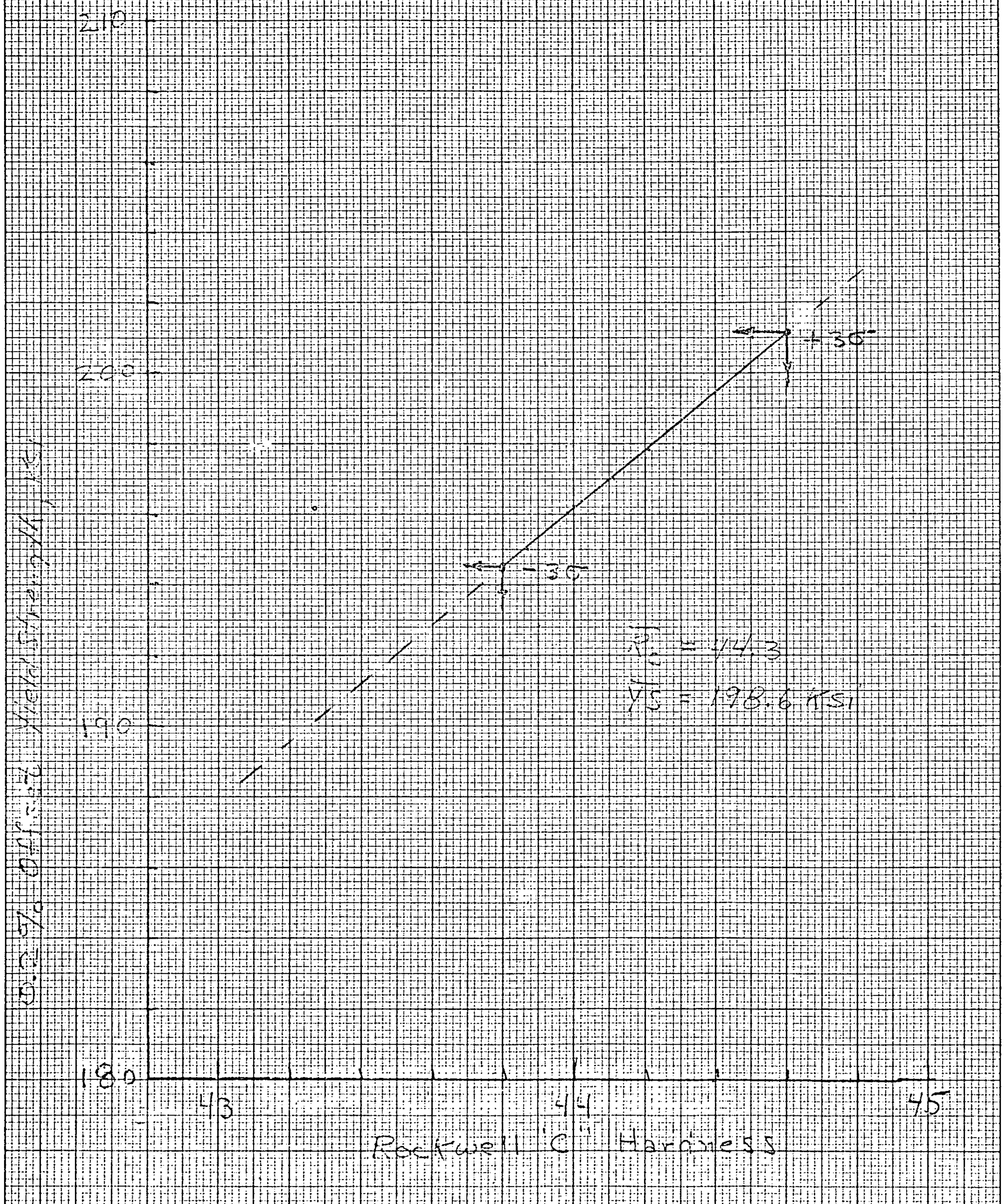


FIG. 10 CORRELATION OF YIELD STRENGTH WITH HARDNESS FOR A-286

24- BOLT SAMPLE

3/20/72

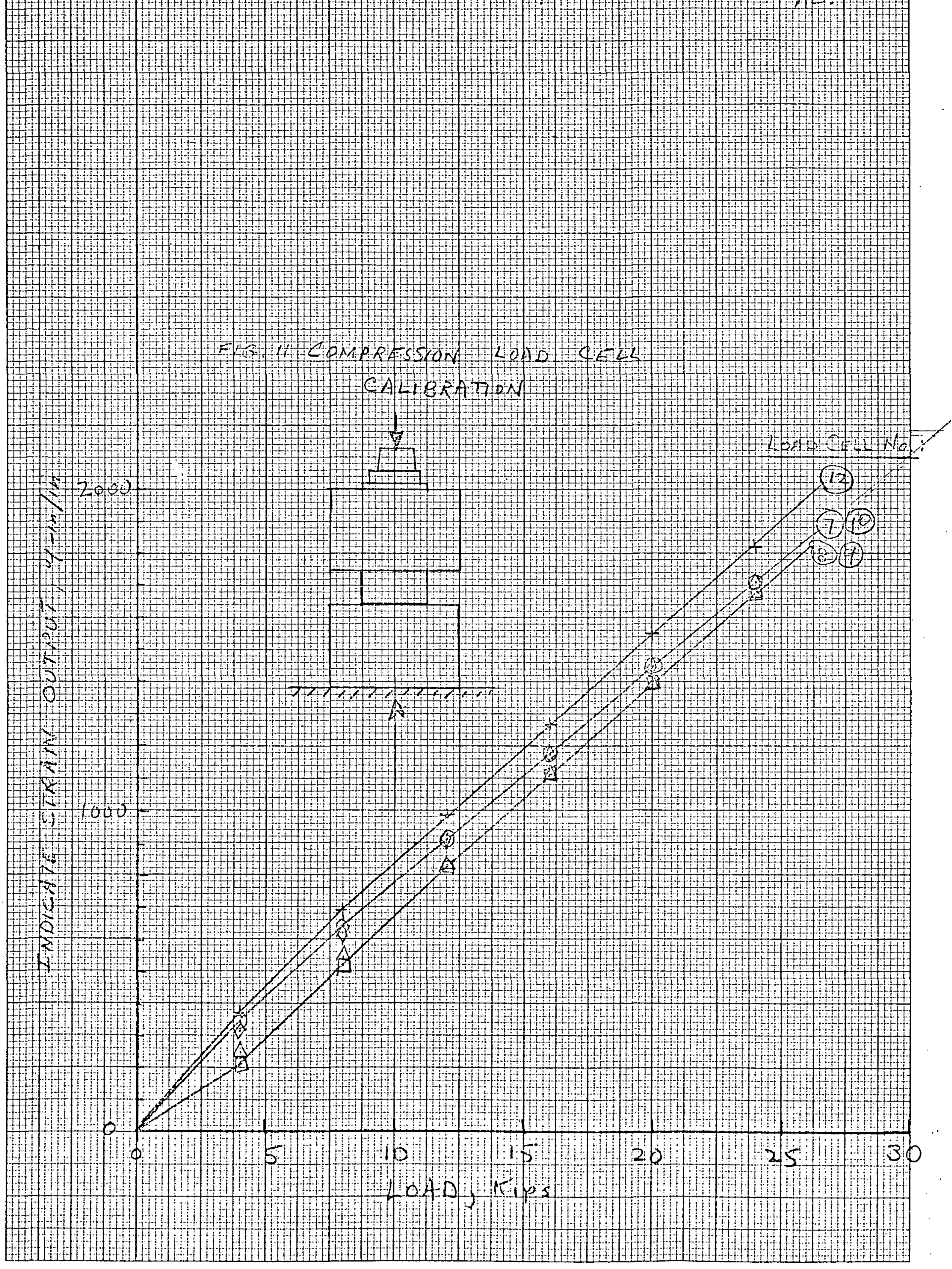


FIG. 11 COMPRESSION LOAD CELL CALIBRATION

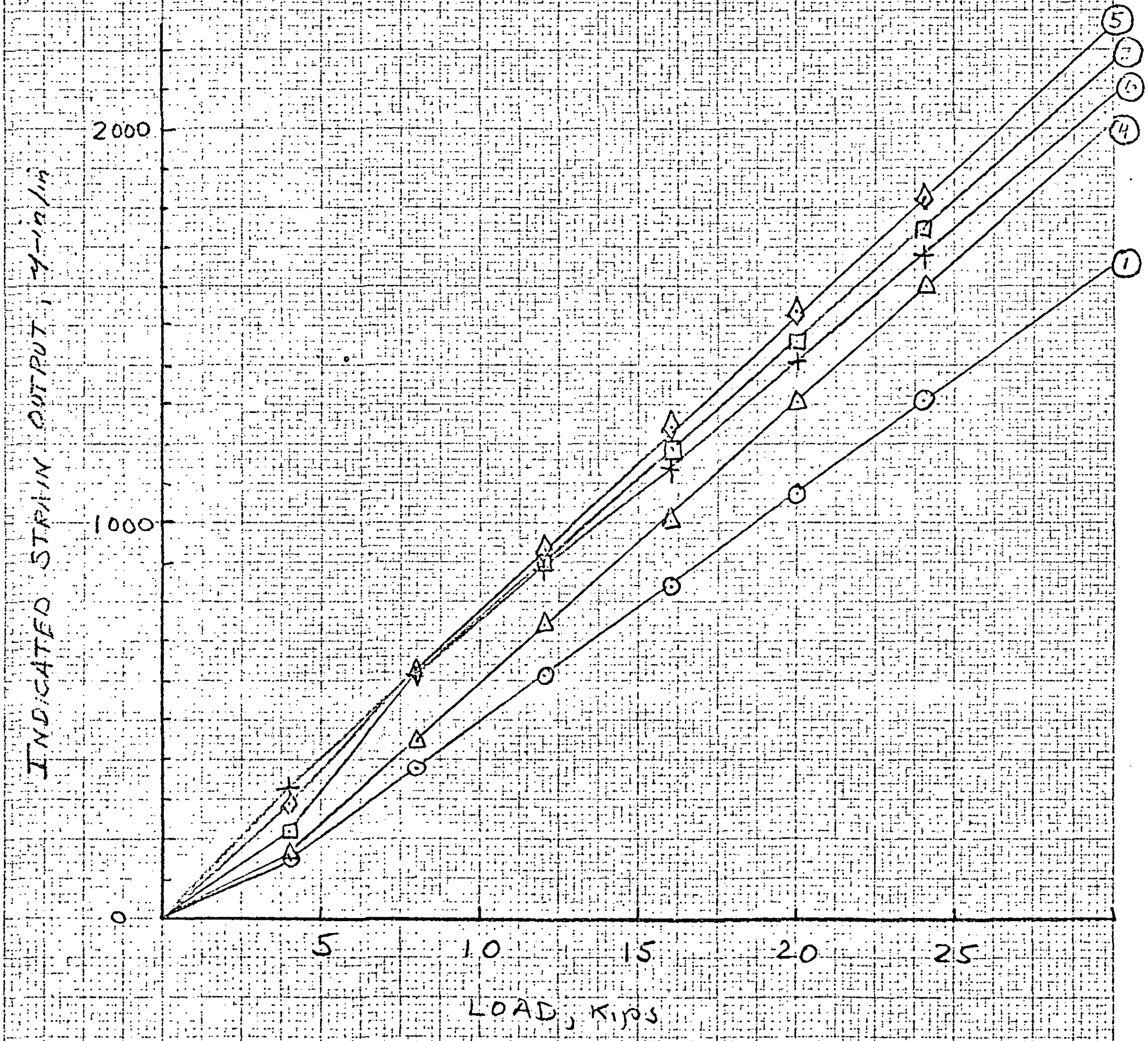
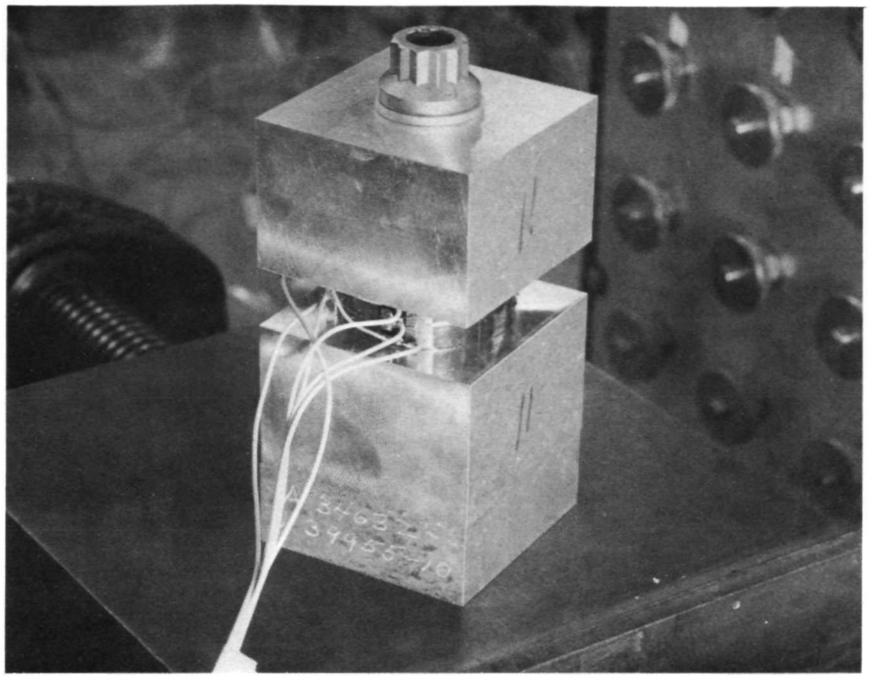
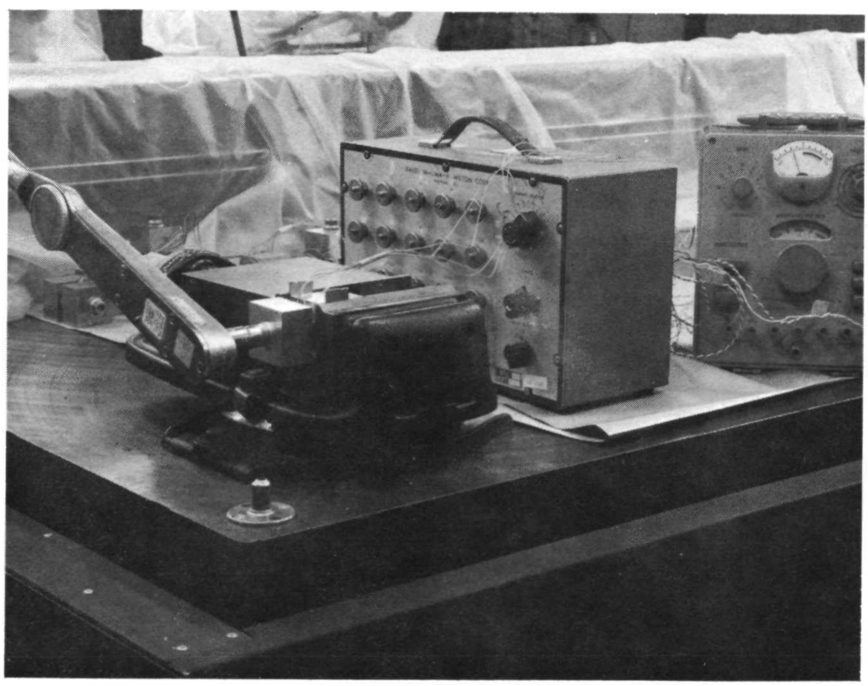


FIG. 12 COMPRESSION LOAD CELL CALIBRATION



(b) Test Sample



(a) Test Setup

FIG. 13

FIG. 14 LOAD VS EXTENSION FOR PLAIN-SHANK BOLTS

3/24/72
RCS.

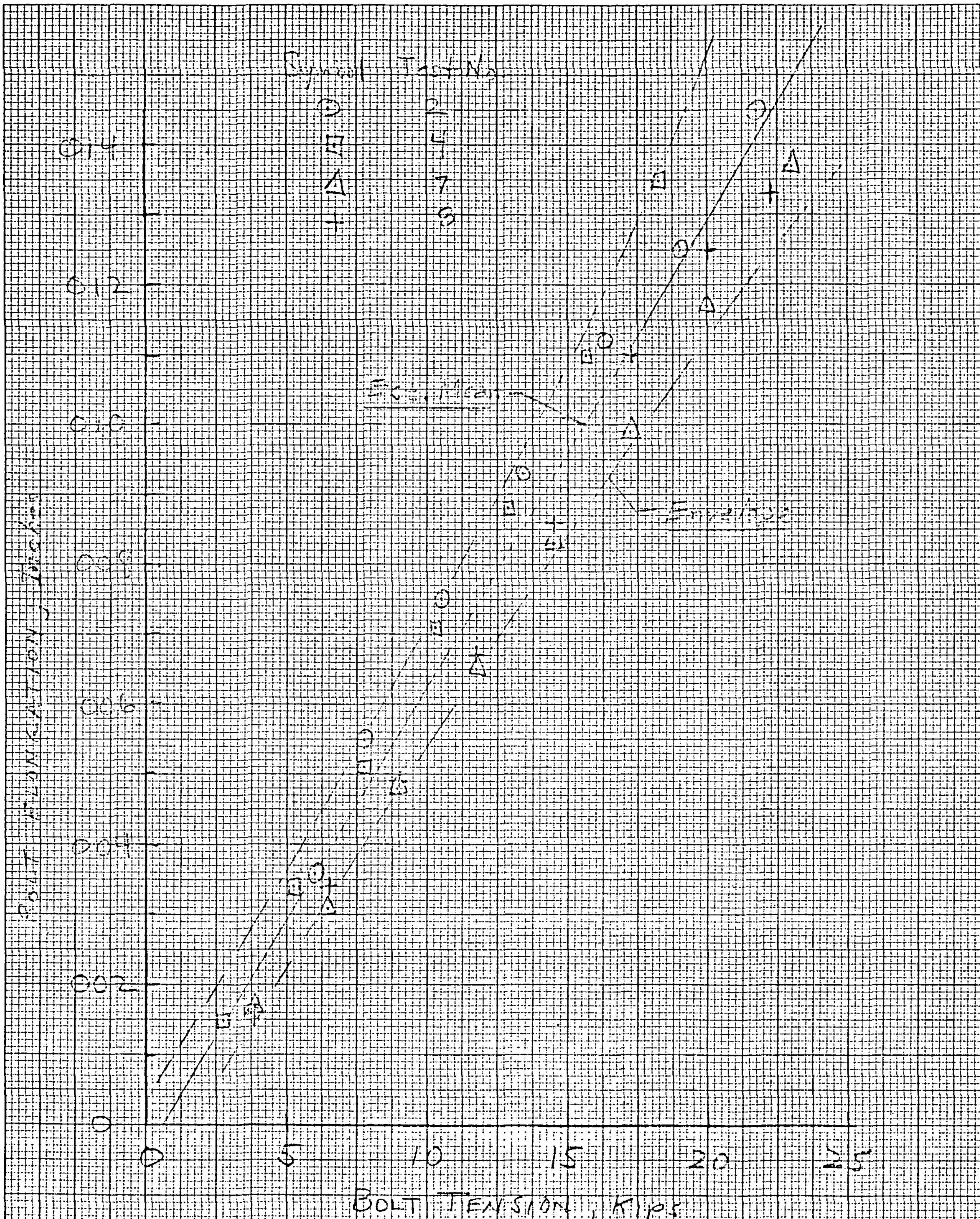


FIG. 15 LOAD VS EXTENSION FOR REDUCED-SHANK BOLTS

3/24/72
RCS.

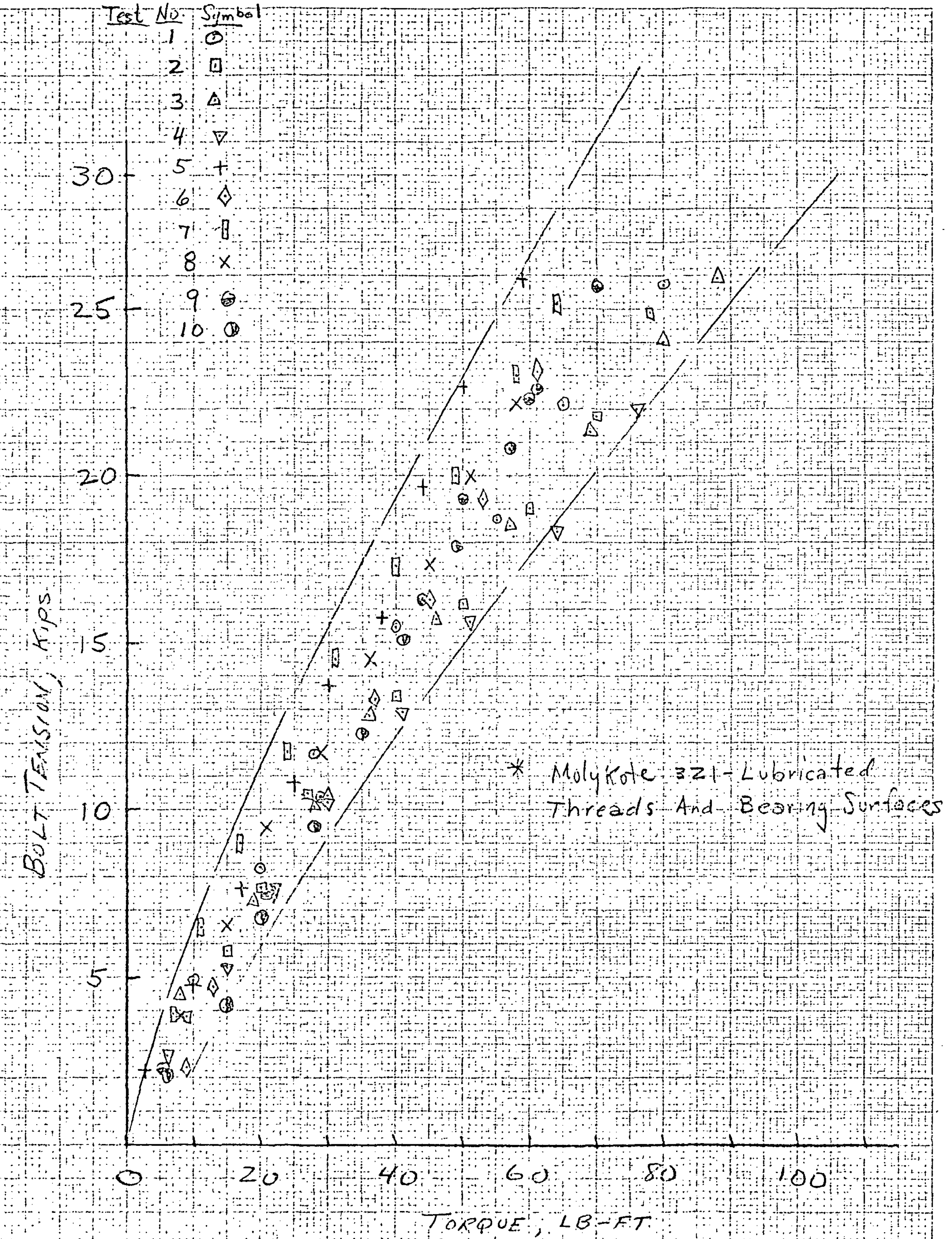


FIG. 16 BOLT TENSION vs. TORQUE*

3/24/72
RCJ.

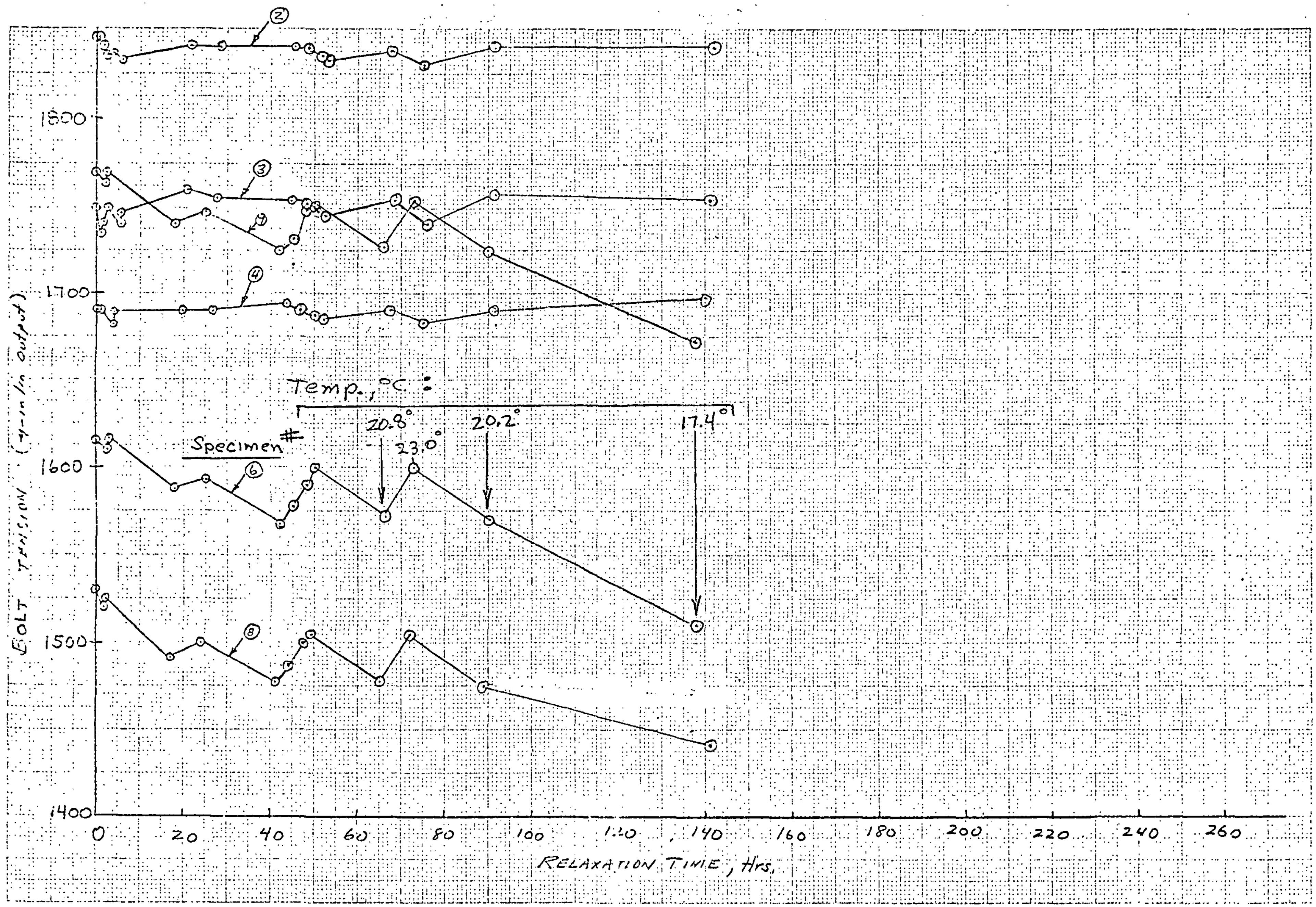


FIG. 17 BOLT TENSION VS. TIME DURING INITIAL TEST PHASE

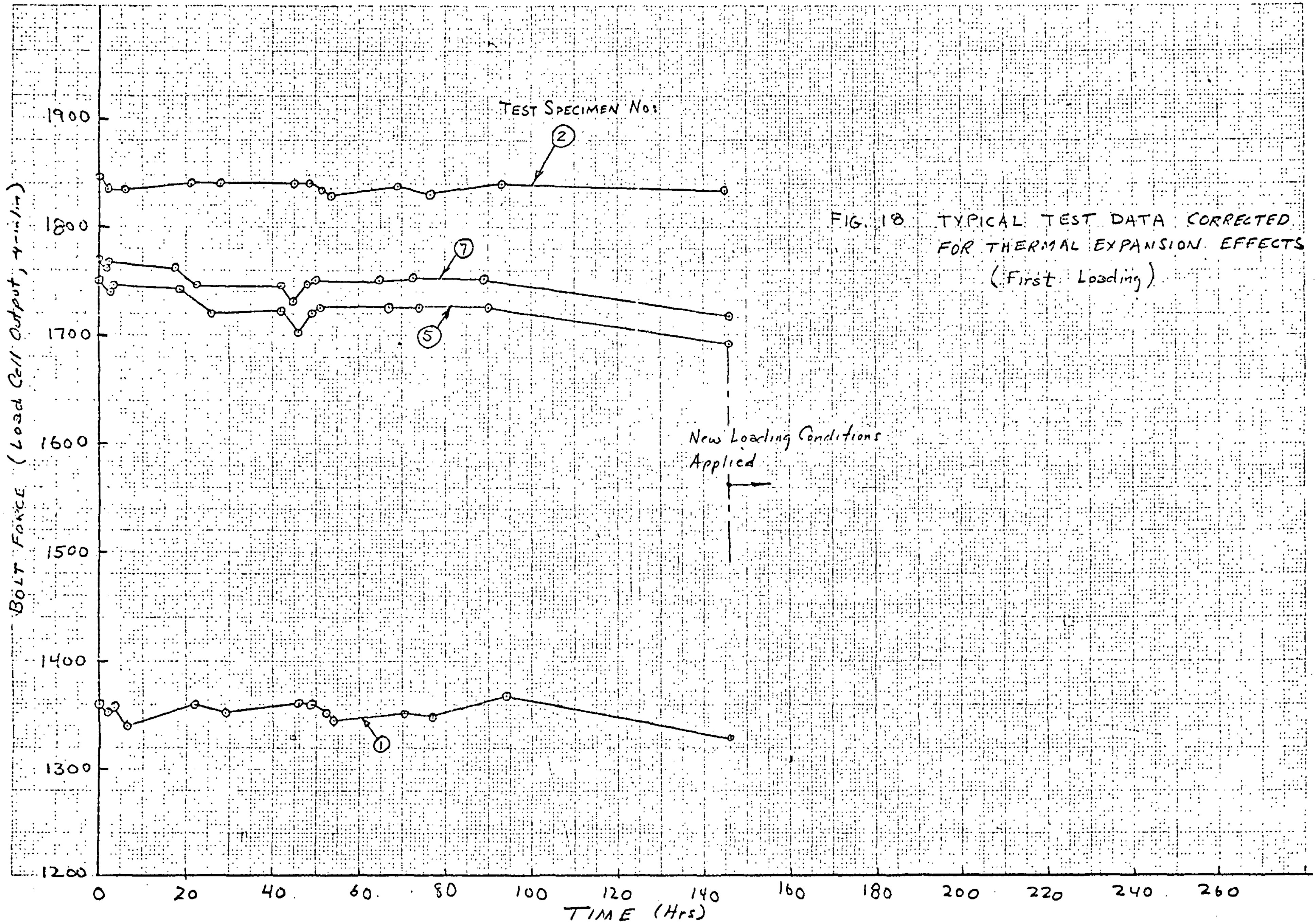


FIG. 18 TYPICAL TEST DATA CORRECTED FOR THERMAL EXPANSION EFFECTS (First Loading)

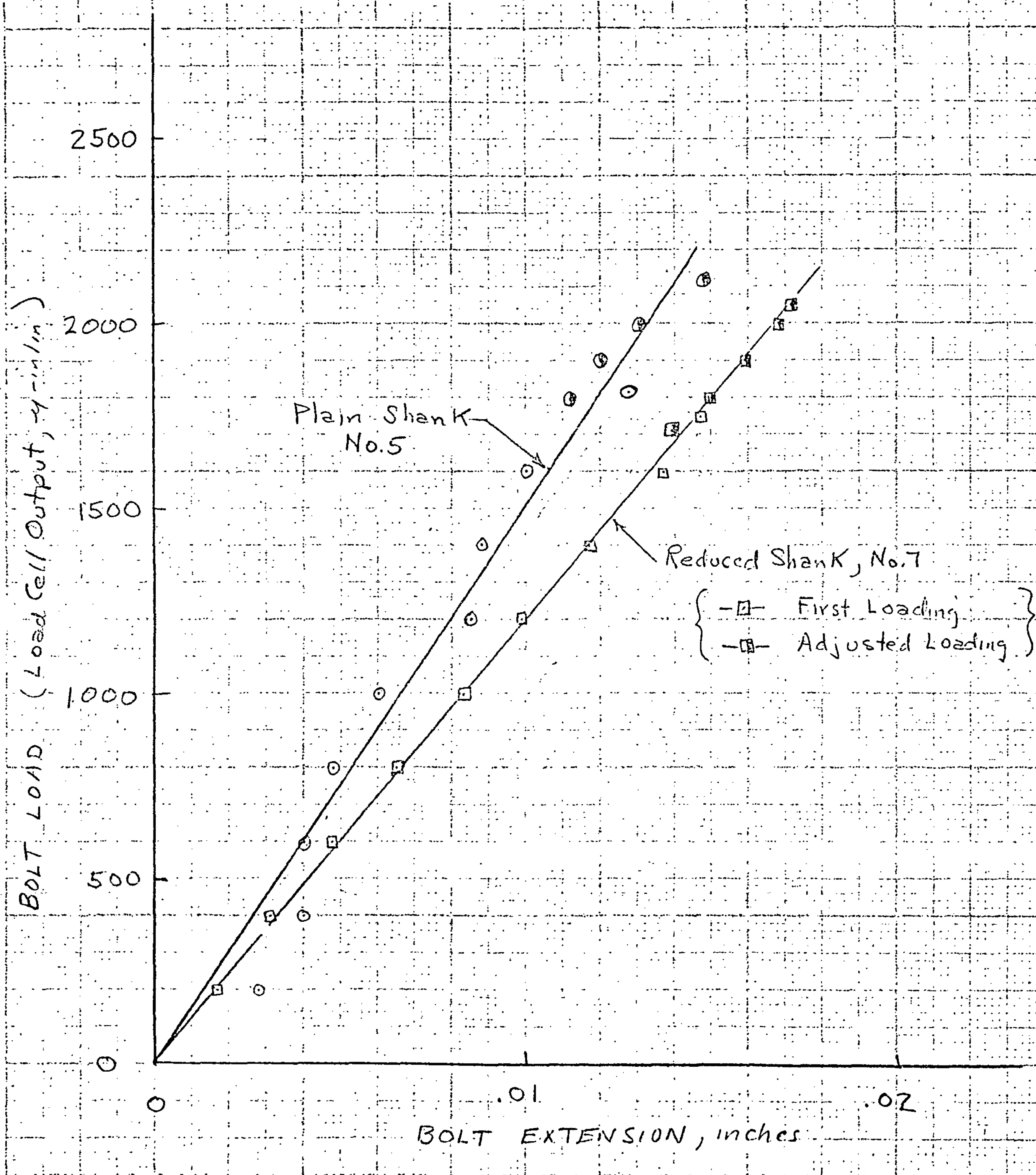


FIG. 19 BOLT LOAD VS. EXTENSION FOR 100% OF YIELD STRENGTH.

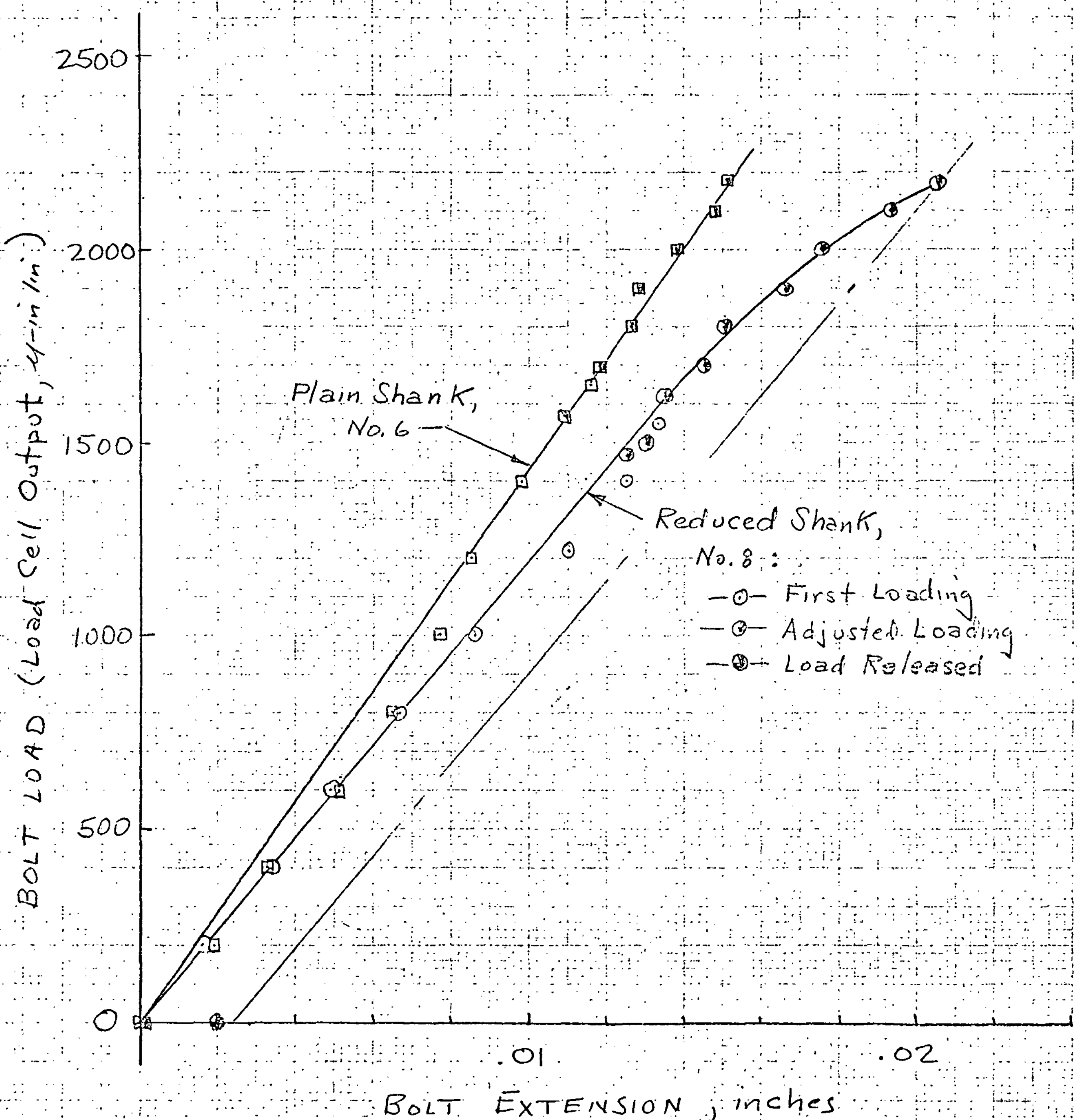


FIG. 20 LOAD VS EXTENSION FOR TWO BOLTS STRESSED UP TO 105% YIELD STRENGTH

3/27/72
RCL.

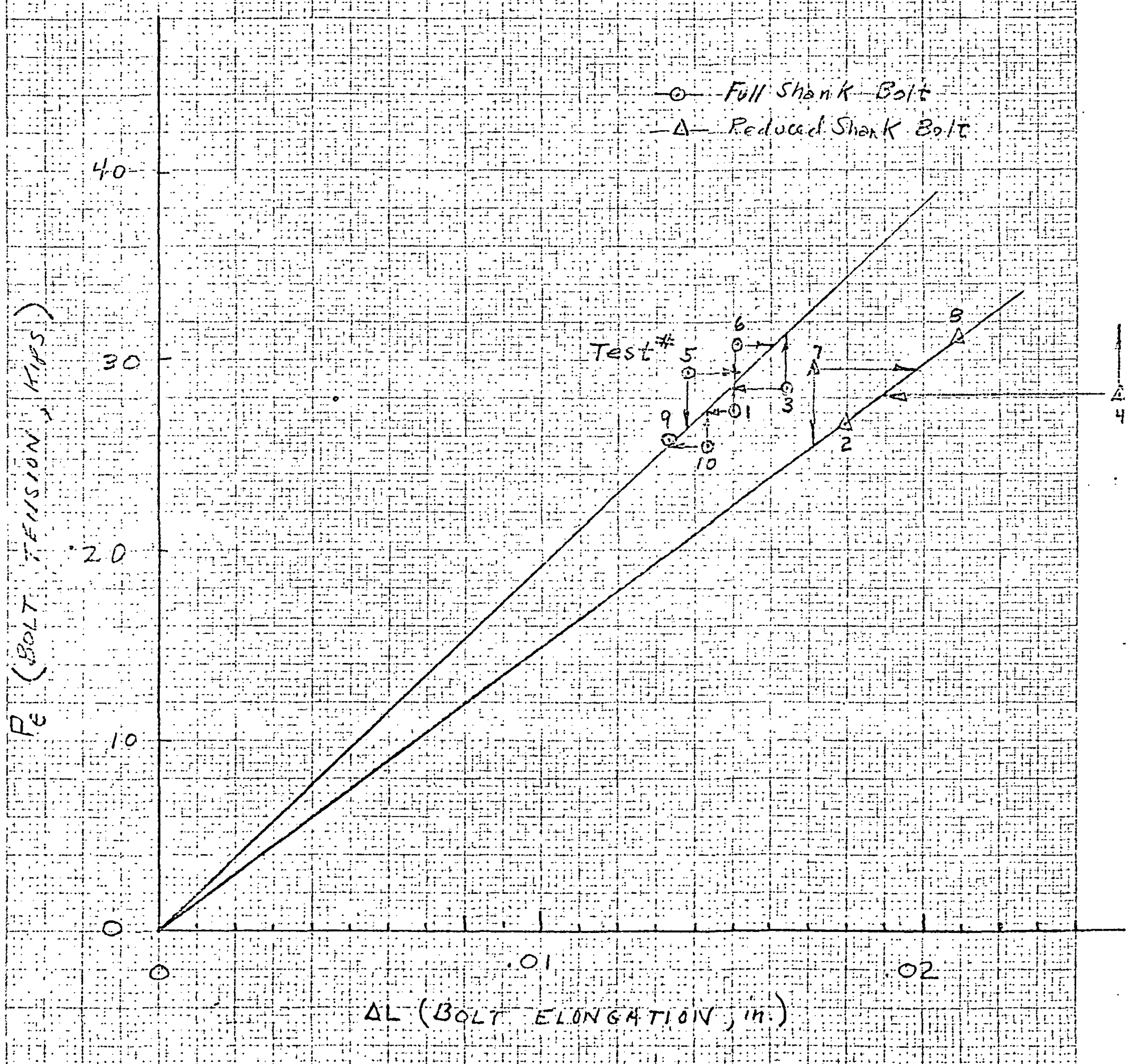


FIG. 21 CORRELATION OF BOLT TENSION WITH BOLT ELONGATION

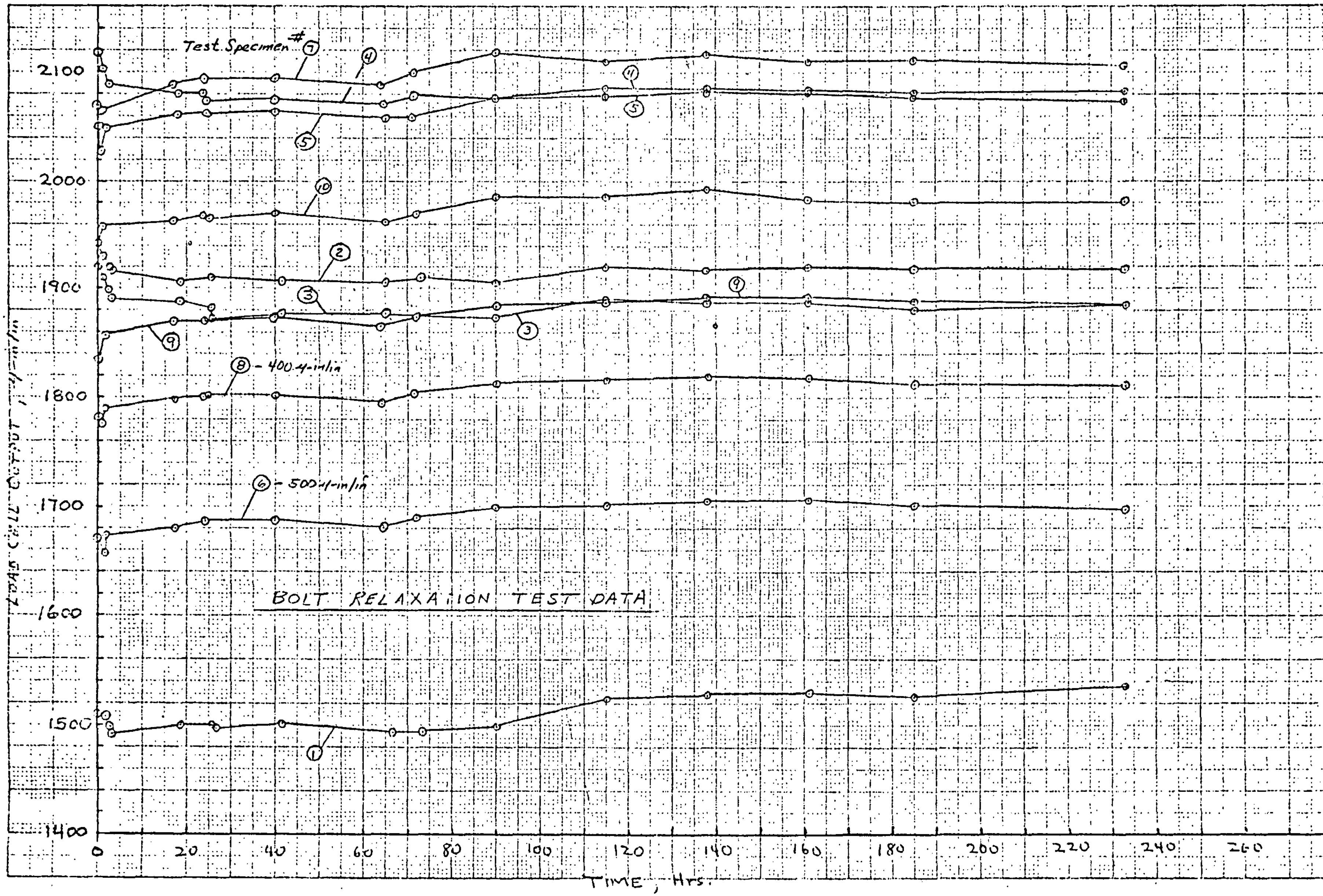
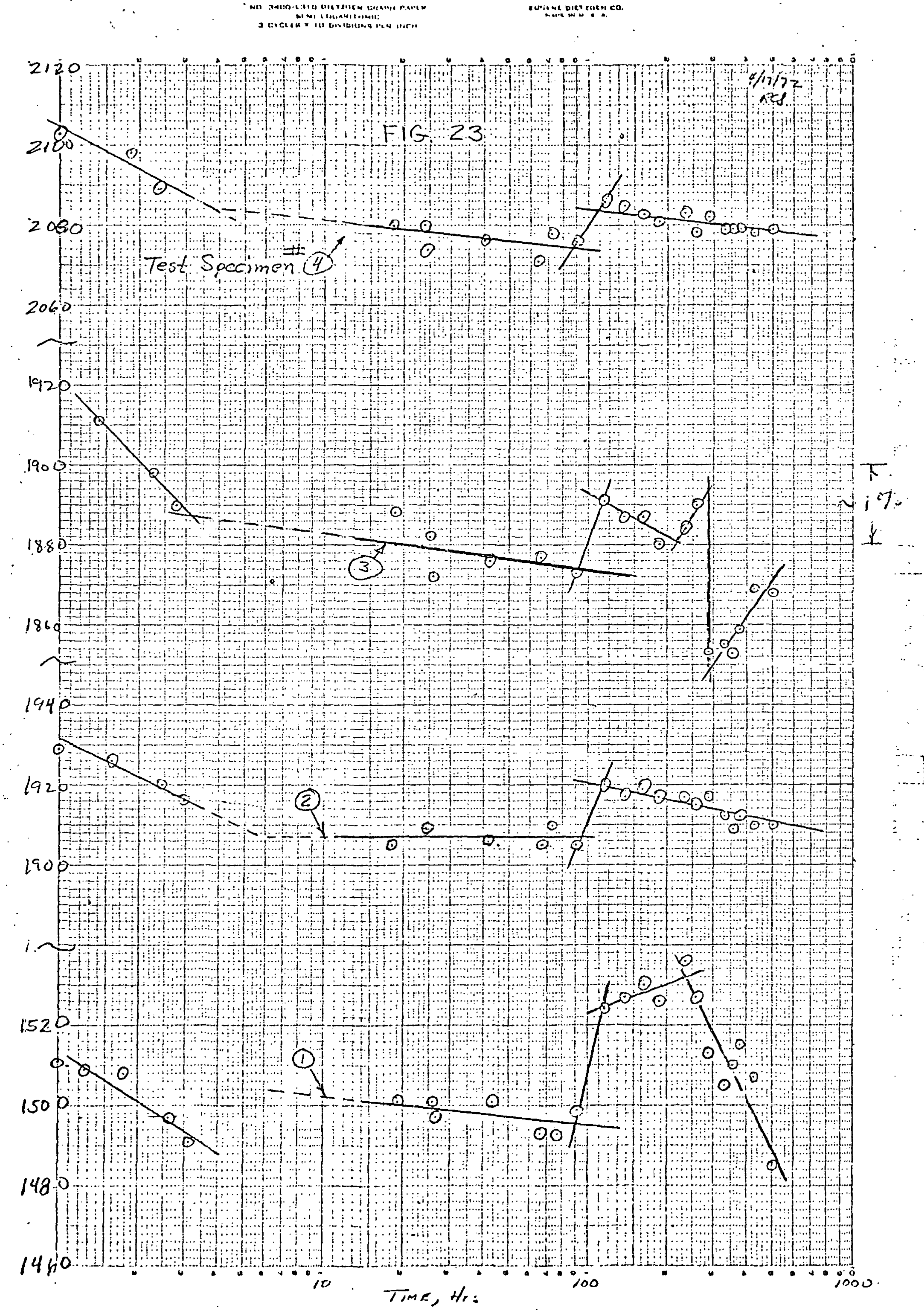
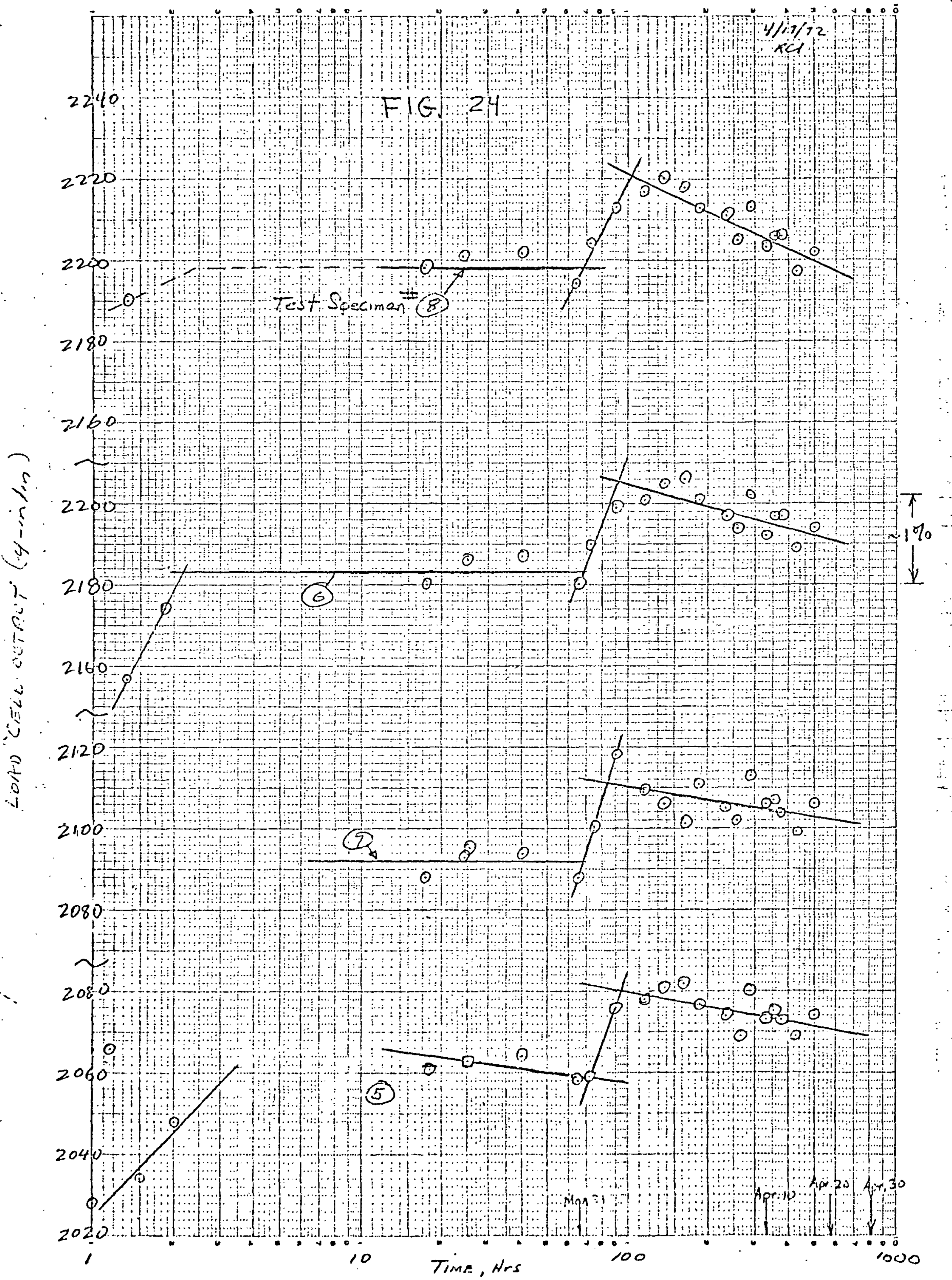


FIG. 22 TEST DATA FOR REVISED LOADING



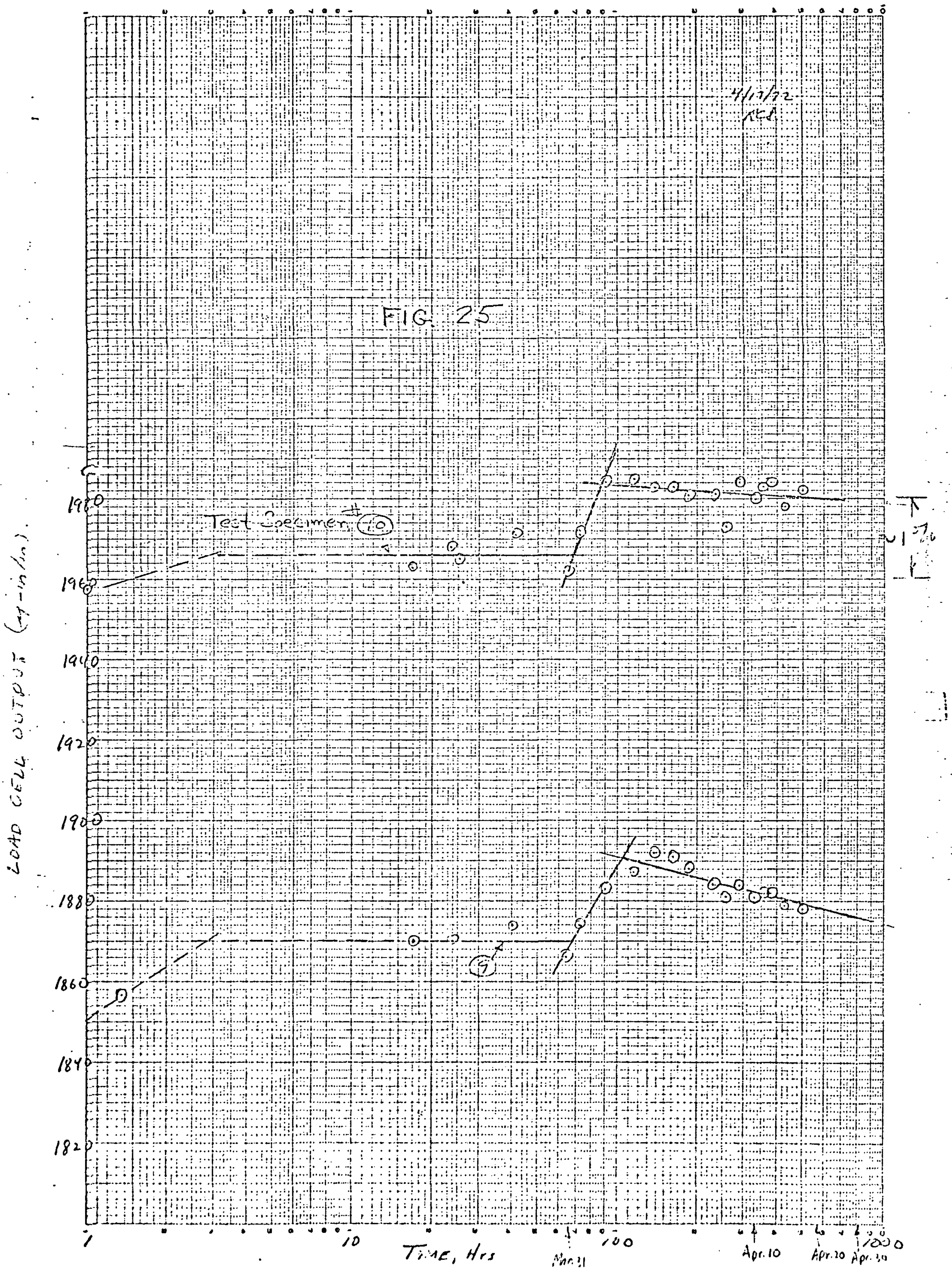
NO. 3400-L/10 DIETZGEN GRAPH PAPER
SEMI-LOGARITHMIC
3 CYCLES X 10 DIVISIONS PER INCH
EUGENE DIETZGEN CO.
MADE IN U.S.A.
FIG. 23
Test Specimen #4
3
2
1
2120
2100
2080
2060
1920
1900
1880
1860
1940
1920
1900
1520
1500
1480
1460
10
100
1000
TIME, Hr.
LOAD CELL OUTPUT (μ-in/in)
~1%

FIG. 24



4/17/72
KCI
Test Specimen # 8
6
7
5
1%
LOAD CELL OUTPUT (μ-in/in)
2240
2220
2200
2180
2160
2200
2180
2160
2120
2100
2080
2080
2060
2040
2020
1
10
100
1000
TIME, Hrs
Mar 31
Apr. 10
Apr. 20
Apr. 30

FIG. 25


4/17/72
RCE
Test Specimen #10
9
1980
1960
1940
1920
1900
1880
1860
1840
1820
LOAD CELL OUTPUT (µ-in/in)
1
10
100
1000
TIME, Hrs
Mar. 31
Apr. 10
Apr. 20
Apr. 30