THE UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING
Department of Mechanical Engineering

Final Report for Phase I

THE EFFECT OF ULTRASONICS ON MATERIALS PROPERTIES

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ORA Project 05718

under contract with:

CINCINNATI MILLING AND GRINDING MACHINES, INC.
CINCINNATI, OHIO

administered through:

OFFICE OF RESEARCH ADMINISTRATION ANN ARBOR

March 1965

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Concluded)

INTRODUCTION

Phase I of this project had two major objectives. The first was to determine whether the effects of ultrasonic vibration on materials properties depended solely upon the stress amplitude. The second objective was to evaluate the role of boundary friction in compression tests.

The results of this investigation prove beyond reasonable doubt that the influence of ultrasonic vibrations on materials properties goes substantially beyond that which might be predicted or calculated from the stress amplitude. Furthermore, the results also correlate very well with those included in Report No. 2 of MPEP, Contract No. N 62558-3436 as reported to the United States Bureau of Naval Weapons by the University of Vienna.

It was impossible to identify and isolate the role of boundary friction in compression tests. The fact that this could not be done with current techniques and instrumentation is explained by the complex nature of the influence and effects of the vibrations as discussed later on in the report.

The nature of the results was not anticipated in the plan of approach nor were they obvious in the results obtained in the earlier stages. Both actual and imagined difficulties with instrumentation and procedure led to many changes in the physical test equipment and in the types of experimentation. Eventually, the true nature of the effects of ultrasonic vibrations revealed themselves and in so doing indicated that many of the earlier results which could not be interpreted and were not believed were indeed genuine.

Almost the last experiments carried out revealed the significant effects of ultrasonic vibration and provided the basis for interpreting many of the apparently anamolous results obtained earlier. Consequently, the specific experimental results are presented below in substantially the inverse order in which they were obtained. Details of the equipment and calibration data are presented in Appendix A.

EXPERIMENTAL RESULTS

Studies were carried out not only with the original test specimen but also with two additional shapes. The original specimens were 4 in. long and provided with threaded holes at the ends. These were tested both in tension and compression both with and without ultrasonic vibration. The most fruitful tests were made with cubes machined from the shank of one of the aluminum specimens from the first group. These cubes were machined to a nominal dimension of 0.100 in.

In addition, cylindrical slugs of both steel and aluminum with length to diameter ratios of 1 were submitted for tests. The aluminum slugs were 0.353 in. in diameter and the steel slugs were 0.300 in. in diameter. The latter presented too much area and strength for the existing test apparatus. Therefore, only one test for the purpose of establishing this fact was carried out. Several of the aluminum slugs were tested subsequent to the series carried out with the cubes but further testing was abandoned because these produced no new information and resulted in substantially less power density than was possible with the cubes.

RESULTS FOR ALUMINUM CUBES

Some 39 tests were carried out with the 0.100-in. aluminum cubes machined from the shank of a previously failed test specimen. The cubes were loaded in compression between the faces of full-hard die blocks mounted on the ultrasonic transducer and reflector respectively.

The load deflection curve for cube No. 11 as shown at the top in Fig. 1 is typical of the significant results obtained by superimposed ultrasonic vibration. In carrying out this test the load was permitted to rise beyond the yield point and to a total deflection of 0.005 in. before vibration was applied. The load was applied through an adjustable-speed, hydraulic drive so that the head speed of the testing machine was maintained at 0.035 in. per minute. When the total deflection reached 0.005 in. as indicated by the first 1 in. of pen deflection on the deflection axis, the ultrasonic transducer was energized and caused to vibrate at a frequency of about 25 kc/sec. This was continued for the next 1/2 in. of pen movement at which point the generator was shut off and deflection was permitted to continue for another 1/2 in. of pen deflection without vibration before the generator was again turned on and the frequency adjusted to approximately 20 kc. This procedure was followed alternately until the total deflection reached a value of 0.045 in. at which point the driving mechanism was reversed and the specimen unloaded.

The characteristic response of load and deflection to the application of ultrasonic vibration is amplified schematically in Fig. 2. The normal strain hardening curve without vibration is indicated in zone (a) at the lower left in Fig. 2. The instant that ultrasonic vibration begins, as indicated at the left side of zone (b), the load drops rapidly and the strain or deflection increases very rapidly throughout zone (b). Despite the fact that the ultrasonic vibration remains in effect, the load increases relatively rapidly at the beginning of zone (c) and then proceeds to parallel the normal strain hardening curve without vibration as indicated in zone (a).

Promptly upon shutting off the vibration the load increases rapidly beyond the trend line of normal strain hardening and then relaxes back to the projected strain hardening line through what has been designated as zone (d).

It is to be noted that the magnitude of the load changes in response to vibration increases substantially with increase in total deflection or plastic strain. Subsequent tests indicated to observable response with this technique was carried out at loads below the yield point. Thus it might be concluded that the observed reaction to vibration is substantially strain-dependent and inasmuch as the vibration amplitude was the same at small deflections as at larger deflections it can be concluded that the load change is not determined solely by the stress amplitude. This latter conclusion is supported also by the fact that the load change is not constant within a given vibration test cycle as indicated by the differences between zones (b) and (c) of Fig. 2.

There may be significance also in the fact that the observed amplitude of vibration at 25 kc in Fig. 1 was 2-1/2 times as great as that observed for the resonance that occurred at 20 kc. Despite this difference, it will be noted that the lower frequency and lower amplitude vibration was at least as effective as the larger amplitude at the higher frequency. This also would seem to indicate that the ultrasonic vibration served to trigger off some internal mechanism or mechanisms whose behavior depended upon the extent of prior plastic strain without vibration.

The lower curve in Fig. 1 was obtained without ultrasonic vibration in a procedure wherein the driving mechanism was stopped for a period of 15 sec after each 0.005 in. of deflection. A similar procedure had been followed in earlier tests and it had been noted that there was a tendency for the load to relax. This also happened during some tests at high total loads wherein the driving belts slipped and caused the head of the testing machine to stop. Consequently, a series of tests such as that carried out for specimen No. 10 in Fig. 1 were made for the purpose of studying this relaxation phenomenon. It was to be expected that slipping of the rubber belts slowly over a period of time would permit the load to relax. However, one cannot account for the overshoot in the increased load when the driving mechanism was restarted. Attention to the overshoot will be emphasized again in subsequent discussions.

Figure 3 is reproduced from the proceedings of the symposium an ultrasonics presented by the United States Bureau of Naval Weapons on June 21, 1963. These results were reported for extrusion wherein the extrusion die was vibrated intermittently in much the same way as the tests for aluminum cube No. 11 as shown in Fig. 1. A striking resemblance is to be noted in the shape of the response curves of this figure when compared with Figs. 1 and 2. It is evident also in Fig. 3 that the effect of ultrasonic vibrations in extrusion likewise fails to sustain the same magnitude of effect which it had immediately after the onset of vibration.

Figure 4 is reproduced from a recent report from the University of Vienna on results obtained with single crystals of zinc that had been irradiated with ultrasonic vibration prior to performing tensile tests. Two features of the results presented in Fig. 4 are to be emphasized. First is the fact that the yield point of the crystals is substantially increased as a result of ultrasonic irradiation. Second is the appearance of an overshoot which increases in magnitude with the amount and intensity of the vibration. It is possible that the overshoot in Fig. 4 is identical with that which appears in Figs. 1, 5-7. In addition, the results obtained in testing the aluminum cubes in compression which are summarized in Tables I through IV appear to reflect the hardening or strengthening of the metals as reported by the University of Vienna.

Table IV summarizes the effects of vibrations for compression tests on oil lubricated cubes. These results are the averages reported in Tables II and III for 11 specimens; 6 were tested without vibration and 5 with vibration. It will be noted that vibration caused the load to be increased from 12-1/2 to 14% at all levels of deflection beyond the yield point of the matetrial. Further examination of Tables II and III confirms the validity of this result when one notes that all of the test data lie in two well-defined groups. Only in two cases out of 44 possible combinations does the highest load obtained without vibration equal the lowest load obtained with vibration; there were no instances of overlapping of the distribution curves.

Comparison of the data in Table I with that of Table II indicates that use of white oil did reduce boundary friction at nonvibrating conditions. Therefore, all but six of the 39 tests made with the aluminum cubes were carried out with white mineral oil as a lubricant.

Figure 8 shows the results of a single test carried out with a 4-in. threaded specimen wherein the central portion of the test region was reduced to the dimensions of a 0.100-in. cube. This specimen was tested with the same vibration program as specimen No. 11 illustrated in Fig. 1. However, this configuration had very poor vibration characteristics resulting in substantially lower amplitude and power density so that the load response to vibration was not as great as with the simple cubes. Despite this fact it will be noted that the same characteristic features of Figs. 1 and 2 are present. Attempts to increase the intensity of vibration by adjusting frequency caused some of the extraneous responses within the vibrated regions. Several distinct shear clevage cracks were noted in the test section when the specimen was removed from the machine. No similar cracks were noted in simple cubes.

TUBULAR ALUMINUM SPECIMENS IN COMPRESSION

Figures 9 and 11 show typical chart records obtained from compression tests on the original tubular shaped aluminum specimen both with and without vibration. Figure 9 shows the smooth, continuous, load-deflection curve that was characteristic of all tests carried out without vibration except for the change noted where the belt slipped at the highest load level.

Figure 10 is typical of many of the earlier tests carried out during the period when the nature of response to ultrasonic vibration was still quite unclear. In the case of specimen No. C-13 the load was applied by hand to selected levels at which point the specimen was vibrated for a substantial period of time and the results noted. Among these results was the relaxation which took place despite attempts to hold absolutely steady. It would appear that at least some of this relaxation took place within the test specimen. In addition it was noted that continued relaxation generated heat within the test section and further that the specimen temperature was increased also by heat conducted from the transducer. In later tests the transducer was cooled by forced air and the dimensional changes resulting from temperature change do not appear in the records. Particular attention is called to the last test cycle of specimen No. C-13 during which the load was applied through the mechanical drive and the frequency of vibration was scanned or manually adjusted more or less randomly resulting in the jagged curve for this last cycle. It is believed that these variations are related to the phenomena discussed in connection with Figs. 1 and 2.

Figure 11 is typical of those tests carried out with ultrasonic vibration superimposed continuously from the beginning of loading. It was noted generally by observing the accelerometer output in the oscilloscope that the resonant frequency shifted during load application making it necessary or at least desirable to make small frequency adjustments. The irregularities indicated near the middle of the curve in Fig. 11 are typical of the response to such attempts to find peak effectiveness.

A summary of the effects of vibration during compression tests with aluminum is given in the data of Tables V through VIII. Table VIII shows that vibration caused the loads to increase at corresponding deflections compared to static testing. It is to be noted furthermore that the percentage increase is greatest at small deflections and decreases continually as the total deflection itself is increased.

It should be emphasized that the deflections at which the results are compared are the same as those given in Tables I through IV for the cubes, and that since the test section of the tubular specimens is almost four times as long as the cubes the corresponding shear strain is several times greater for the cubes than for the tubular specimens. The percentages at the bottom of Table VIII show the same trend as that reported by the University of Vienna wherein it was stated that the hardening or strengthening of irradiated zinc crystals decreased with an increase in prior strain. This was true within the strain range reported but they called attention to the fact that the increase appeared to become asymptotic to some minimum value. The results of Table VIII reflect that same trend and therefore seem to confirm or substantiate that conclusion.

A comparison of the results in Table VIII with those of Table IV seems to indicate that the amount of strengthening has indeed become asymptotic at the deflections used in comparing results for the cubes. Thus a deflection of 0.010 in. for the cubes corresponds to substantially the same shear strain as 0.045 in. deflection for the longer tubular spcimens. Attention is called also to the fact that the total deflection at a load just above the yield point for both the cubes and tubular specimens is reduced by about 35% whereas the deflection at the 1350 pound load in Table IV corresponds to a substantially greater shear strain than was achieved with the tubular specimens. Both the 4000 and 5000 pound loads of Table VIII must be considered as close to the yield point.

TUBULAR STEEL SPECIMENS IN COMPRESSION

The relatively thin walled steel specimens produced catastrophic buckling under compressive loads in consrast to the aluminum specimens which bulged but did not buckle in the ordinary meaning of the word. Ultrasonic vibration did have a substantial influence on the behavior of the steel specimens under compression but it was exceedingly difficult to evaluate and repeat.

Figure 12 shows a typical load deflection curve for a steel specimen tested under compression without vibration. The load built-up to a maximum which represented a point of instability after which it buckled and deflection proceeded very rapidly in the interval characterized by the rippling line substantially in the middle of the figure.

Figure 14 is representative of the most pronounced influence of vibration observed during this series. The onset of vibration caused the specimen to buckle very rapidly and then as the frequency was changed through a scanning, buckling was slowed down near the middle of the record only to be accelerated again as resonance was once more achieved. These results are thought to be interesting but in no way comparable to those obtained at other test conditions in this investigation. It is quite possible that the super position of ultrasonic vibration excited membrane vibrations in a lateral direction to the test specimen which could be expected to affect stability and buckling characteristics.

Such quantitative information obtained from compression of the steel test specimens as were deemed reliable are summarized in Tables IX and X. Little can be concluded from these tables except for the possible fact of a lowering of the buckling load under the influence of vibration.

TENSILE TESTS ON ALUMINUM

Typical chart records for the majority of the tensile tests on aluminum are given in Figs. 16 through 21. Figures 16, 17, and 18 were all obtained without vibration and are reproduced and presented as an indication of the degree of repeatability inherent in the equipment, materials properties, and test procedure.

Figures 19 and 20 are representative of both procedures and results obtained in the earlier phases of the program. Figure 21 is typical of results obtained in the presence of vibration during the latter stages of the program wherein it became evident that the ultrasonic power available was quite small in relation to the area of the test section and its length. Despite these limitations, numerous tests were run and summaries of the more dependable results are given in Tables XI and XII.

One might conclude from these results that vibration reduces the breaking strength of the aluminum. This conclusion would appear to be justified inasmuch as the highest breaking load with a vibrated specimen exceeded that of the lowest of the non-vibrated specimens by only 50 pounds. In other words, there was very little overlapping of the distribution curves for these two conditions. A similar result will be noted later for steel in Tables XIII and XIV.

Figure 22 shows the results obtained from a tension test on the last remaining tubular specimen. This test was carried out with the same vibration program as that indicated in Fig. 1. It will be noted that except for the attenuation resulting from a 30:1 difference in the volume of irradiated metal, the same characteristic response appears in Fig. 22 as for specimen No. 11 in Fig. 11.

TENSION TESTS ON STEEL

Figures 23 and 24 show typical results from both early and more recent studies and tests with the tubular steel specimens. Figure 25 shows the last test carried out on steel wherein one of the tubular specimens was tested in tension using the same program of vibration indicated in Fig. 1. Although the magnitude of the response is small, one nevertheless can recognize essentially the same characteristics as those designated in Fig. 2.

The bulk of the quantitative information obtained for tensile tests on steel is summarized in Tables XIII and XIV where, as in the case of aluminum, it might be concluded that the breaking strength is reduced by the super position of ultrasonic vibration. In addition one might also be justified in concluding on the other hand that vibration increases the yield point for steel. In closing, it appears justified to call attention to the similarity between the average tensile results for both aluminum and steel with curves (a) and (b) obtained for single crystals as shown in Fig. 4.

CONCLUSIONS

Ultrasonics appears to have more effect than simply stress amplitude. This is supported by four observations:

(a) The load reduction increases with strain beyond the yield point.

(b) The load reduction is itself decreased after an initial period of rapid strain.

(c) The load level is increased in general with intermittent irradiation (confirmed for compression tests only on aluminum).

(d) The load is increased briefly (overshoot) after vibration is stopped.

The effects of ultrasonics increase with power density but are extremely difficult to measure quantitatively because of the complex modes of motion and an apparent mixture of two or more mechanisms.

It was impossible to sort out the effects of boundary friction except in the compression of aluminum cubes with and without white oil. Boundary friction will be easier to evaluate in the experiments of Phase I.

The observation reported in item (b) above appears to be substantiated by results reported for extrusion.

The hardening or strengthening of single crystals, as reported elsewhere in the literature, could be one of the mechanisms created by ultrasonic vibration in the polycrystalline materials used for this investigation. This is evident in the compression data for aluminum which correlates with the results in Fig. 4 for all power levels and up to moderate plastic strain. In addition, the results for tension corresponded well with the low power results in Fig. 4. Finally, the rapid and substantial rise in load of zone (d) in Fig. 2 has the same qualitative shape as curves (a), (b), and (c) of Fig. 4 and represents the same conditions of prior irradiation.

The summary comparison of Table VIII supports the conclusion of the University of Vienna report (see Fig. 4) to the effect that the amount of the hardening or strengthening is decreased at greater amounts of prior strain.

The summary comparison of Table IV supports the further conclusion of the University of Vienna report to the effect that the hardening not only decreases for higher prestrain but may become asymptotic to a minimum value which in turn might be either plus or minus. In this case it was plus.

The sudden drop in load accompanying onset of vibration and its dependence upon prior plastic strain could be evidence of a new mechanism different from those manifest in the behavior of single crystals with prior radiation.

It is evident that further fundamental research not only is warranted but must be done to identify the mechanisms arising out of ultrasonic irradiation of metals. It remains to be determined whether the strengthening is indeed distortion hardening or whether it is the result of either the elimination or more uniform distribution of dislocations within the structural lattice. On the other hand, conditions at the grain boundaries may also play a dominant role. In any event, ultrasonic vibrations have been proven to influence metal beyond simple super position of stress and merit further research both with regard to the load carrying behavior of metals and metal fabrication properties. The uniqueness of the results of ultrasonics compared to lower frequency stress variations may be associated with time rate of change of stress, in which case the results will correlate with shock wave behavior. Both are known to occur naturally in metal cutting and forming; therefore, it is important to understand what effect they have before it can be decided whether they can be ignored, must be controlled, or can be put to useful purposes.

TABLE I

COMPARISON OF LOADS AND DEFLECTIONS AT TYPICAL POINTS FOR COMPRESSION TESTS ON ALUMINUM CUBES

(Dry Static)

Specimen	Load at Deflection, lb				Deflection at Load, in.	
No.	0.010 in.	0.020 in.	0.030 in.	0.045 in.	800 lb	1350 lb
1	830	1035	1170	1530	0.0085	0.0380
2	855	1070	1250	1560	0.0080	0.0355
3	830	1045	1235	1555	0.0095	0.0355
Average	838	1050	1218	1548	0.0087	0.0363
Range	25	35	80	30	0.0015	0.0025

TABLE II

COMPARISON OF LOADS AND DEFLECTIONS AT TYPICAL POINTS FOR COMPRESSION TESTS ON ALUMINUM CUBES

(Static with Oil)

Specimen	Load at Deflection, lb				Deflection at Load, in.	
No.	0.010 in.	0.020 in.	0.030 in.	0.045 in.	800 lb	1350 lb
7	785	980	1150	1510	0.0085	0.0370
10	835	1035	1200	1450	0.0120	0.0400
A-1	800	1010	1170	1500	0.0100	0.0380
A-2	760	950	1110	1440	0.0120	0.0410
A-3	745	935	1080	1400	0.0125	0.0425
A-4	735	925	1070	1400	0.0130	0.0430
Average	786±31.7	970±36	1130±43	1450±39	0.0113	0.0402
Range	100	100	130	110	0.0045	0.006

TABLE III

COMPARISON OF LOADS AND DEFLECTIONS AT TYPICAL POINTS FOR COMPRESSION TESTS ON ALUMINUM CUBES

(Vibrated with Oil)

Specimen	Load at Deflection, lb				Deflection at Load, in.	
No.	0.010 in.	0.020 in.	0.030 in.	0.045 in.	800 lb	1350 lb
11	855	1155	1225	1575	0.0080	0.0360
12	875	1085	1260	1610	0.0075	0.0350
13	835	1050	1235	1555	0.0087	0.0360
14	955	1180	1385	1735	0.0055	0.0280
15	925	1140	1340	1690	0.0065	0.0315
Average	899±49	1102±55	1287±66	1633±74	0.0072	0.0334
Range	120	130	160	180	0.0032	0.0080

TABLE IV

SUMMARY OF THE EFFECTS OF VIBRATION FOR COMPRESSION TESTS ON ALUMINUM CUBES

(Oil Lubricated)

		Load at Deflection, lb				Deflection at Load, in.	
		0.010 in.	0.020 in.	0.030 in.	0.045 in.	800 lb	1350 lb
Vibrated		889±49	1102±55	1287±66	1633±74	0.0072	0.0334
Static		786±31.7	970±36	1130±43	1450±39	0.0113	0.0402
Change	Units	103	132	157	183	0.0041	0.0068
	%	+13.1	+13.6	+13.9	+12.6	-36.4	-16.7

TABLE V

SUMMARY OF STATIC COMPRESSION TESTS ON ALUMINUM

Specimen No.	Yield Load, lb	Load at 0.045 in. Deflection	Original Area, $in.^2$	Reduction, in. (a)	Reduction, in. (b)
A-5	3730	6780	0.0974	0.037	0.042
B-22	4500	--	0.0979	--	0.056
C-22	4600	--	0.0977	--	0.045
B-23	3680	7490	0.0974	0.058	0.054
C-17	4100	7000	0.0974	0.059	0.056
Average	4122	7090	0.0976	--	--
Range	920	710	0.0005	--	--

(a) Indicated by chart record.
(b) Measured on specimen subsequent to unloading.

TABLE VI

SUMMARY OF ULTRASONIC COMPRESSION TESTS ON ALUMINUM

Specimen No.	Yield Load, lb	Load at 0.045 in. Deflection	Original Area in.^{2}	Reduction, in.		Remarks
				(a)	(b)	
A-6	3500	7600	0.0966	0.0585	0.059	Continuous vibration at 23.2 kc
A-30	4400	7200	0.0966	0.058	0.0567	Continuous vibration at 23.2 kc
B-3	3700	7300	0.0966	0.0585	0.0577	Continuous vibration at 23.0 kc
C-13	3700	7550	0.0966	0.042	0.0437	Continuous vibration with frequency scanning hand loaded
Average	3820	7412	0.0966	0.0542	0.054	
Range	900	400	0.000	0.0165	0.015	

(a) Indicated by chart record.
(b) Measured on specimen.

TABLE VII

COMPARISON OF LOADS AND DEFLECTIONS AT TYPICAL POINTS FOR COMPRESSION TESTS ON ALUMINUM

Specimen	Load at Deflection, lb				Deflection at Load, in.		Remarks
No.	0.010 in.	0.020 in.	0.030 in.	0.045 in.	4000 lb	5000 lb	
A-5	3730	5050	5860	6780	0.0115	0.020	Static
B-23	4750	5840	6600	7490	0.007	0.012	Static
C-17	4400	5500	6200	7000	0.0095	0.0155	Static
Average	4293	5463	6220	7090	0.0093	0.0158	
Range	820	790	740	710	0.0045	0.008	
A-6	5300	6400	7000	7600	0.005	0.0085	Vibrated
A-30	4900	5900	6600	7200	0.006	0.011	Vibrated
B-3	5000	6000	6600	7300	0.006	0.010	Vibrated
C-13	4960	6260	6900	7550	0.007	0.0105	Vibrated
Average	5040	6140	6775	7412	0.006	0.010	
Range	400	500	400	400	0.002	0.002	

TABLE VIII

SUMMARY OF THE EFFECTS OF VIBRATION FOR COMPRESSION TESTS ON ALUMINUM

		Load at Deflection, lb				Deflection at Load, in.	
		0.010 in.	0.020 in.	0.030 in.	0.045 in.	4000 lb	5000 lb
Vibrated		5040	6140	6775	7412	0.006	0.010
Static		4293	5463	6220	7090	0.0093	0.0158
Change	Units	747	677	555	322	0.0033	0.0058
	%	+17.4	+12.4	+8.9	+4.5	-35.5	-36.5

TABLE IX

SUMMARY OF STATIC COMPRESSION TESTS ON STEEL

Specimen No.	Yield Load, lb	Maximum Load, lb	Load at 0.045 in. Deflection	Original Area, in.^{2}	Deflection at Buckling, in.	Reduction, in.	
						(a)	(c)
B-3	5370	6500	--	0.0326	--	--	0.031*
B-23	5370	6800	--	0.0326	--	--	0.027*
C-6	5400	6970	4300[c]	0.0322	0.010	--	0.085*
B-20	5700	6000	3600	0.0325	0.012	0.040	0.037
C-?	5900	6230	3700	0.0325	0.011	0.037	0.036
Average	5480	6500	3870	0.0325	0.011	0.0385	0.0365
Range	530	970	700	0.0004	0.002	0.003	0.001

(a) Indicated on chart record.
(b) Measured on specimen after test.
(c) Load at 0.020 in. deflection = 5100 lb
* Not included in Average or Range

TABLE X

SUMMARY OF ULTRASONIC COMPRESSION TESTS ON STEEL

Specimen No.	Yield Load, lb	Maximum Load, lb	Load at 0.045 in. Deflection	Original Area, $in.^2$	Deflection at Buckling, in.	Reduction, in. (a)	Reduction, in. (b)	Remarks
A-21 (d)	5500 may be higher	7250	3500	0.0324	0.0075	--	0.0697*	Continuous vibration with frequency scanning
A-28	4560	5630	3350	0.0325	0.0095	0.038	0.0376	Load at 0.020 = 4880 lb Intermittent vibration with frequency scanning
B-7	6100	6350	4100	0.0324	0.0085	--	0.0366	Load at 0.020 = 5650 lb Continuous vibration with frequency scanning
B-17	6000 (c)	6700	3900	0.0324	0.0065	--	0.047	Load at 0.020 = 5500 lb Continuous vibration with frequency scanning
D-10	5700	6000	3400	0.0325	0.0110	0.039	0.0383	Load at 0.020 = 5300 lb Continuous vibration with frequency scanning
D-11	5200	5500	3200	0.0326	0.0110	0.038	0.0353	Load at 0.020 = 4300 lb Continuous vibration with frequency scanning
D-13	5100	5820	3500	0.0325	0.0100	0.038	0.0358	Load at 0.020 = 5200 lb Continuous vibration with frequency scanning
Average	5438	6172	3542	0.0325	0.0092	0.0384	0.0384	
Range	1540	1750	900	0.002	0.0045	0.001	0.0117	

(a) Indicated by chart records
(b) Measured on specimen after test.
(c) Chart record not reliable.
(d) Data taken from Sanborn may not be reliable.
* Not included in Average or Range.

TABLE XI

SUMMARY OF STATIC TENSILE TESTS ON ALUMINUM

Specimen No.	Yield Load, lb	Breaking Load, lb	Original Area, $in.^2$	(a) Deflection at Failure, in.	(b) Total Elongation, in.
A-4	4500	7300	0.0975	0.064	0.0559
A-7	5200	7500	0.0981	--	0.051
A-14	4900	7200	0.0969	--	0.054
A-33	5000	7600	0.0981	--	0.053
C-24(c)	5200	7500	0.0976	0.049(c)	0.0485
A-8	4750	7150	0.0974	0.057	0.0487
A-20	4770	7250	0.0974	0.059	0.0495
Average	4903	7357	0.0976	0.060	0.052
Range	450	300	0.0014	0.007	0.008

(a) Indicated on chart record.
(b) Measured on specimen after test.
(c) Specimen previously vibrated without loading, L&N deflection. Sensitivity was two times normal and inadequate.

TABLE XII

SUMMARY OF ULTRASONIC TENSILE TESTS ON ALUMINUM

Specimen No.	Yield Load, lb	Breaking Load, lb	Original Area, $in.^2$	(a) Deflection at Failure, in.	(b) Total Elongation, in.
A-10	5300	7200	0.0981	--	0.051
B-11	4900	6780	0.0974	0.061	0.0487
B-28	4700	7080	0.0974	0.062	0.0565
B-29	4750	7200	0.0981	--	0.053
B-32	5200	6800	0.0974	--	0.0499
B-33	4850	7250	0.0978	--	0.058
Average	4950	7050	0.0977	0.0657	0.0528
Range	550	470	0.0007	0.013	0.0093

(a) Indicated by chart.
(b) Measured after test.

TABLE XIII

SUMMARY OF STATIC TENSILE TESTS ON STEEL

Specimen No.	Yield Load, lb	Maximum Load, lb	Breaking Load, lb	Original Area, in.^{2}	(a) Deflection at Failure, in.	(b) Total Elongation, in.
A-2	5087	--	6900	0.0322	--	0.033
A-5	5087	--	7100	0.0326	--	0.031
A-9	5800	--	7200	0.0322	--	--
A-12	5200	--	6900	0.0326	--	0.021
A-24	5000	6900	6700	0.0322	0.0265	0.0299
C-20	5700	7400	7250	0.0324	0.0245	0.022
A-10	5300	7700	--	0.0326	--	--
B-1	5900	7200	7000	0.0323	0.0275	0.022
B-8	5700	7180	7120	0.0323	0.0230	0.0207
Average	5420	7280	7030	0.0324	0.0254	0.0247
Range	900	800	550	0.0004	0.0045	0.012

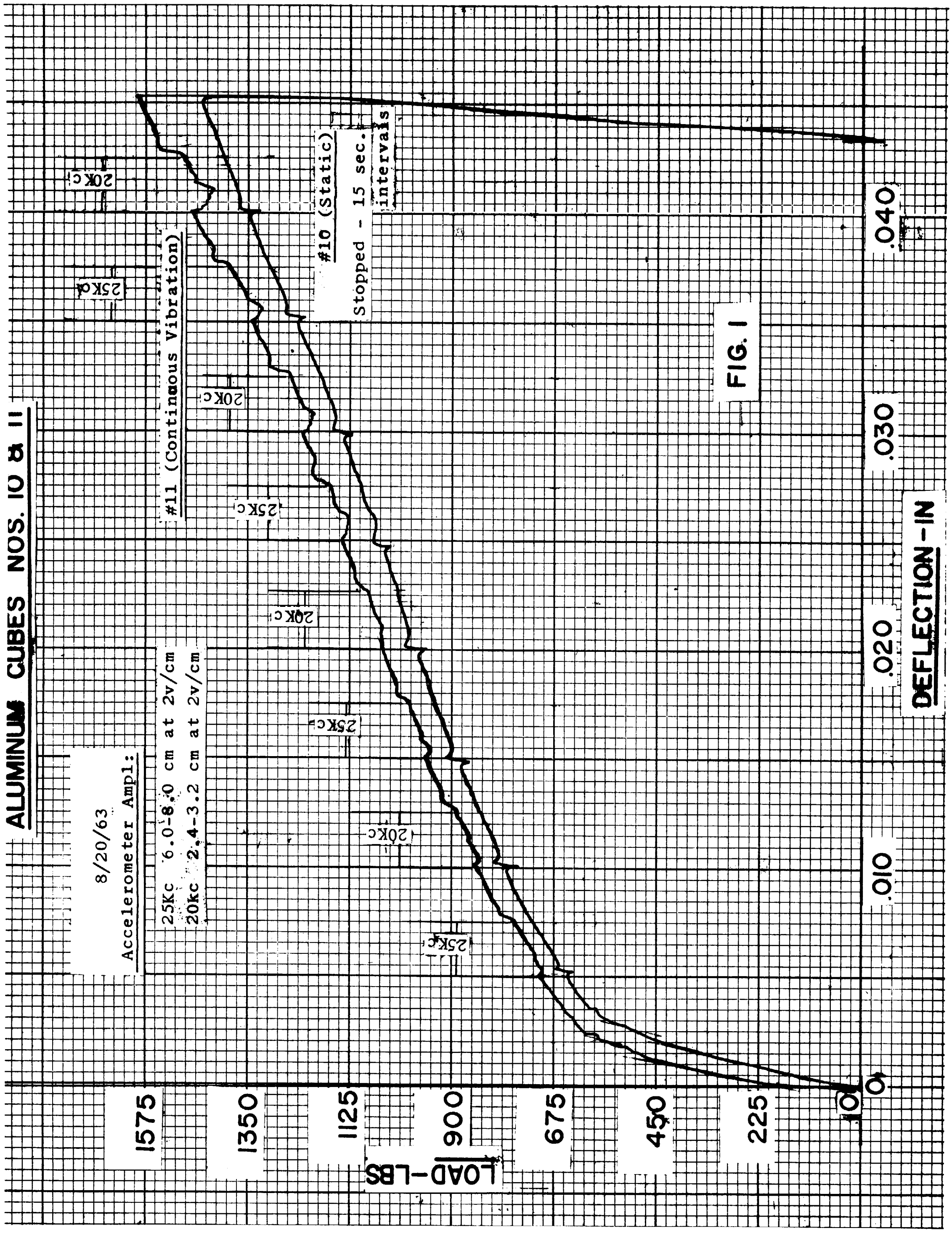
(a) Indicated on chart record.
(b) Measured on specimen after test.

TABLE XIV

SUMMARY OF ULTRASONIC TENSILE TESTS ON STEEL

Specimen No.	Yield Load, lb	Maximum Load, lb	Breaking Load, lb	Original Area, in.^{2}	(a) Deflection at Failure, in.	(b) Total Elongation, in.
A-15	6500	--	7200	0.0326	--	0.036
A-14	6400	--	6700	0.0326	--	0.026
A-4	5000	--	6500	0.0322	--	0.028
B-27	5600	7180	7000	0.0323	0.0250	0.019
A-13	5370	--	7400	0.0326	--	--
A-11	--	--	6300	0.0322	--	0.030
A-23	5400	6950	6600	0.0323	0.022	0.0218
C-20	6100	7610	7450	0.0323	0.0245	0.0186
C-17	6000	7190	6890	0.0323	0.0275	0.0358
C-10	5300	6450	6300	0.0323	0.0195	0.0187
C-23	5700	6980	6750	0.0323	0.0295	0.0215
Average	5737	7060	6830	0.0324	0.0246	0.025
Range	1500	1160	1150	0.0004	0.010	0.029

(a) Indicated on chart record.
(b) Measured on specimen after test.


ALUMINUM CUBES NOS. 10 & 11
8/20/63
Accelerometer Ampl:
25Kc 6.0-8.0 cm at 2v/cm
20kc 2.4-3.2 cm at 2v/cm
#11 (Continuous Vibration)
#10 (Static)
Stopped - 15 sec. intervals
20Kc
25Kc
20Kc
25Kc
20Kc
25Kc
20Kc
25Kc
FIG. 1
LOAD-LBS
1575
1350
1125
900
675
450
225
0
0
.010
.020
.030
.040
DEFLECTION-IN

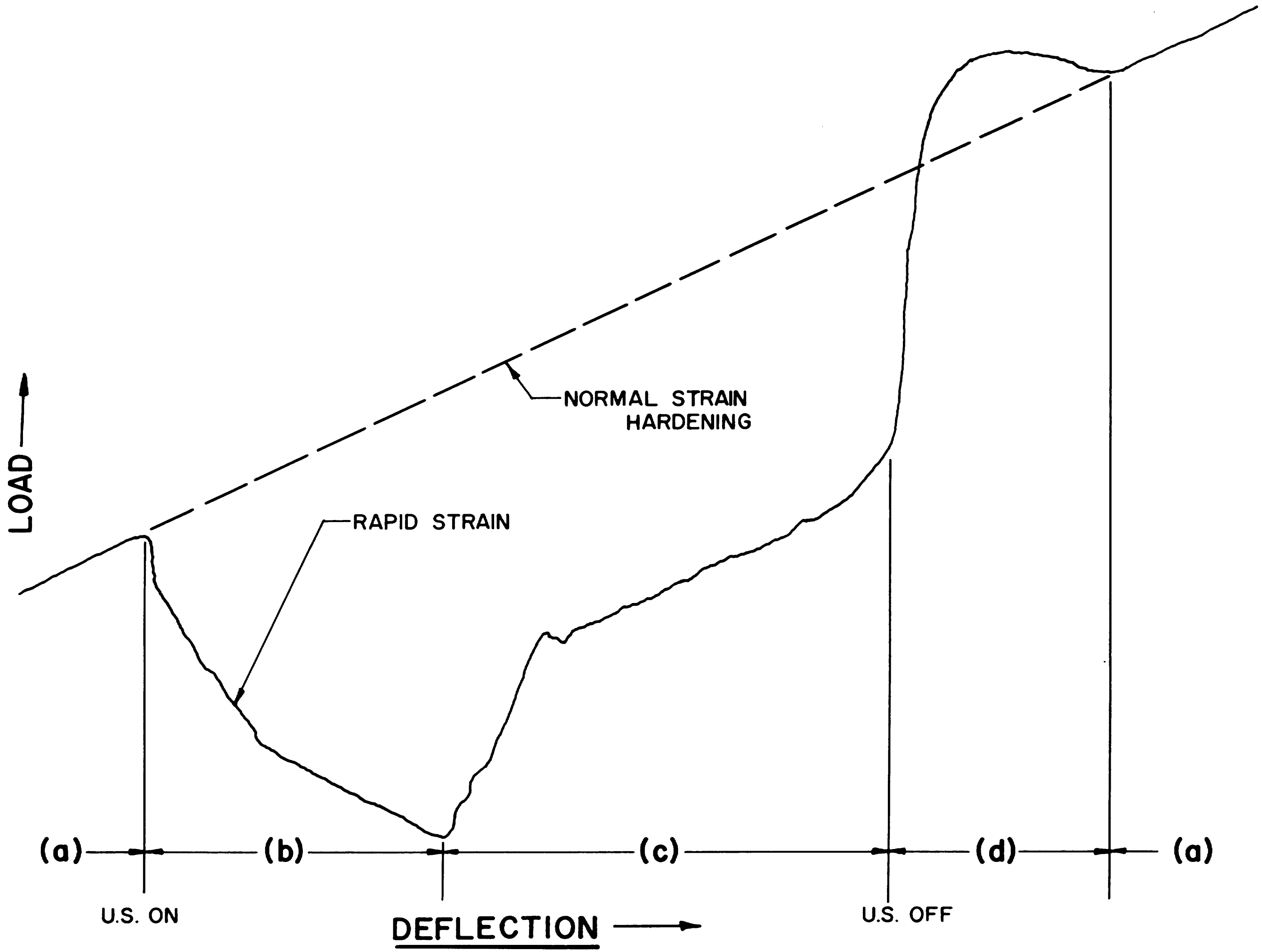


Fig. 2. Aluminum cubes in compression.

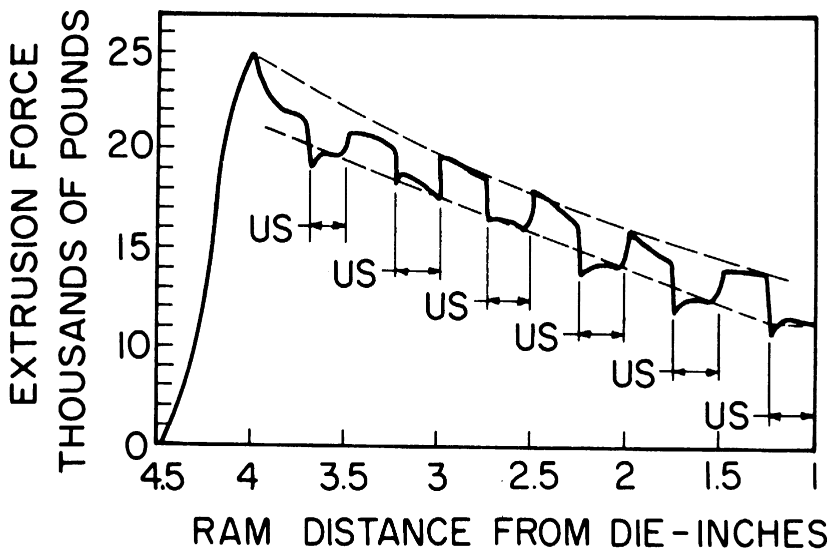


Fig. 3. Pulsed ultrasonic extrusion of aluminum billet with shear die. Extrusion rate: 2 ipm "US" indicates interval of ultrasonic application.

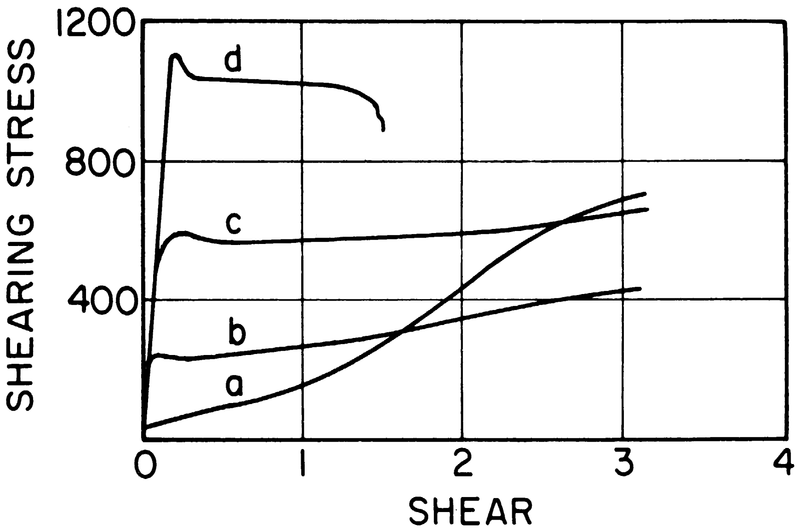
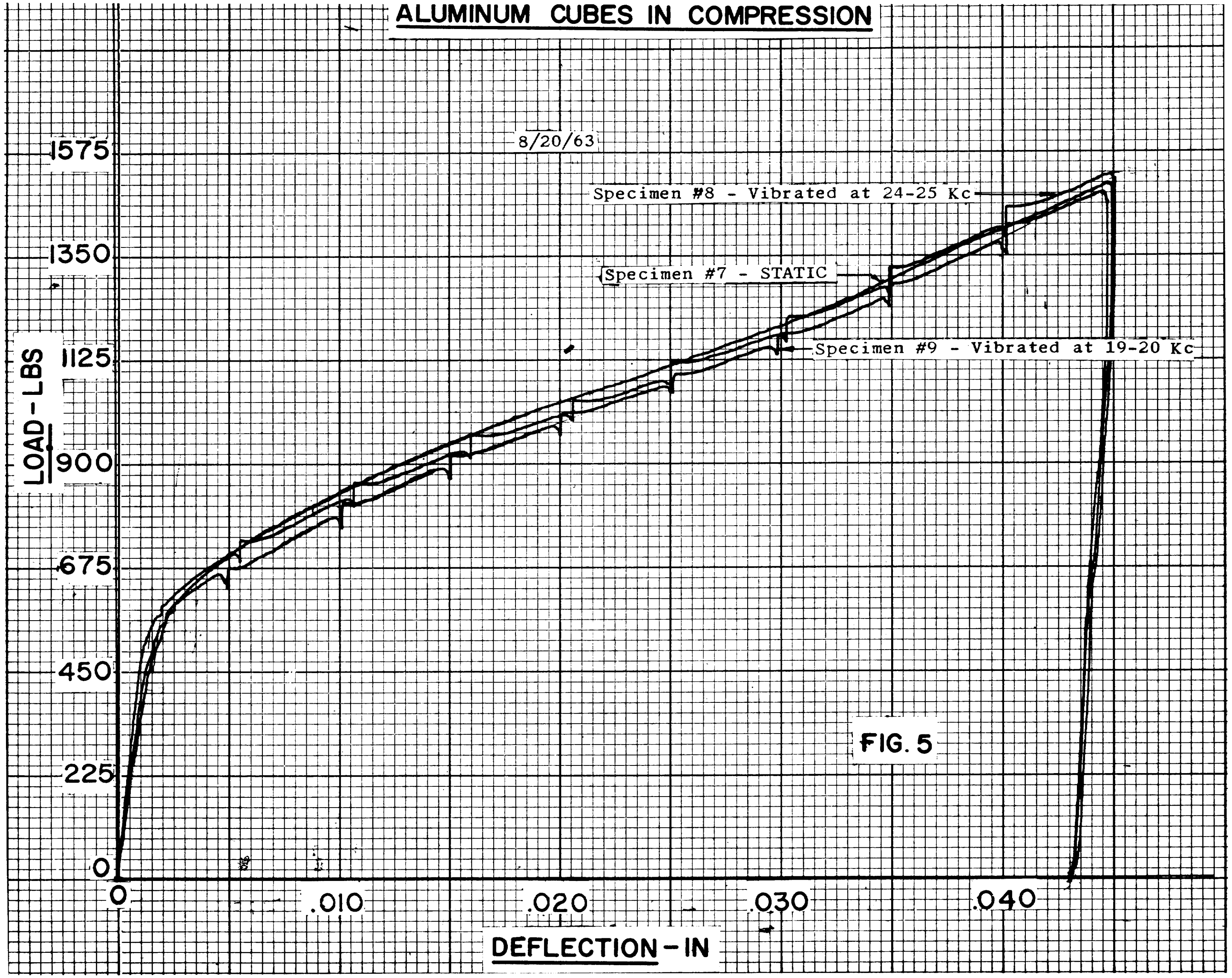


Fig. 4. Yield-stress curves of zinc crystals after ultrasonic treatment with different intensities (10 min, 20 kc/sec). a. Without radiation. b. Low. c. Medium. d. High intensity. (From Interim Report No. 2, MPEP Contract No. N 62558-3436, Physikalisches Institut der Universitat Wiens, distributed by the U. S. Bureau of Naval Weapons, August 20, 1963.)


ALUMINUM CUBES IN COMPRESSION
8/20/63
Specimen #8 - Vibrated at 24-25 Kc
Specimen #7 - STATIC
Specimen #9 - Vibrated at 19-20 Kc
1575
1350
1125
900
675
450
225
0
LOAD-LBS
0
.010
.020
.030
.040
DEFLECTION-IN
FIG. 5

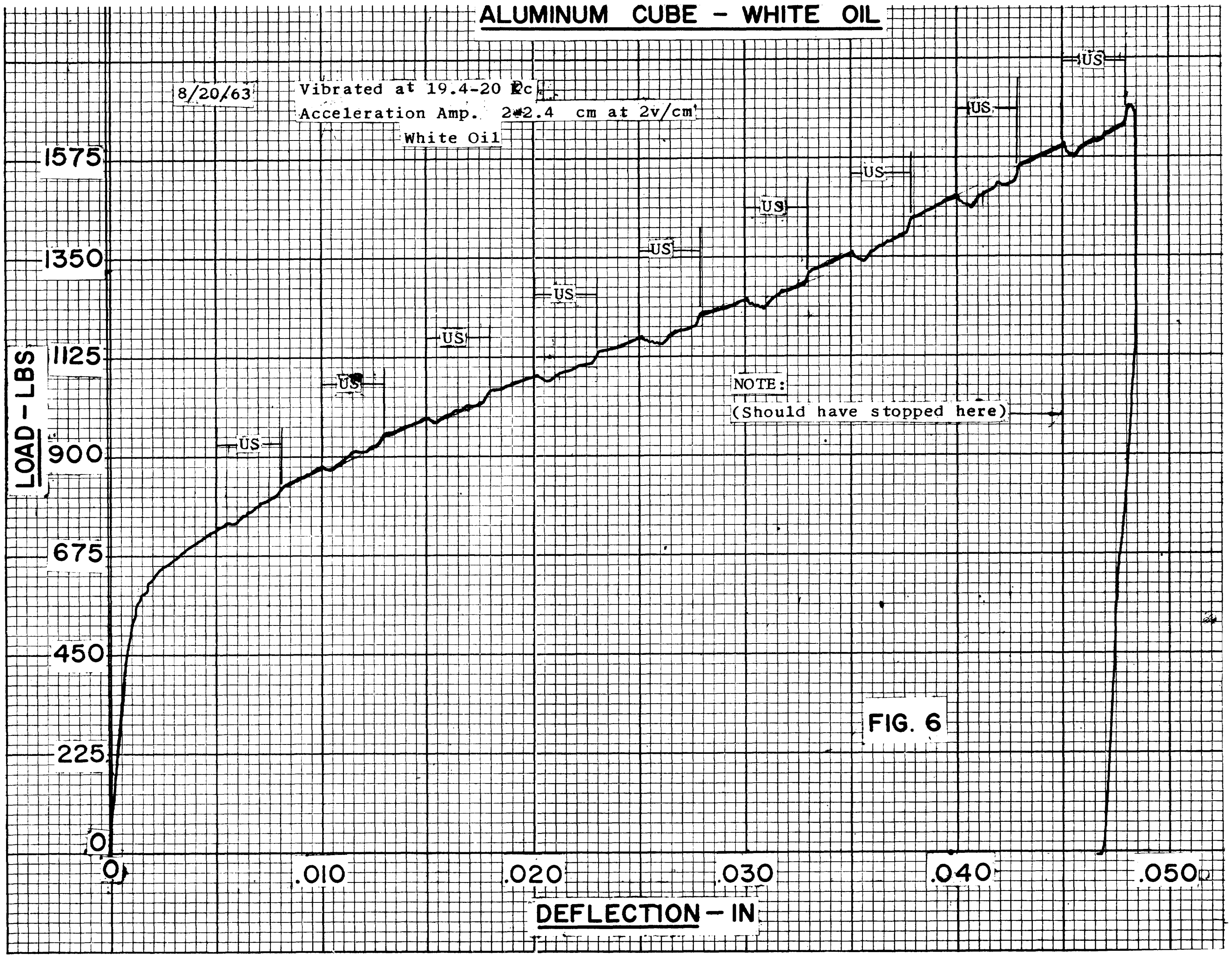

ALUMINUM CUBE - WHITE OIL
8/20/63
Vibrated at 19.4-20 Kc
Acceleration Amp. 2.4 cm at 2v/cm
White Oil
LOAD - LBS
1575
1350
1125
900
675
450
225
0
US
NOTE:
(Should have stopped here)
0
.010
.020
.030
.040
.050
DEFLECTION - IN

FIG. 6

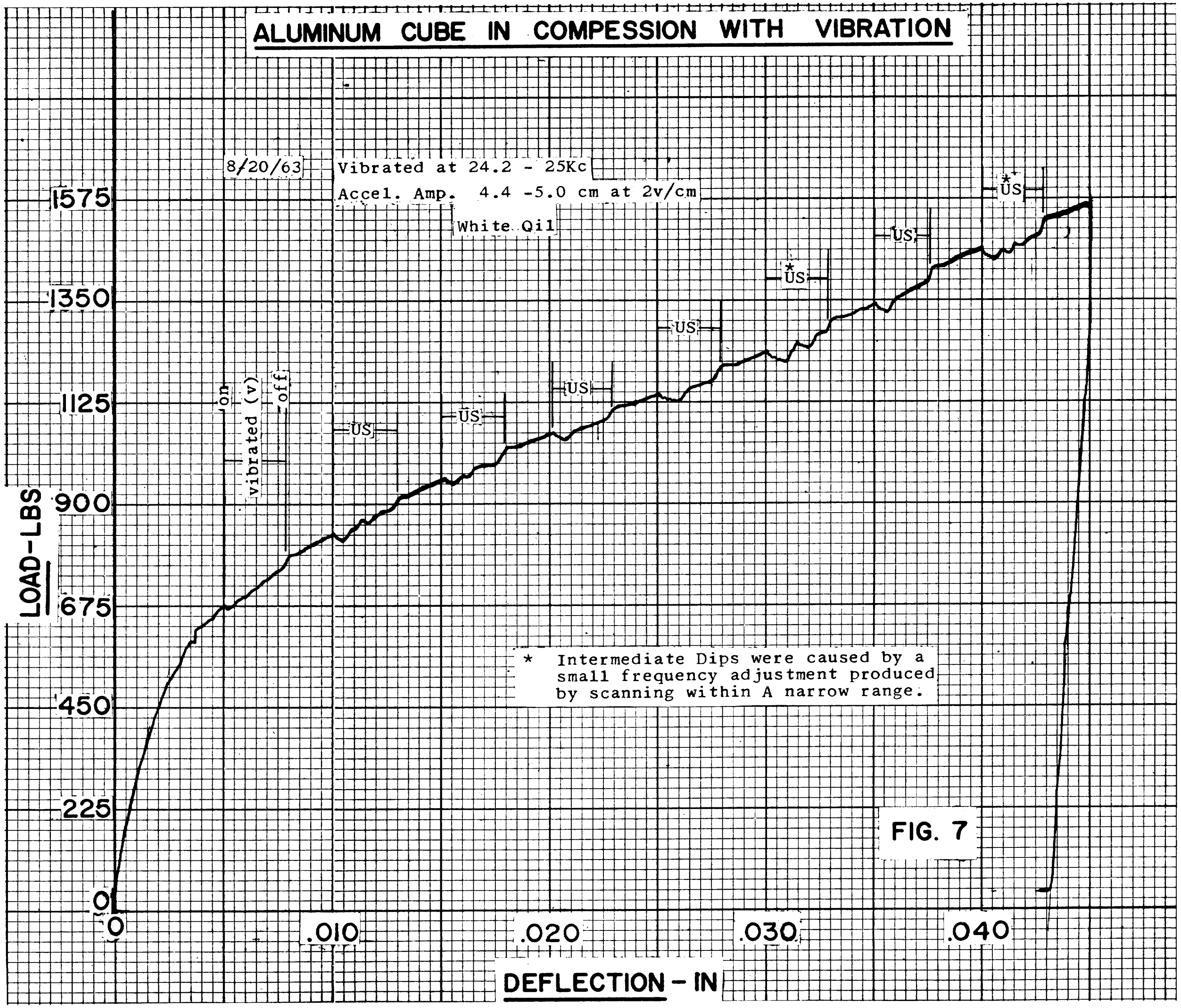

ALUMINUM CUBE IN COMPESSION WITH VIBRATION
8/20/63
Vibrated at 24.2 - 25Kc
Accel. Amp. 4.4 -5.0 cm at 2v/cm
White Oil
LOAD-LBS
1575
1350
1125
900
675
450
225
0
on
vibrated (v)
off
US
*US
* Intermediate Dips were caused by a small frequency adjustment produced by scanning within A narrow range.
0
.010
.020
.030
.040
DEFLECTION - IN

FIG. 7

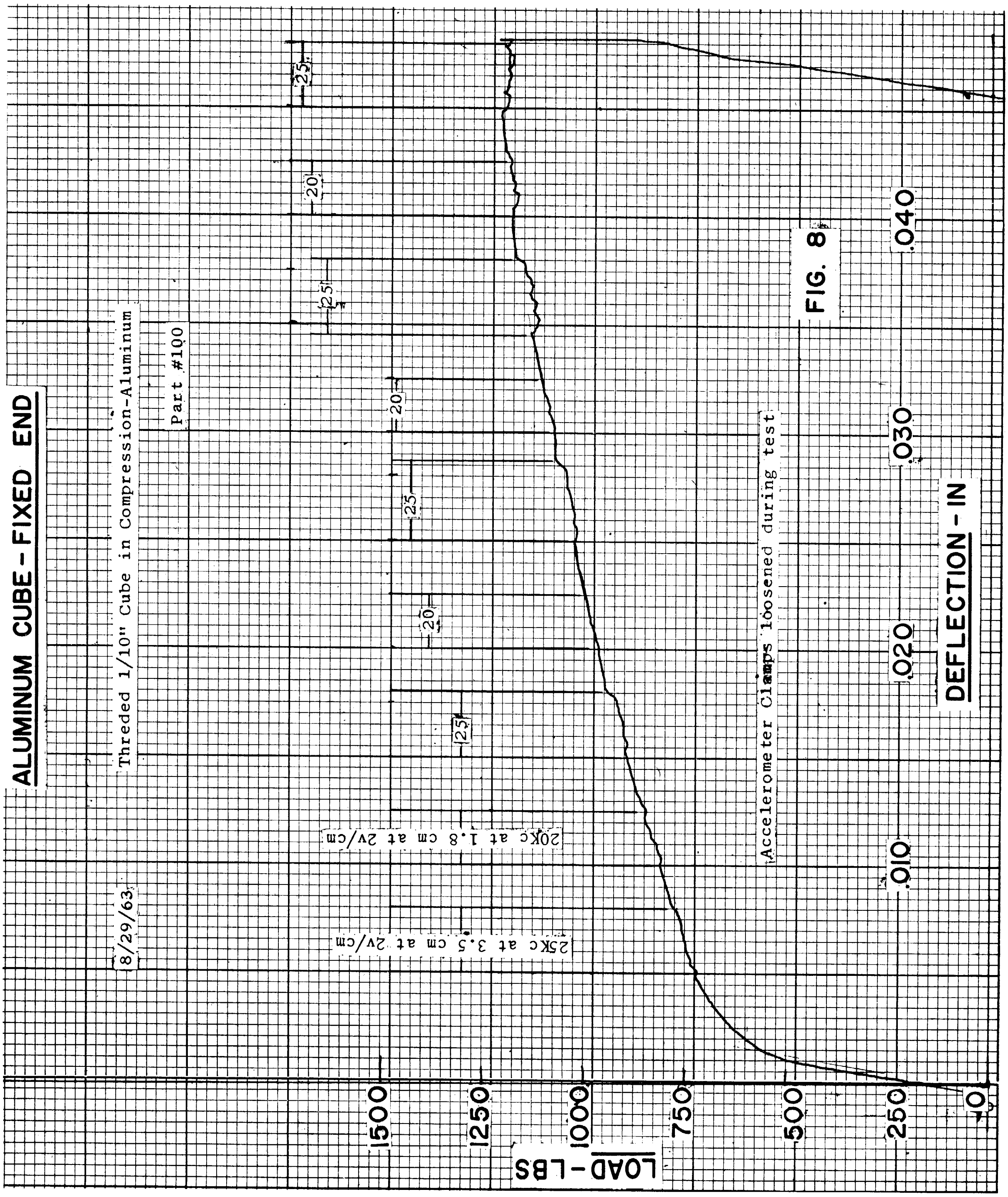
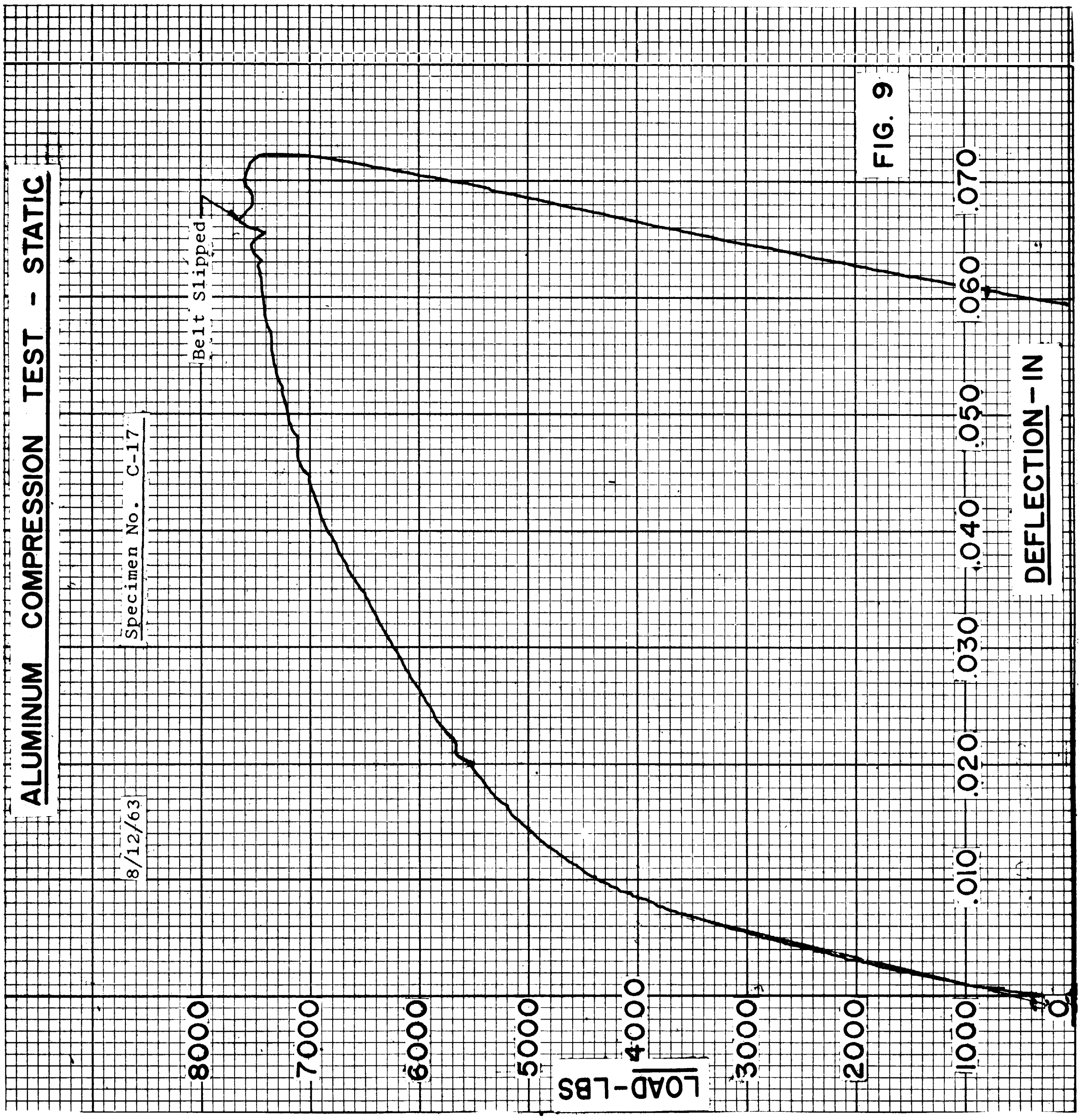
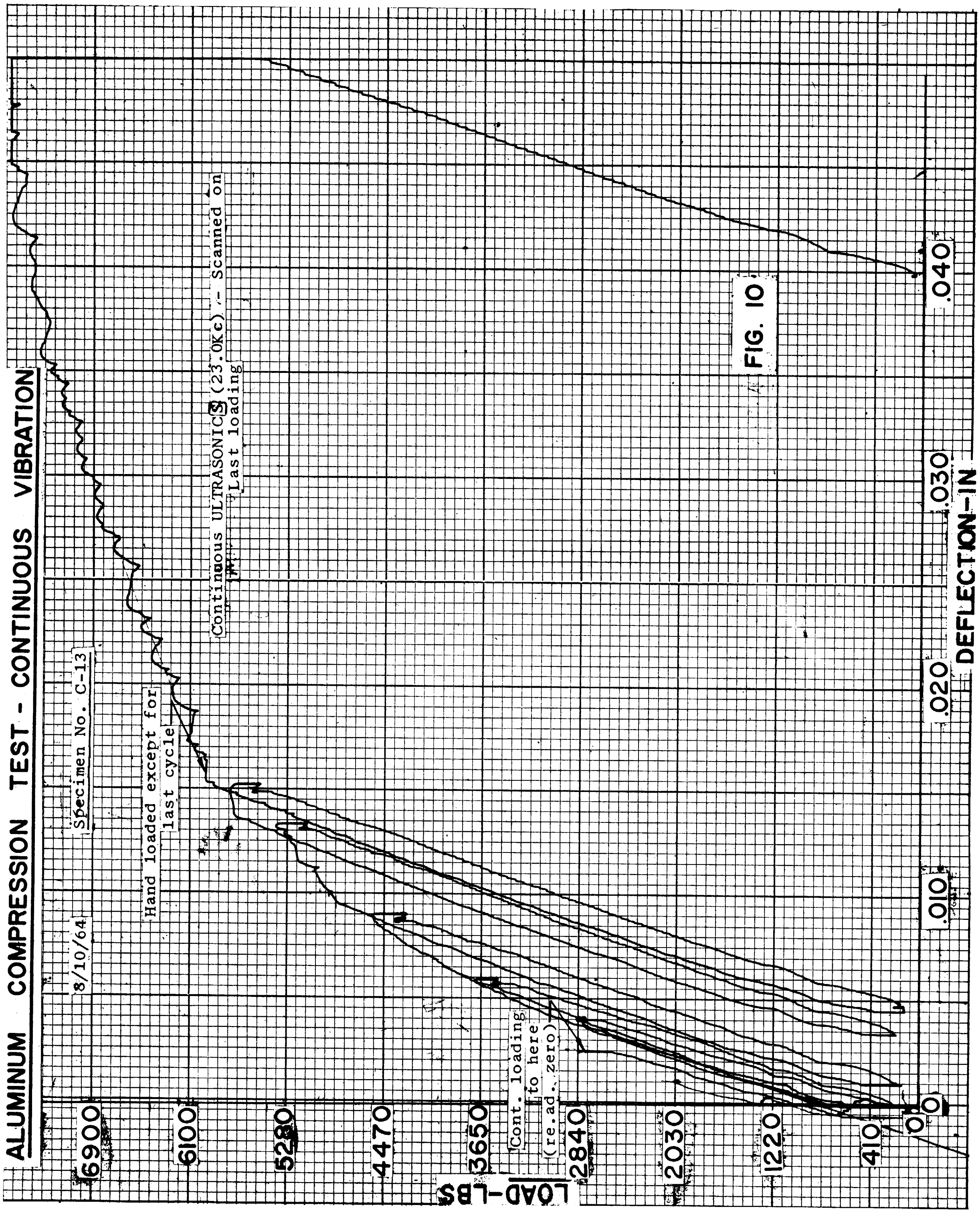
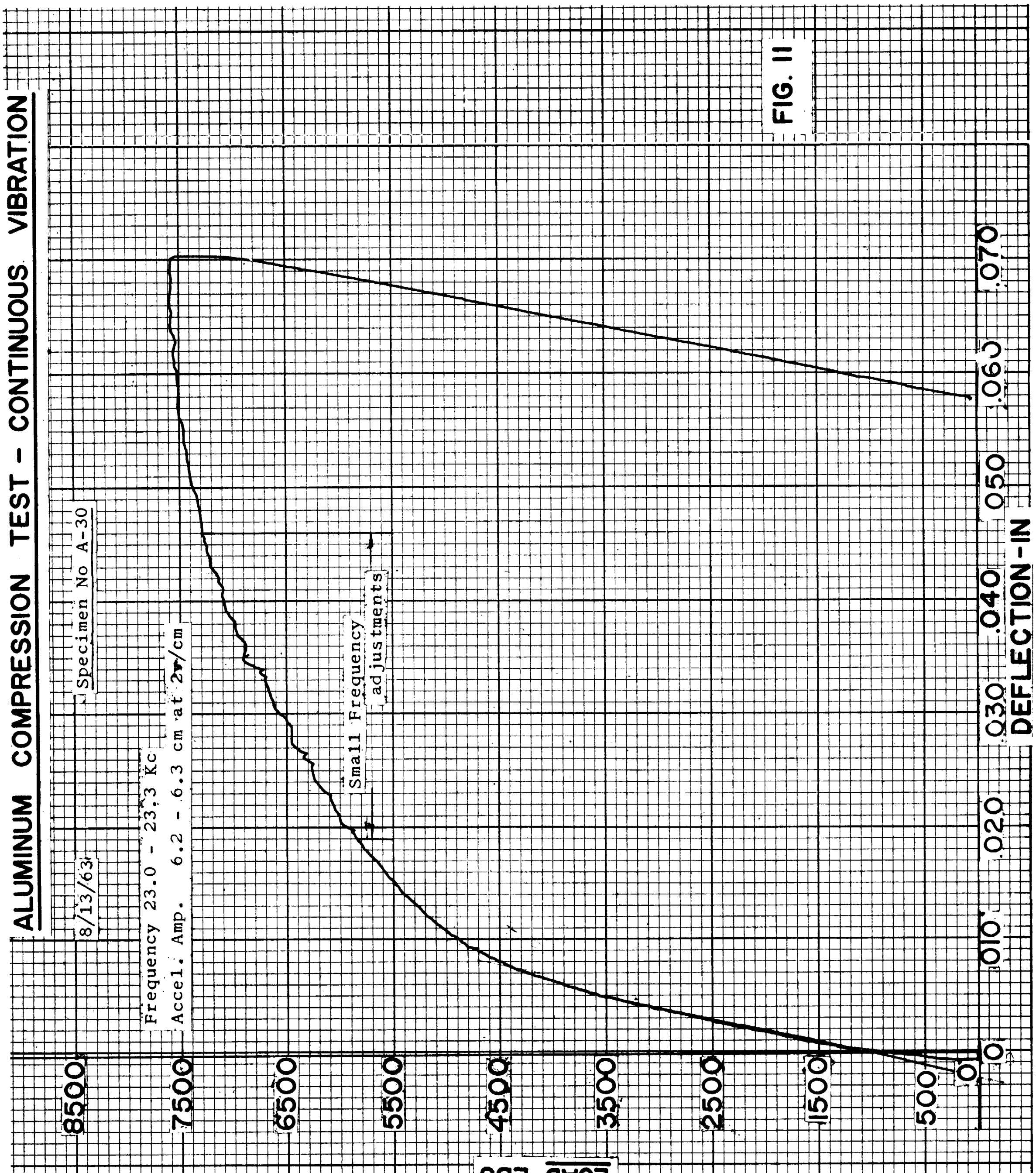
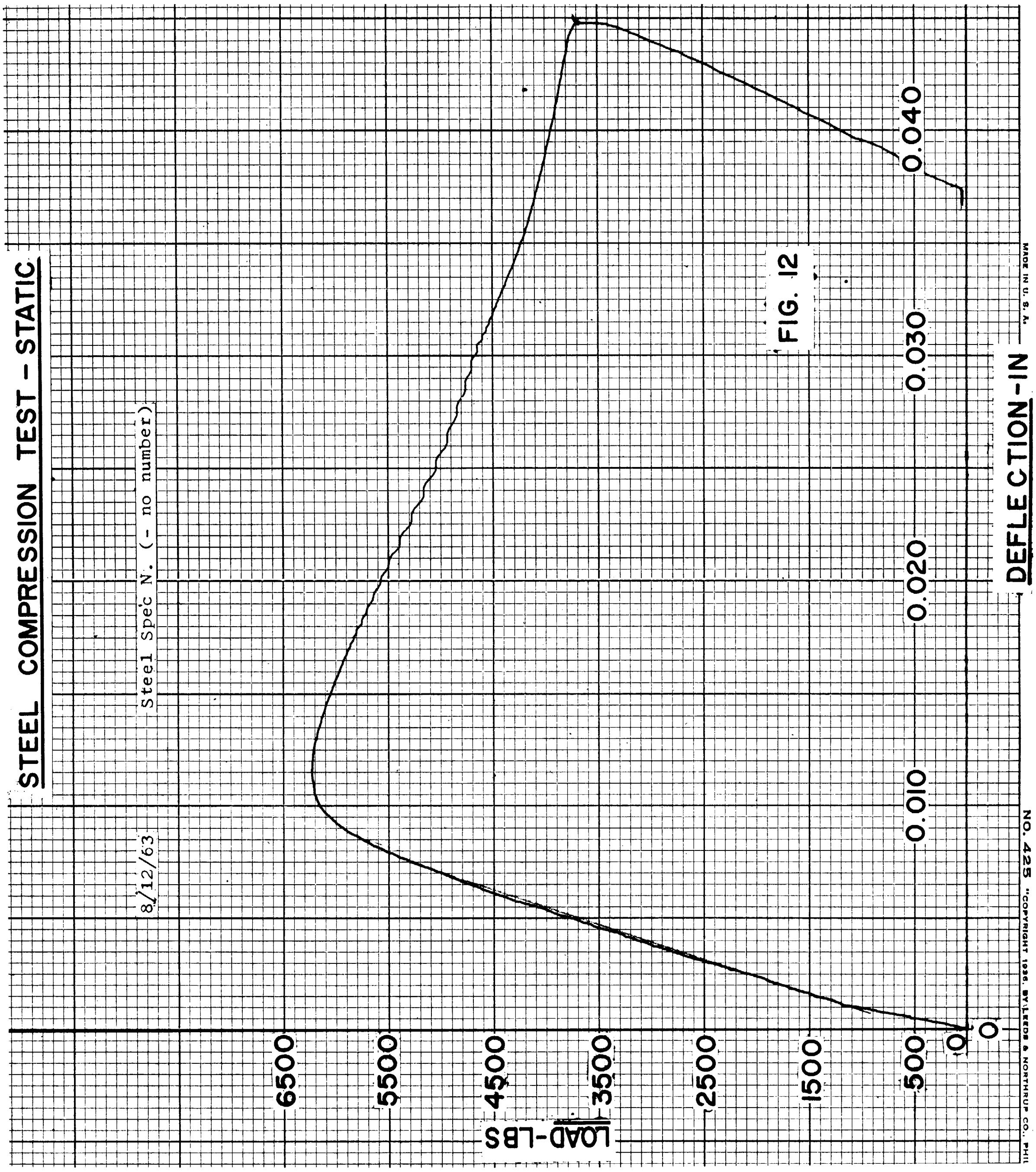

ALUMINUM CUBE - FIXED END
Threded 1/10" Cube in Compression-Aluminum
Part #100
8/29/63
20Kc at 1.8 cm at 2v/cm
25Kc at 3.5 cm at 2v/cm
Accelerometer Clamps loosened during test
DEFLECTION - IN
0
.010
.020
.030
.040
LOAD - LBS
250
500
750
1000
1250
1500
25
20
25
20
25
20
25

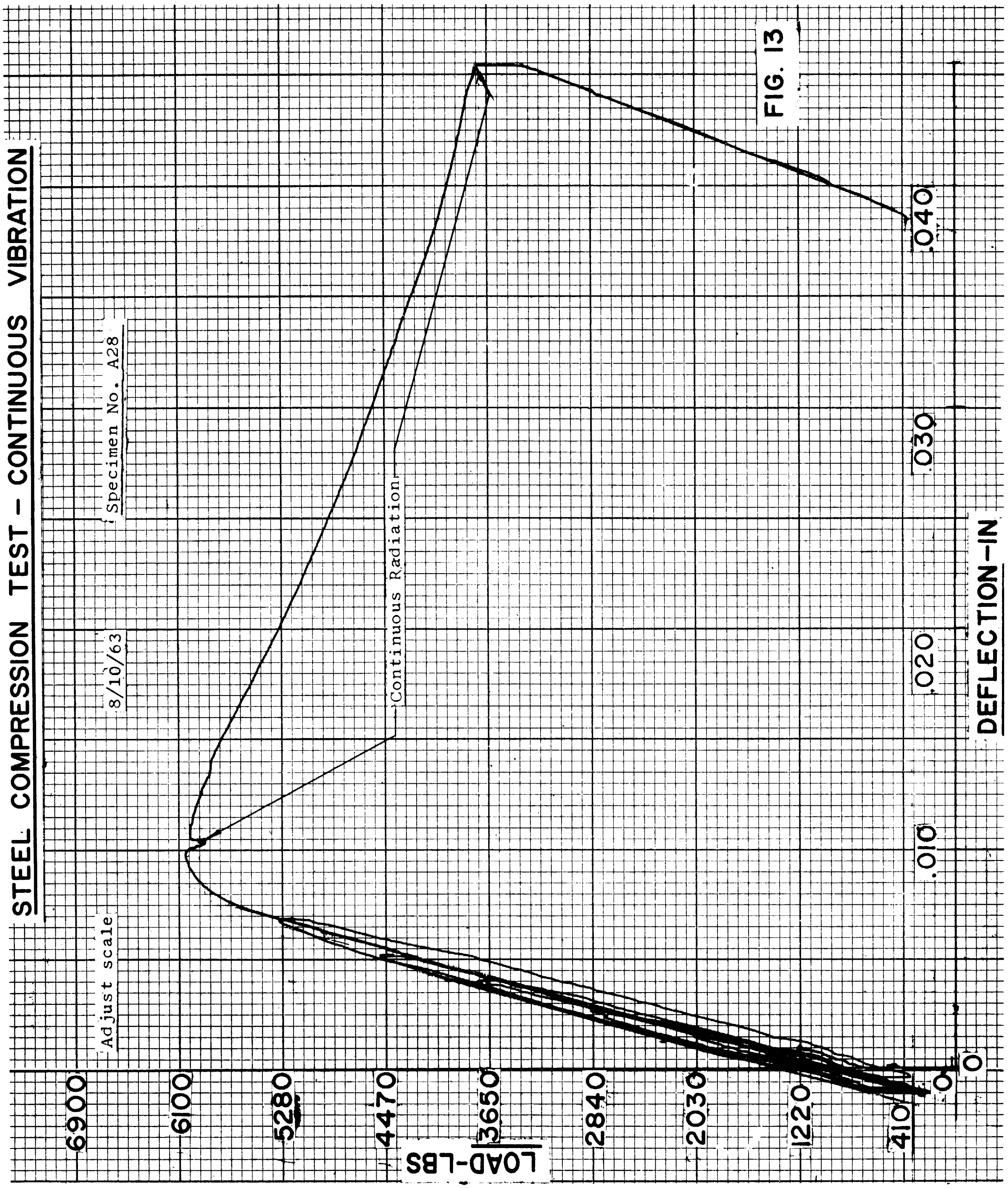
FIG. 8


ALUMINUM COMPRESSION TEST - STATIC
Specimen No. C-17
8/12/63
Belt Slipped
FIG. 9
DEFLECTION-IN
.010
.020
.030
.040
.050
.060
.070
LOAD-LBS
0
1000
2000
3000
4000
5000
6000
7000
8000


ALUMINUM COMPRESSION TEST - CONTINUOUS VIBRATION
8/10/64
Specimen No. C-13
Hand loaded except for last cycle
Continuous ULTRASONICS (23.0Kc) - Scanned on Last loading
Cont. loading to here (re.ad. zero)
6900
6100
5280
4470
3650
2840
2030
1220
410
0
LOAD-LBS
0
.010
.020
.030
.040
DEFLECTION-IN
FIG. 10


ALUMINUM COMPRESSION TEST - CONTINUOUS VIBRATION
FIG. 11
8/13/63
Specimen No A-30
Frequency 23.0 - 23.3 Kc
Accel. Amp. 6.2 - 6.3 cm at 2g/cm
Small Frequency adjustments
LOAD-LBS
8500
7500
6500
5500
4500
3500
2500
1500
500
0
DEFLECTION-IN
0
.010
.020
.030
.040
.050
.060
.070


STEEL COMPRESSION TEST - STATIC
Steel Spec N. (- no number)
8/12/63
FIG. 12
LOAD-LBS
6500
5500
4500
3500
2500
1500
500
0
DEFLECTION-IN
0
0.010
0.020
0.030
0.040
NO. 425 "COPYRIGHT 1936, BY LEEDS & NORTHRUP CO., PHIL
MADE IN U.S.A.


STEEL COMPRESSION TEST - CONTINUOUS VIBRATION
Specimen No. A28
8/10/63
Adjust scale
Continuous Radiation
LOAD-LBS
6900
6100
5280
4470
3650
2840
2030
1220
410
0
DEFLECTION-IN
.010
.020
.030
.040
FIG. 13

STEEL COMPRESSION TEST—CONTINUOUS VIBRATION

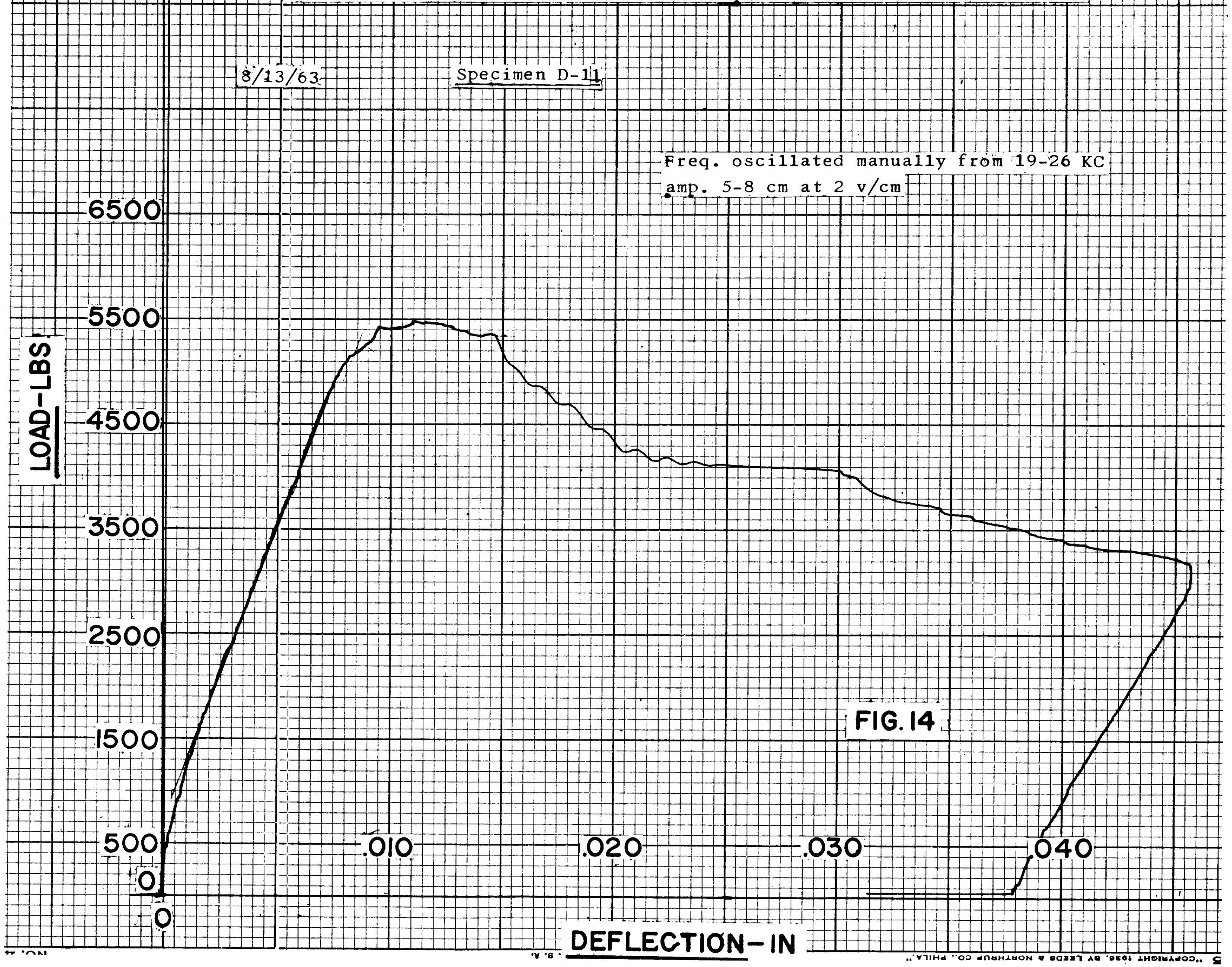
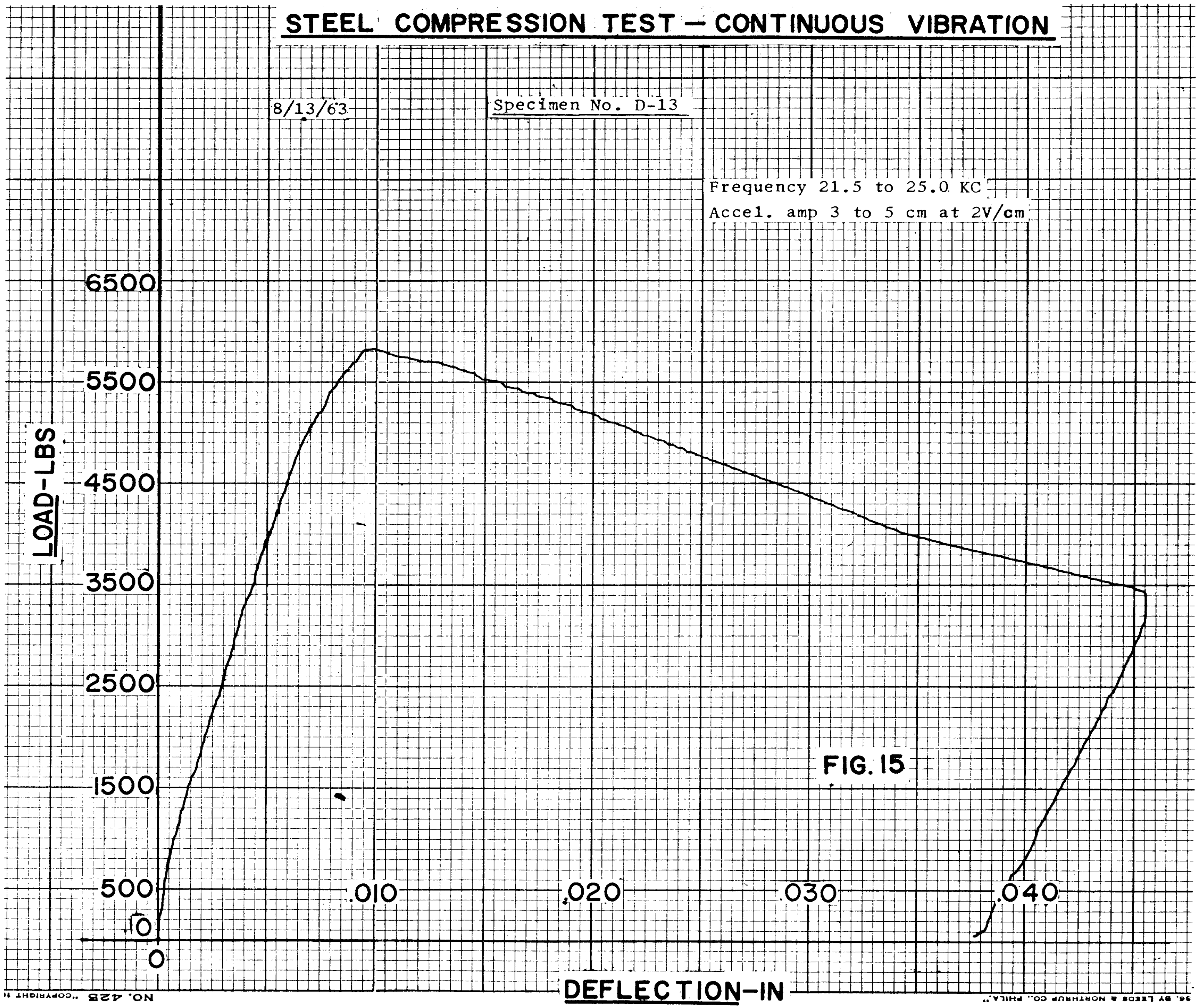
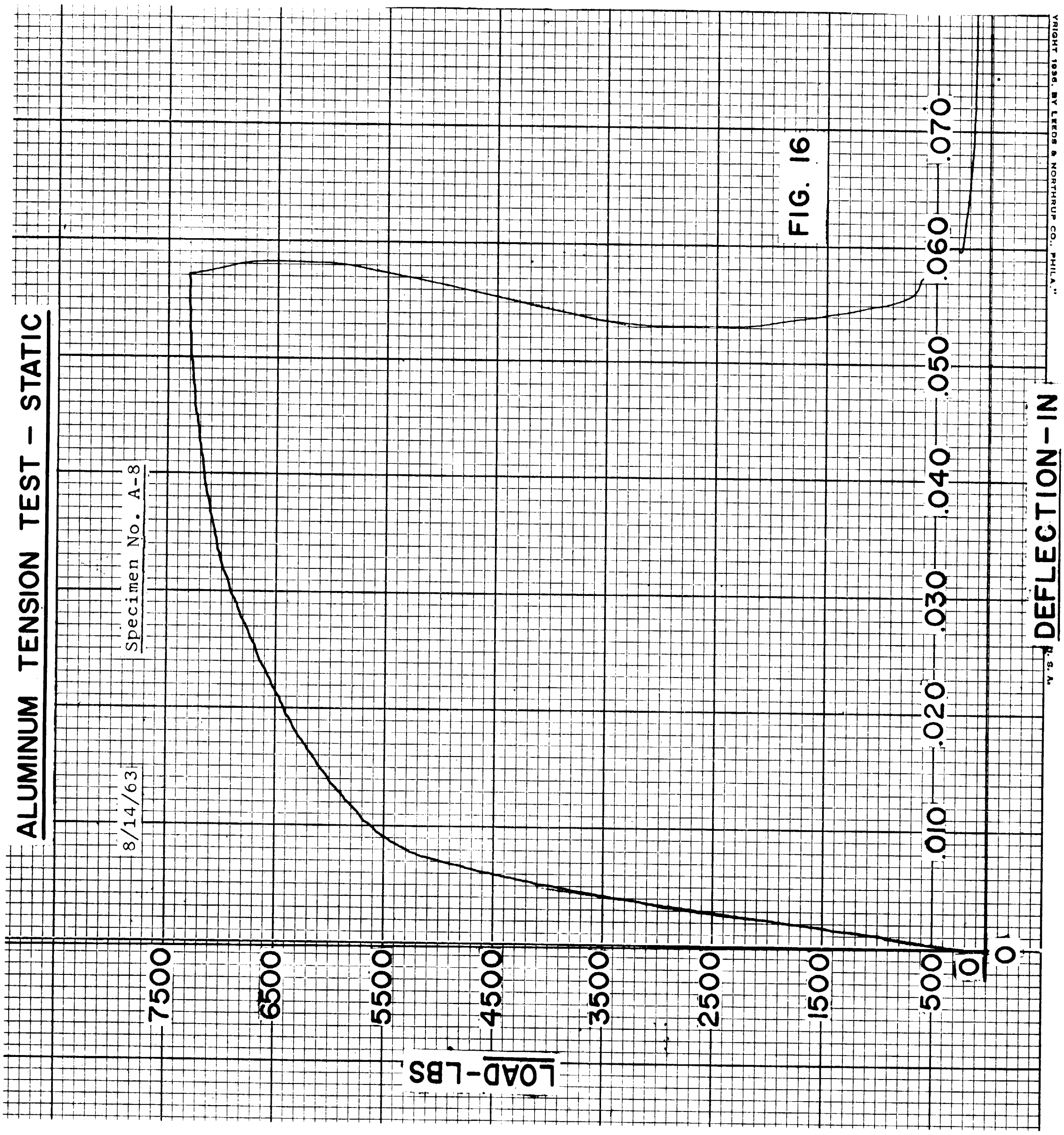
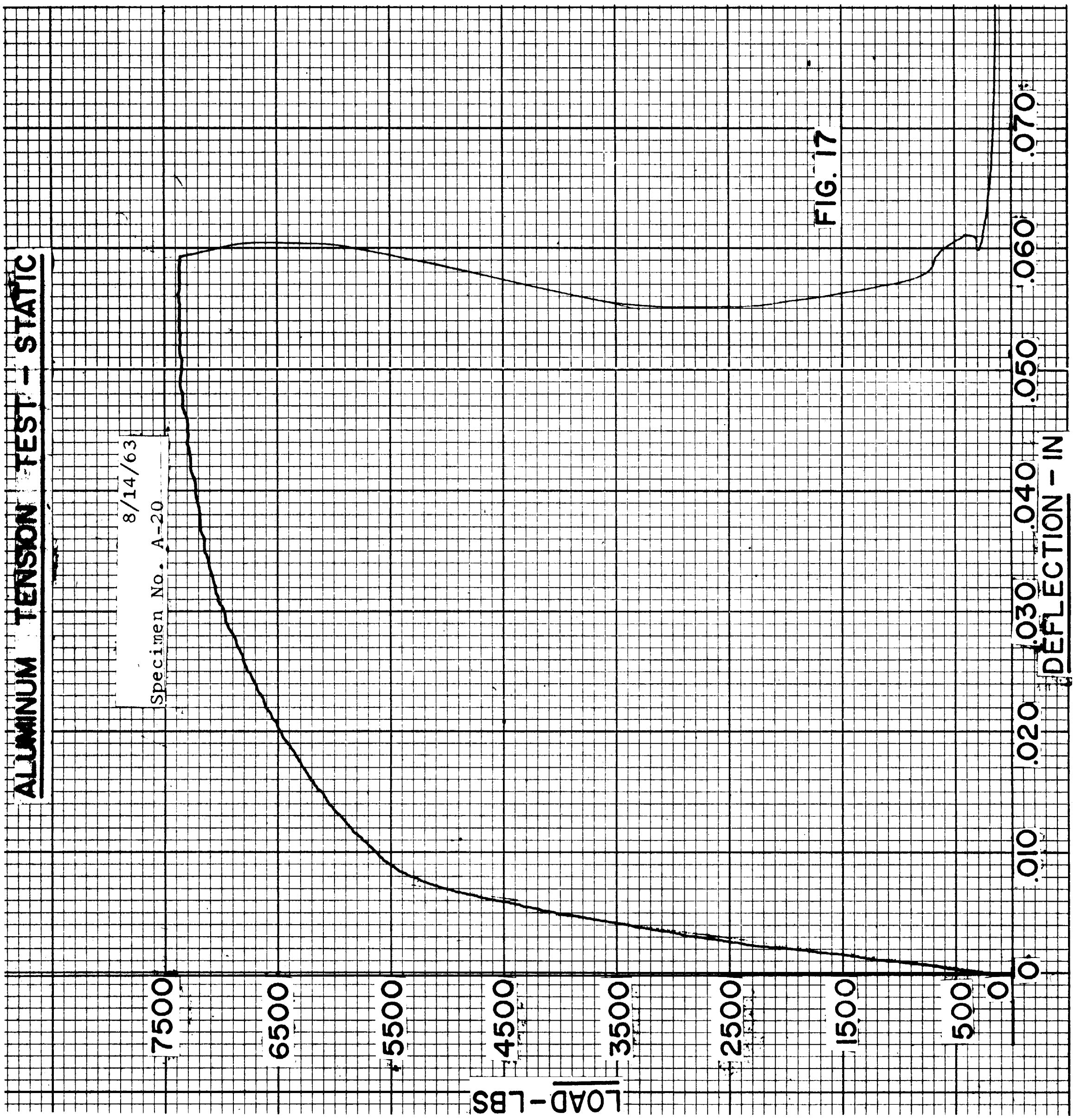
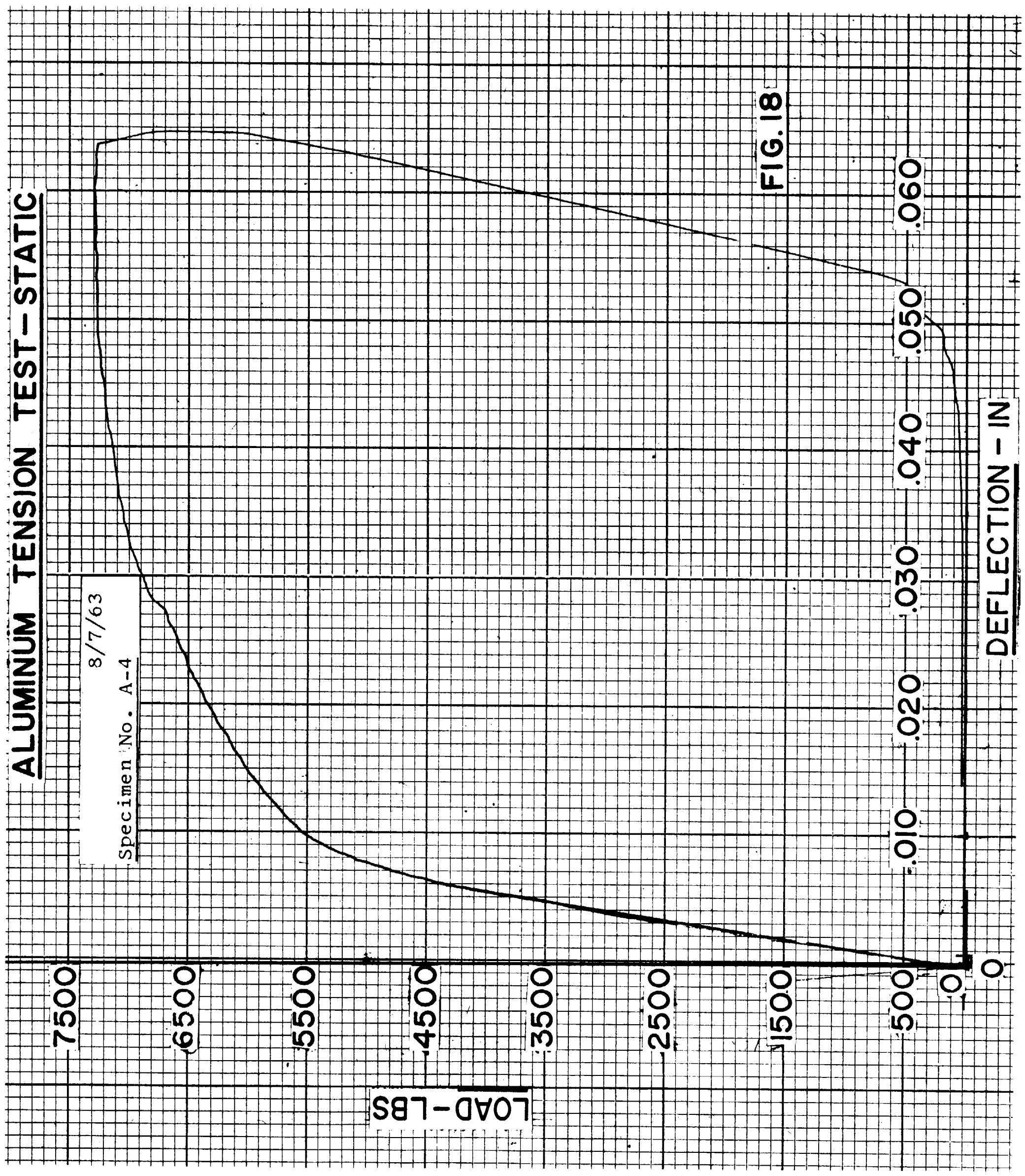


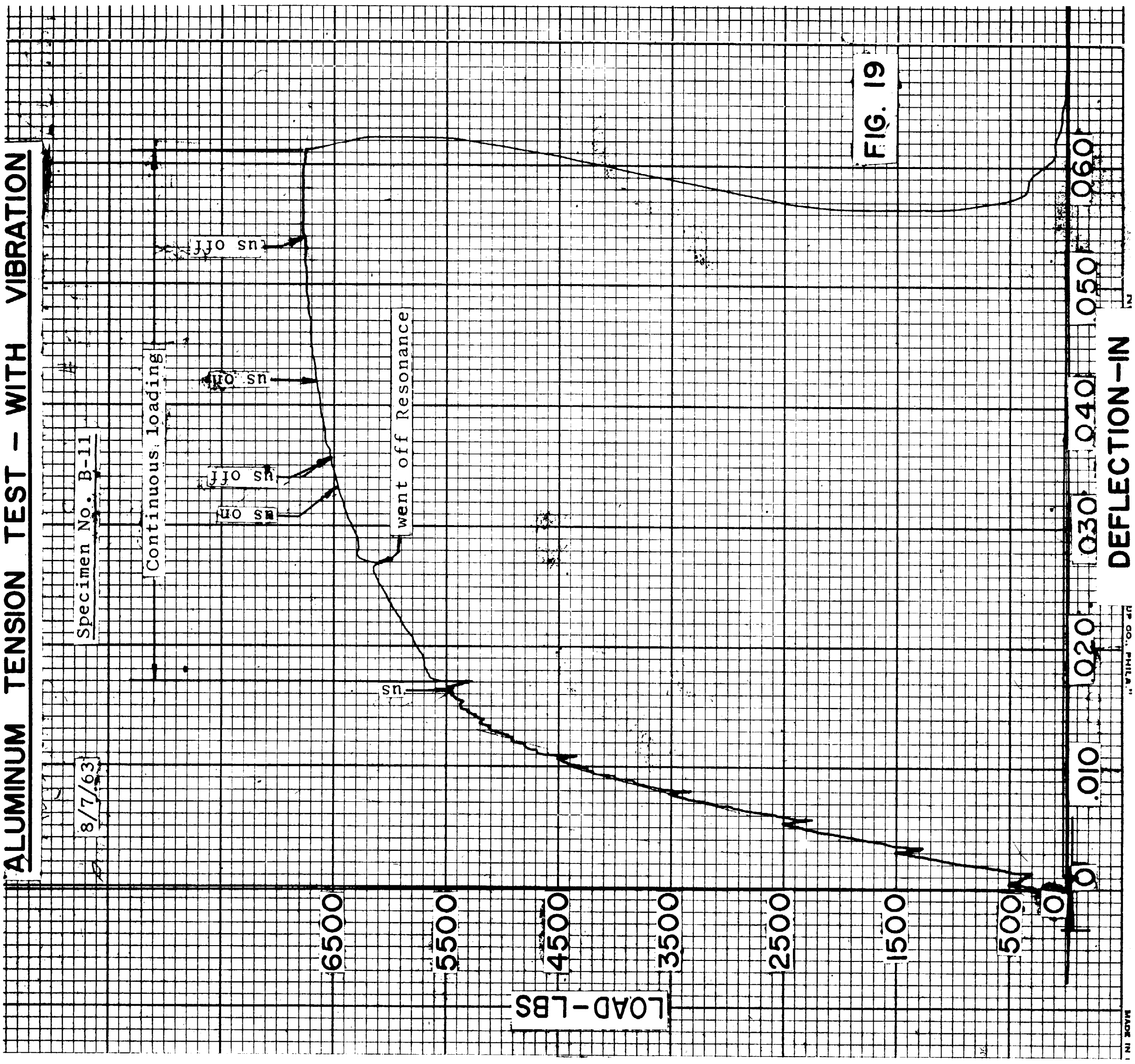
FIG. 14

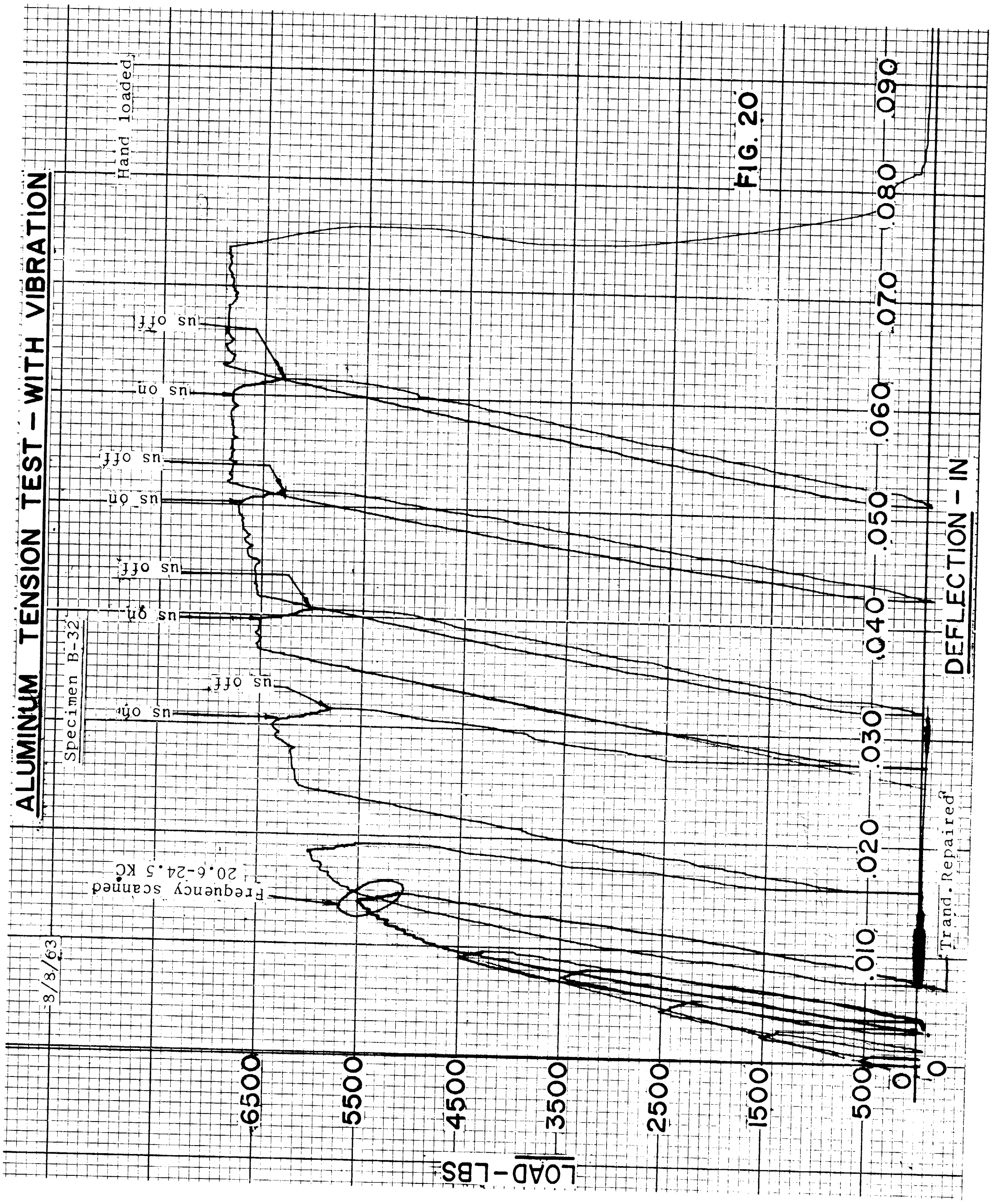

STEEL COMPRESSION TEST — CONTINUOUS VIBRATION
8/13/63
Specimen No. D-13
Frequency 21.5 to 25.0 KC
Accel. amp 3 to 5 cm at 2V/cm
LOAD-LBS
6500
5500
4500
3500
2500
1500
500
10
0
.010
.020
.030
.040
DEFLECTION-IN
NO. 428 "COPYRIGHT 1
"S, BY LEEDS & NORTHRUP CO., PHILA."
FIG. 15


ALUMINUM TENSION TEST - STATIC
Specimen No. A-8
8/14/63
FIG. 16
LOAD-LBS
7500
6500
5500
4500
3500
2500
1500
500
0
DEFLECTION-IN
.010
.020
.030
.040
.050
.060
.070
0


ALUMINUM TENSION TEST - STATIC
8/14/63
Specimen No. A-20
FIG. 17
LOAD-LBS
7500
6500
5500
4500
3500
2500
1500
500
0
DEFLECTION - IN
0
.010
.020
.030
.040
.050
.060
.070


ALUMINUM TENSION TEST-STATIC
8/7/63
Specimen No. A-4
FIG. 18
LOAD-LBS
7500
6500
5500
4500
3500
2500
1500
500
0
DEFLECTION - IN
0
.010
.020
.030
.040
.050
.060


ALUMINUM TENSION TEST - WITH VIBRATION
Specimen No. B-11
8/7/63
Continuous loading
us off
us on
us off
us on
went off Resonance
us
6500
5500
4500
3500
2500
1500
500
0
LOAD-LBS
0
.010
.020
.030
.040
.050
.060
DEFLECTION-IN
FIG. 19


ALUMINUM TENSION TEST - WITH VIBRATION
Specimen B-32
8/8/63
Hand loaded
FIG. 20
us on
us off
Frequency scanned 20.6-24.5 KC
Trand. Repaired
LOAD-LBS
6500
5500
4500
3500
2500
1500
500
0
DEFLECTION - IN
.010
.020
.030
.040
.050
.060
.070
.080
.090

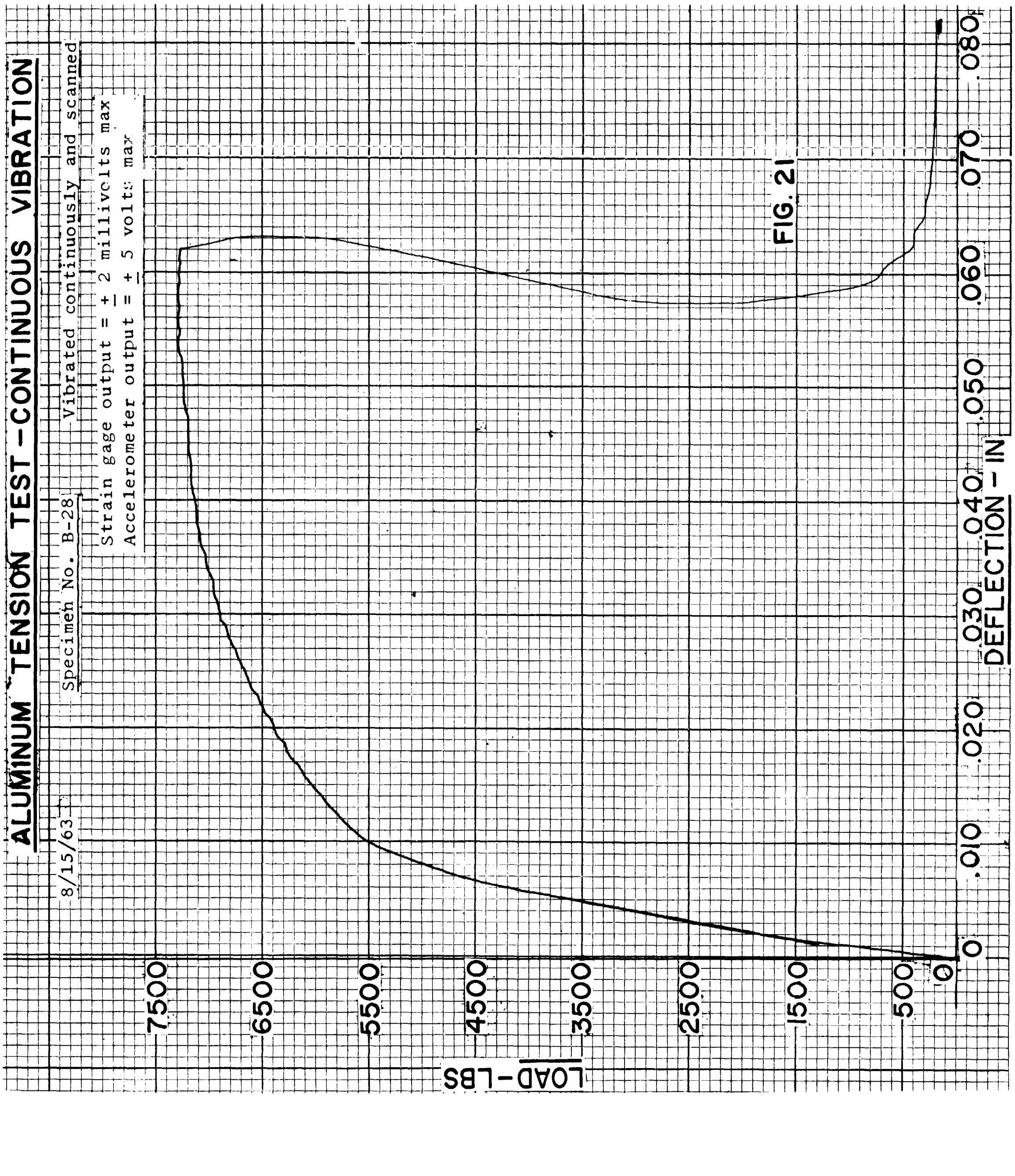
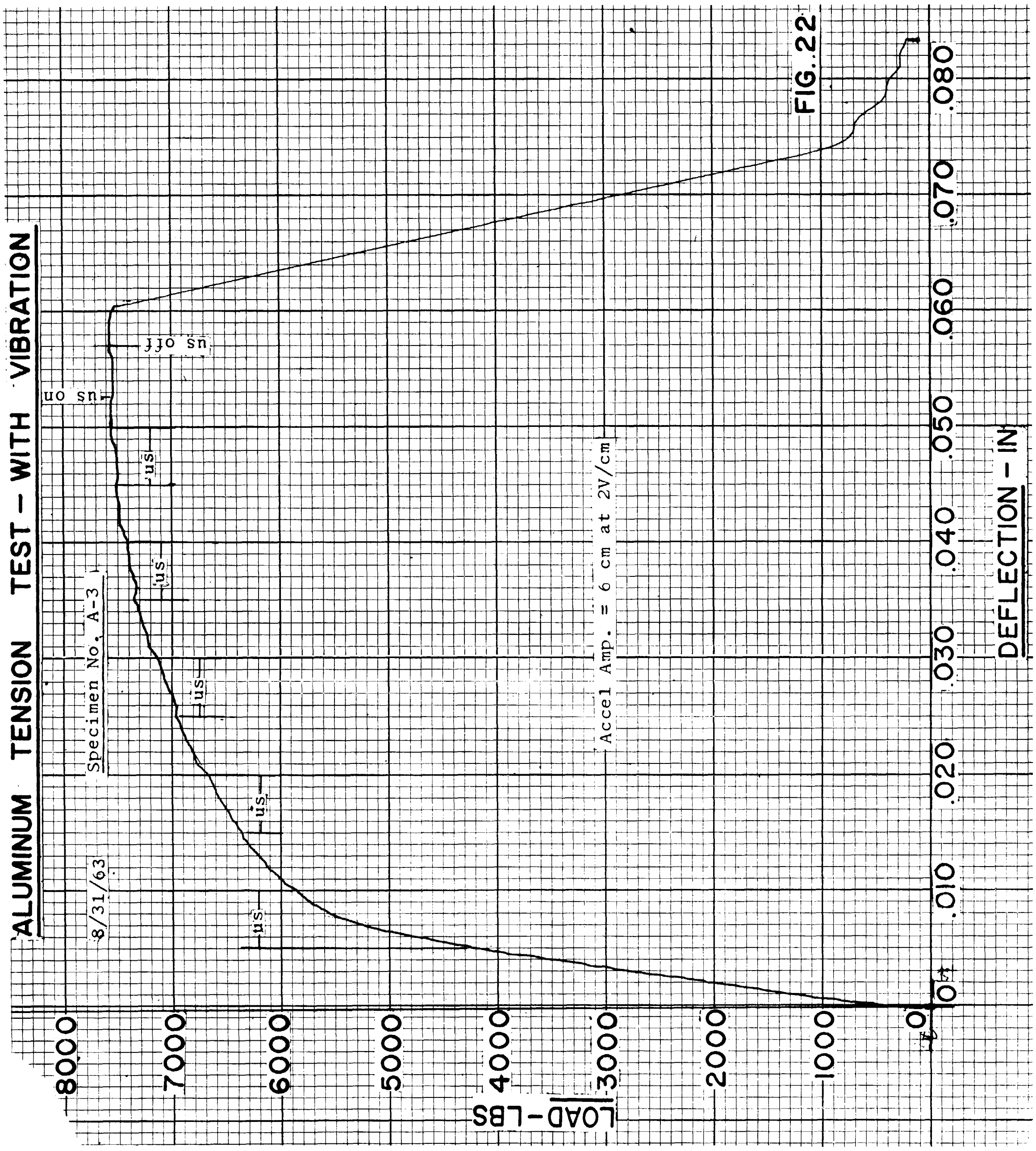
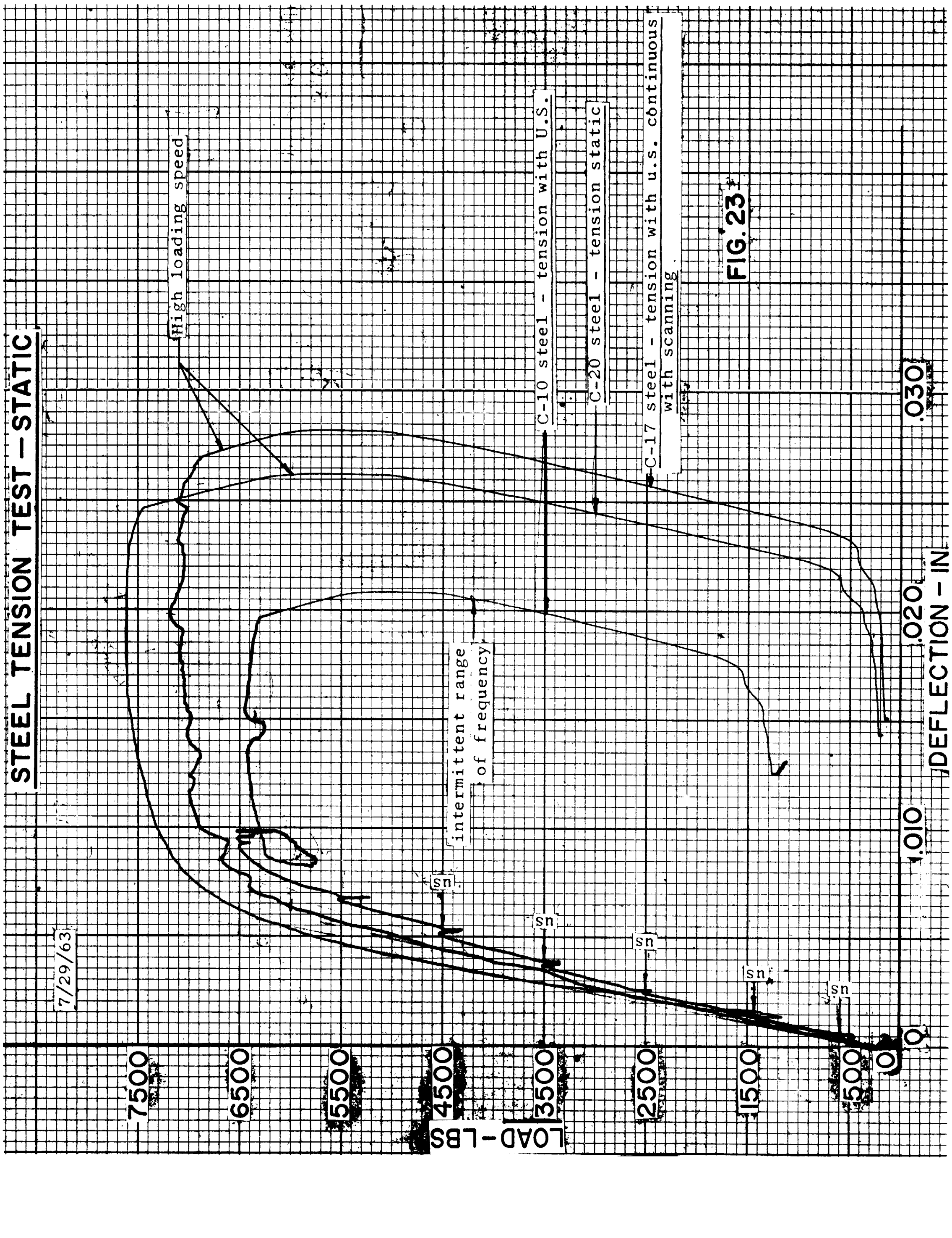
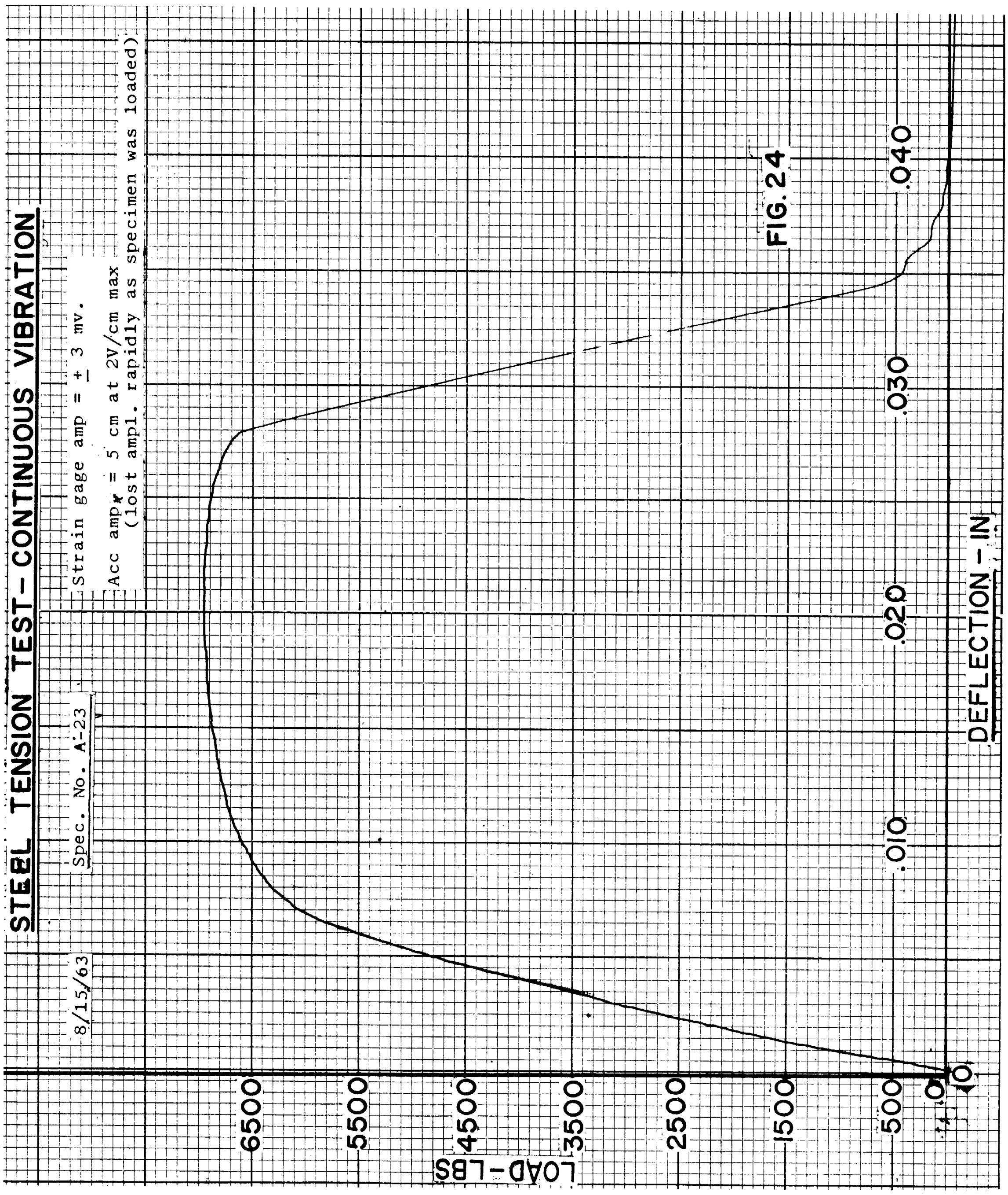

ALUMINUM TENSION TEST - CONTINUOUS VIBRATION
8/15/63
Specimen No. B-28
Vibrated continuously and scanned
Strain gage output = ± 2 millivolts max
Accelerometer output = ± 5 volts max
LOAD-LBS
7500
6500
5500
4500
3500
2500
1500
500
0
DEFLECTION - IN
0
.010
.020
.030
.040
.050
.060
.070
.080

FIG. 21


ALUMINUM TENSION TEST - WITH VIBRATION
FIG. 22
8/31/63
Specimen No. A-3
Accel Amp. = 6 cm at 2V/cm
us
us
us
us
us
us on
us off
LOAD-LBS
8000
7000
6000
5000
4000
3000
2000
1000
0
DEFLECTION - IN
0
.010
.020
.030
.040
.050
.060
.070
.080



STEEL TENSION TEST — STATIC
7/29/63
High loading speed
C-10 steel - tension with U.S.
C-20 steel - tension static
C-17 steel - tension with u.s. continuous with scanning
intermittent range of frequency
sn
FIG. 23
LOAD-LBS
7500
6500
5500
4500
3500
2500
1500
500
0
DEFLECTION - IN.
.010
.020
.030


STEEL TENSION TEST - CONTINUOUS VIBRATION
8/15/63
Spec. No. A-23
Strain gage amp = ± 3 mv.
Acc amp = 5 cm at 2V/cm max
(lost ampl. rapidly as specimen was loaded)
FIG. 24
LOAD-LBS
6500
5500
4500
3500
2500
1500
500
0
DEFLECTION - IN
0
.010
.020
.030
.040

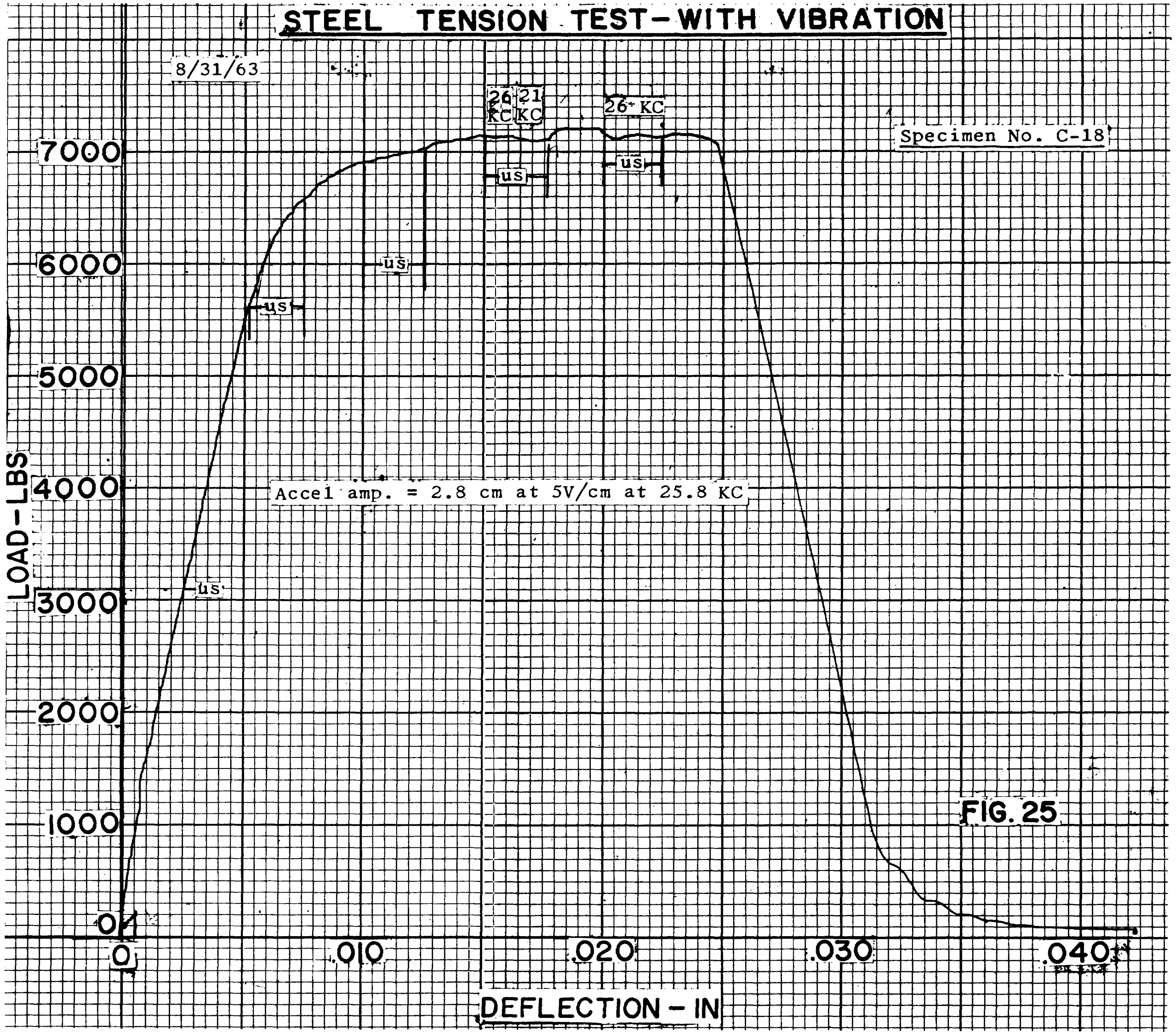

STEEL TENSION TEST-WITH VIBRATION
8/31/63
26 KC
21 KC
26+ KC
Specimen No. C-18
us
us
us
us
us
Accel amp. = 2.8 cm at 5V/cm at 25.8 KC
LOAD-LBS
7000
6000
5000
4000
3000
2000
1000
0
0
.010
.020
.030
.040
DEFLECTION - IN

FIG. 25

APPENDIX A

TEST APPARATUS AND CALIBRATION

TEST APPARATUS

The most important elements of the test apparatus are illustrated in Figs. A-1, A-2, and A-3. Figure A-1 gives a general view showing the testing machine with the specimen, transducer, and the ball-bearing guide post die set in which the test specimen and deflection system are mounted. The ultrasonic generator and associated oscillator are shown at the left along with the oscilloscope which was used both to indicate vibration amplitude through the output of accelerometers as well as the output of strain gages mounted directly on the test section and the voltage output of the ultrasonic generator.

At the right is shown the four-channel amplifier recorder which was used to produce the load deflection information in electrical form for recording on the x-y plotter shown at the extreme right.

Figures A-2 and A-3 give close-ups of the specimen area and in the latter case of the specimen itself with the quartz crystal accelerometers clamped in place as during typical test both with tubular specimens and with the aluminum tube specimens between the hardened die blocks.

Details of the electrical circuitry are figen in Figures A-4 through A-8.

CALIBRATION

Calibration of the load-indicating circuit was achieved directly through the application of dead-weight loading on the loading arm of the testing machine as shown in Fig. A-1. This procedure was used for both load cells of which two were required, one for tension and the other for compression.

Several different approaches were used at various times during the study for the purpose of indicating strain or elongation. The final set-up for this purpose consisted of three differential transformers mounted so as to indicate the displacement between the upper and lower holders of the die set. Details of the circuitry have been illustrated previously. Calibration was achieved through the use of gage blocks between the upper and lower holders of the die set.

Monitoring of the vibratory strain particularly in the test sections was exceedingly difficult. It was impractical to rely solely upon strain gages for the purpose since the gage is destroyed either before or shortly after the yield point and the more significant effects vibration were observed primarily as post-yield phenomenon.

Both strain gages and accelerometers were used, however, to monitor the vibration at various stages during Phase I. The latter states and in particular those during which most of the data presented in this report were obtained was monitored with accelerometers. It was noted in general that the maximum vibratory stress as indicated by strain gages always occurred in the vicinity of that frequency which produced the greatest output from the accelerometers. However, this was not always true as indicated by the oscilloscope records in Fig. A-9.

The traces at the upper left in Fig. A-9 are typical of the conditions at which maximum stress or strain amplitude was achieved in the test section. This is in contrast to the conditions shown at the lower right where the accelerometer amplitude is maximum but the strain gage amplitude is less than half. The shoulders of the test section reflect considerable energy and because of their location and dimensions could resonate at slightly different frequencies than the test section. This evidently happened.

The strain gages in the test section were calibrated statically with the same procedure used for the load circuit. The gage in the test section was an 120 ohm, foil gage hooked up as one leg of an 120 ohm dc bridge energized with 24.6 v dc. The calibrated outputs for the tubular specimens were:

(Steel) 3380 psi/mv of bridge output; and
(Aluminum) 1235 psi/mv.

Calibration of the accelerometers produced the following results:

$$E = Caf^{2.8} \tag{1}$$

where:

E = accelerometer output amplitude, mv
a = vibration amplitude, in.
f = frequency, cps

The above results were obtained for frequencies from 100 to 400 cps. Extrapolation to ultrasonic frequencies leads to ridiculously low amplitudes. The exponent of 2.0 yields amplitudes in good accord with the stress calibration. Therefore, the accelerometer calibration was set at

$$a = \frac{16}{5} \frac{E}{f^2} \tag{2}$$

Using Eq. (2), the maximum amplitude achieved at the shoulders of the test section would be about 128 uin.

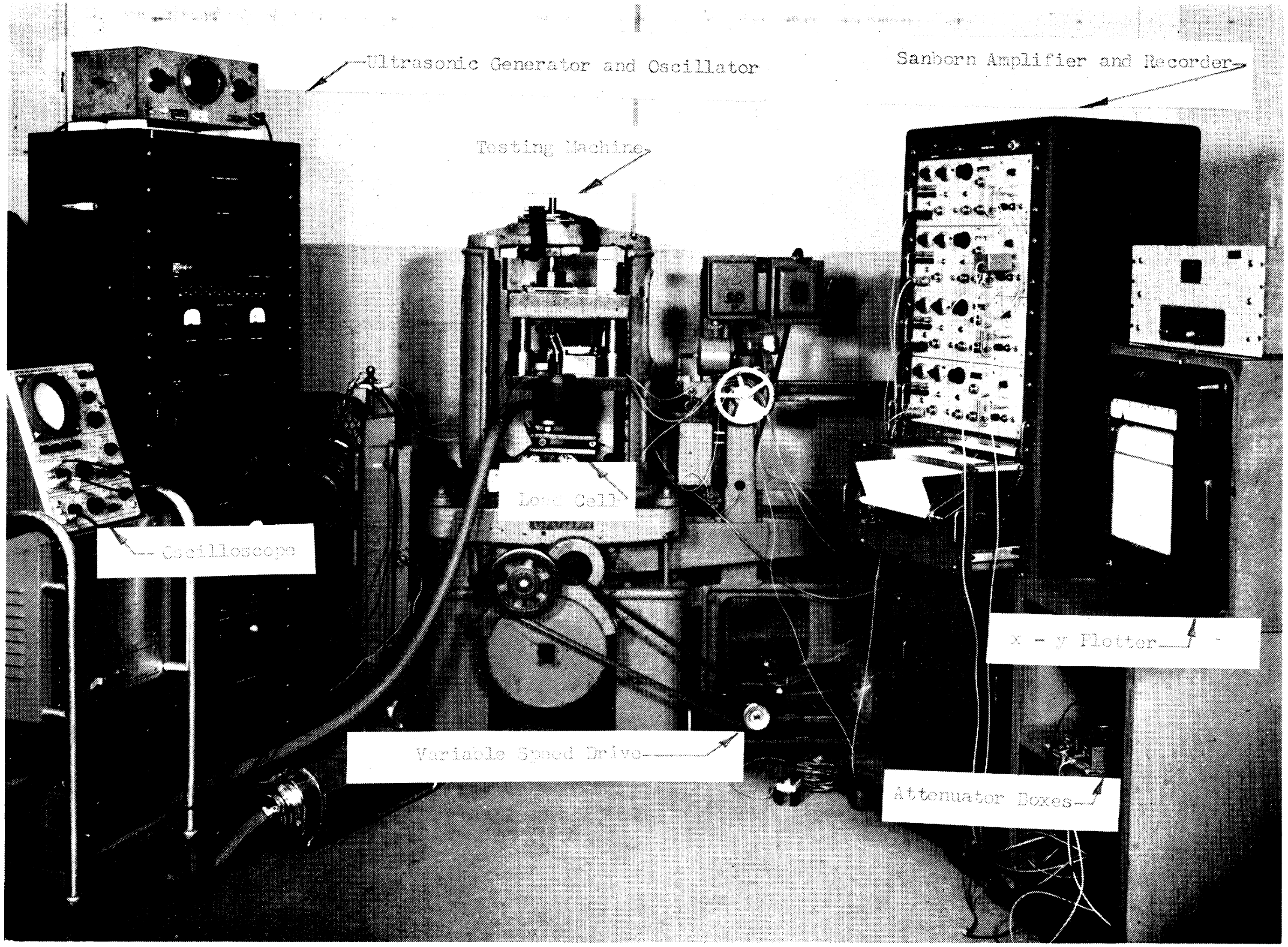


Fig. A-1. General view of test set-up.

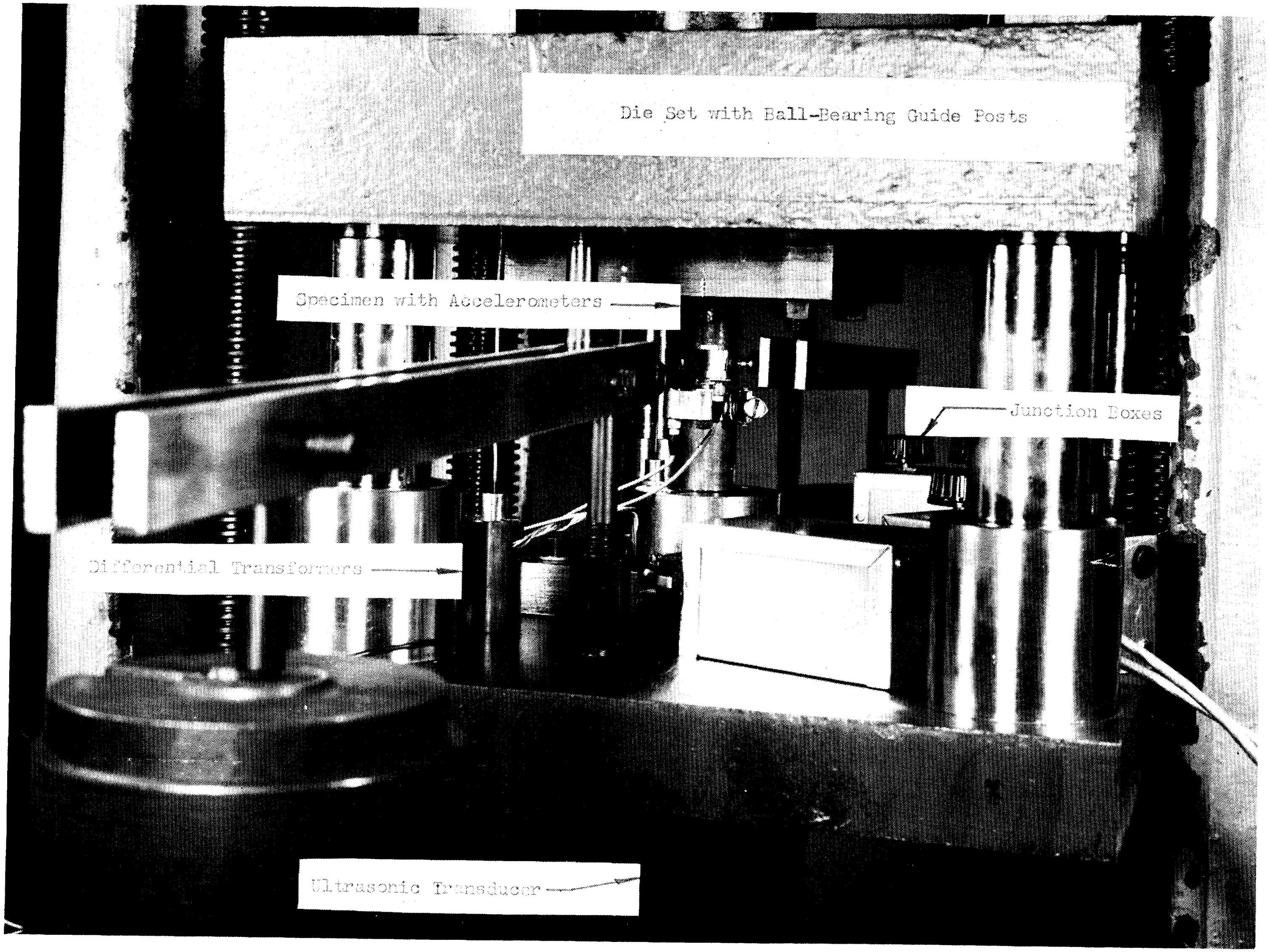


Fig. A-2. Close up of specimen area.

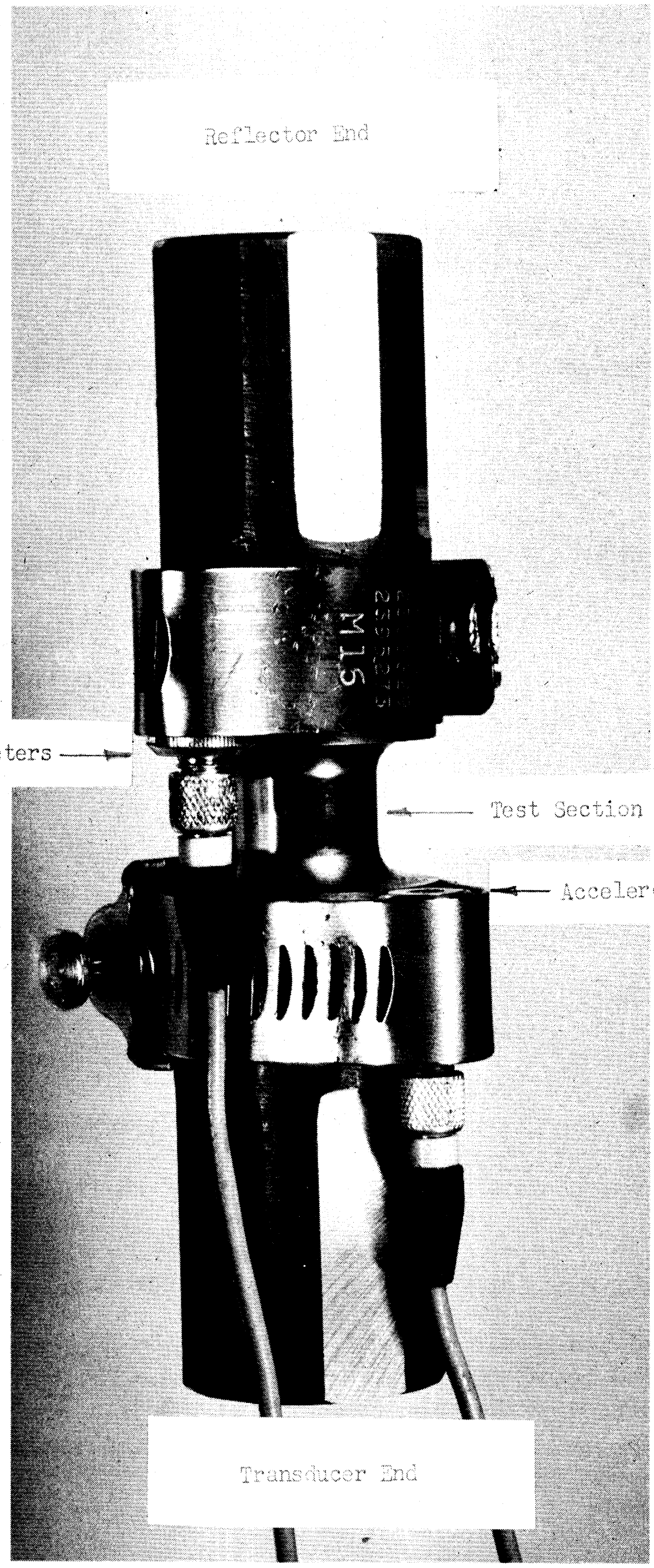


Fig. A-3. Specimen with accelerometers.

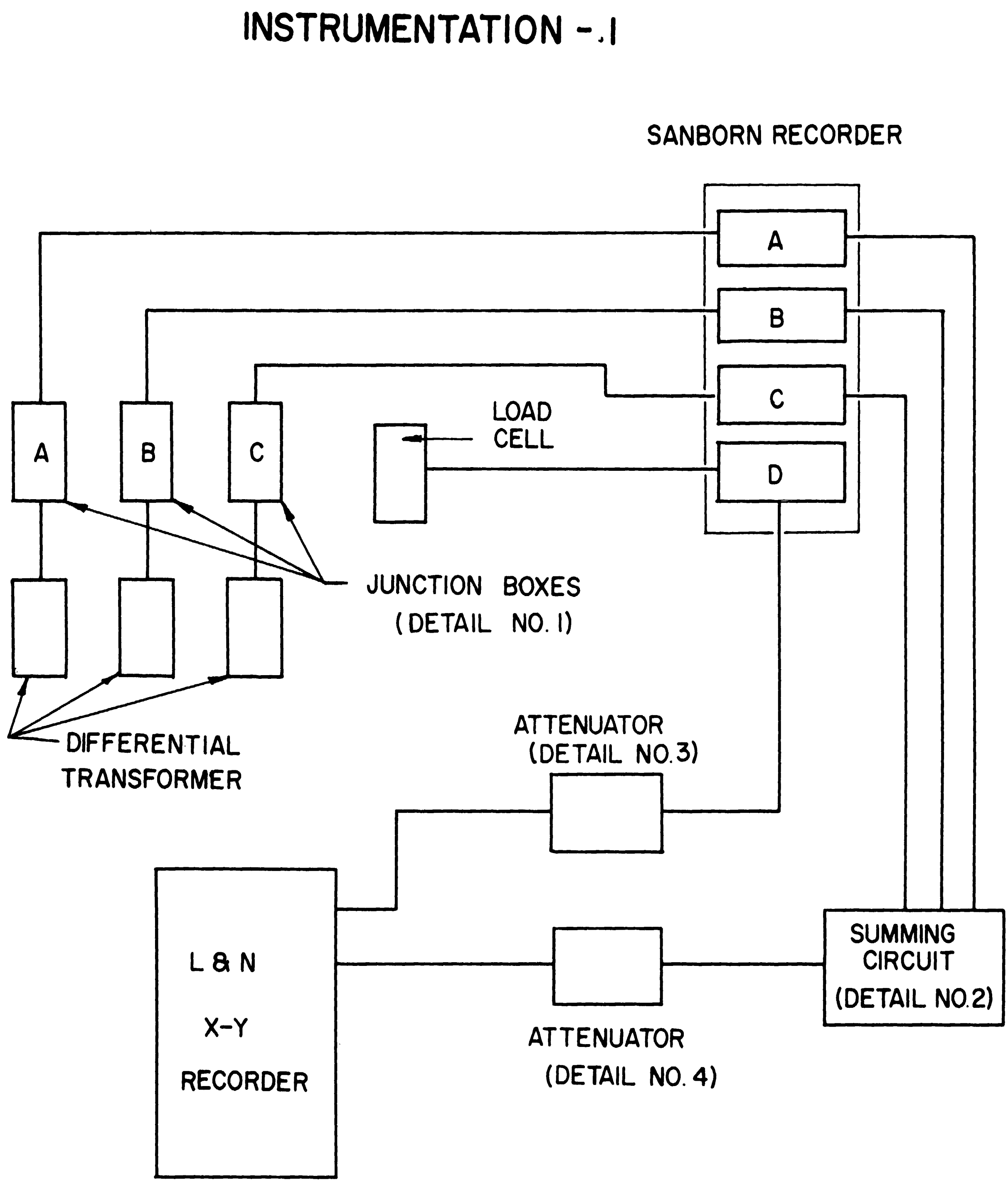


Fig. A-4. Schematic of load deflection circuit.

DETAIL NO. I

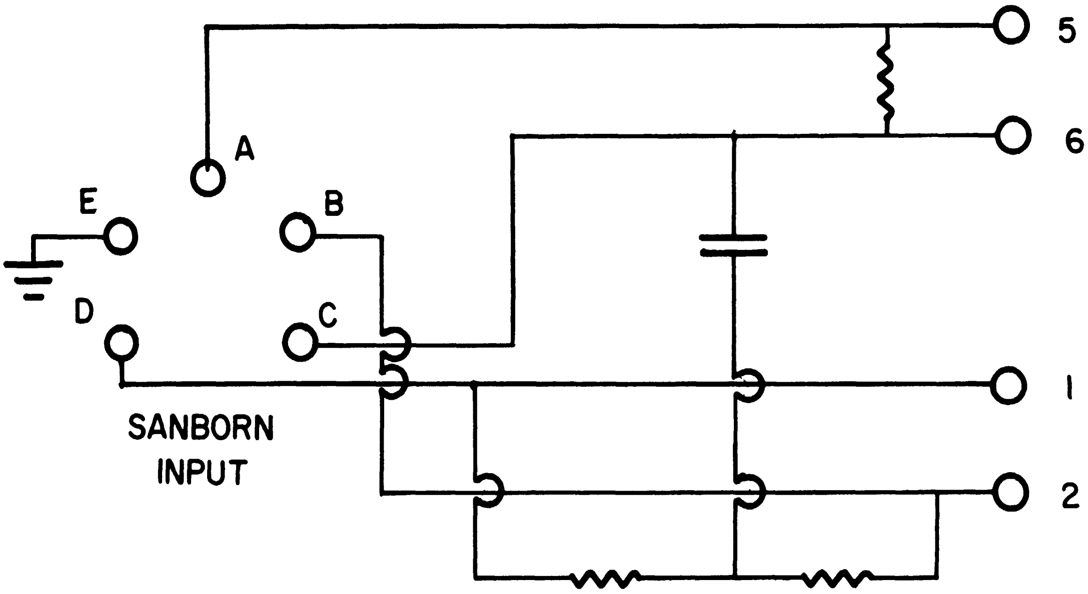


Fig. A-5. Compensation circuit for linear variable differential transformer.

DETAIL NO. 2

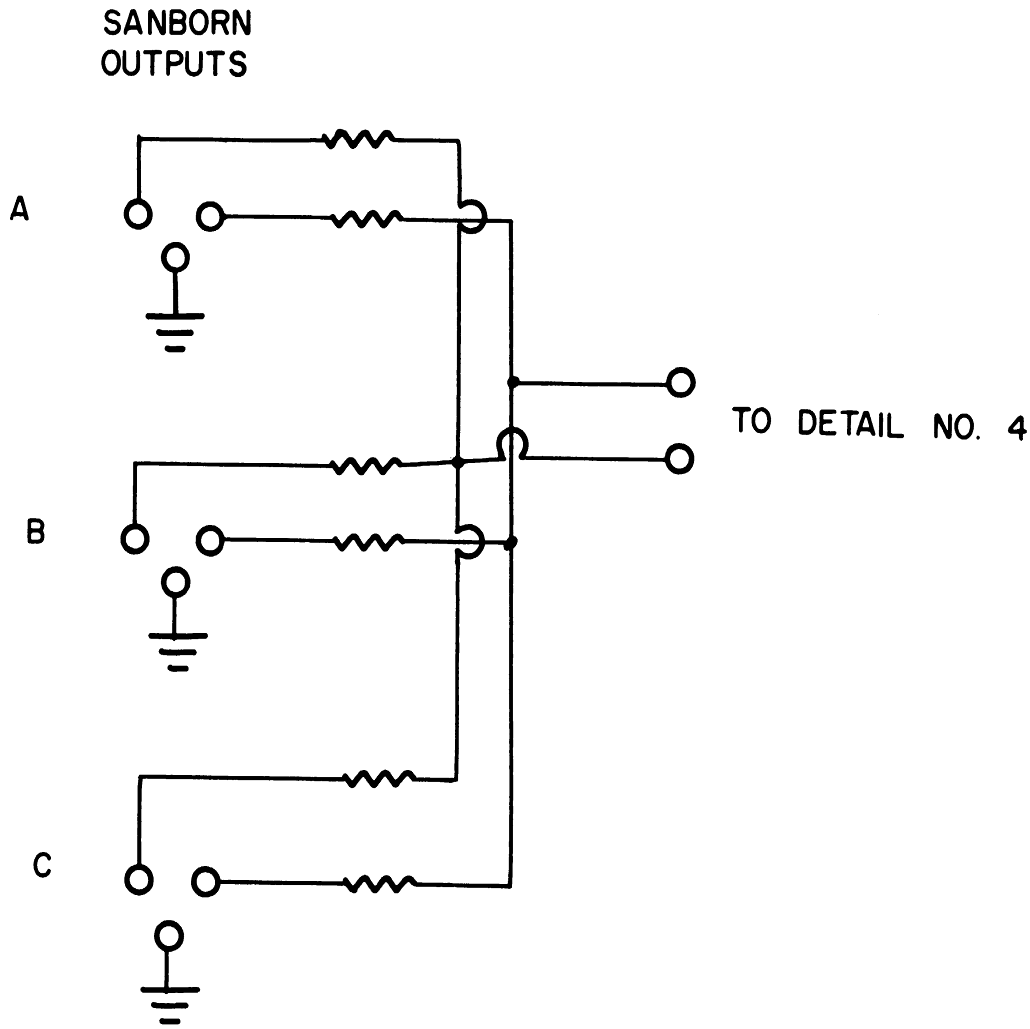
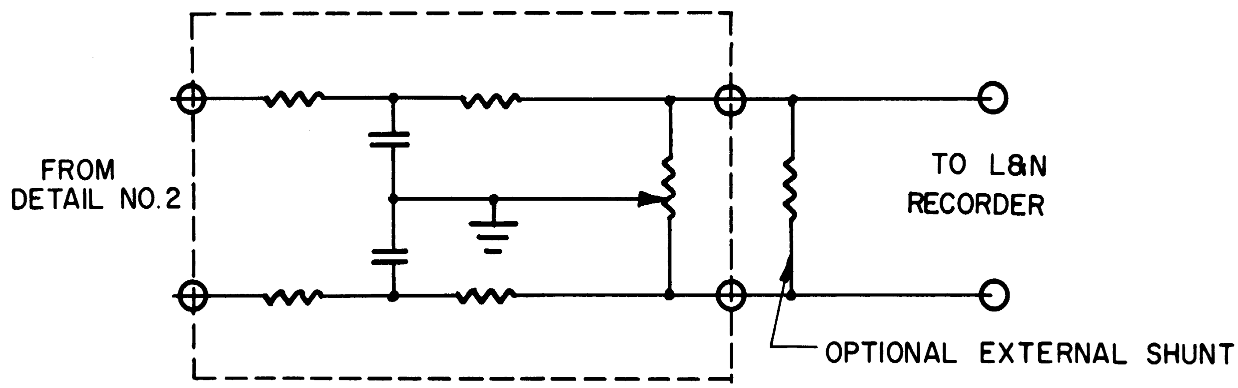


Fig. A-6. Deflection summing circuit.

DETAIL NO. 4 (DEFLECTION AXIS-X)



DETAIL NO. 3 (LOAD AXIS-Y)

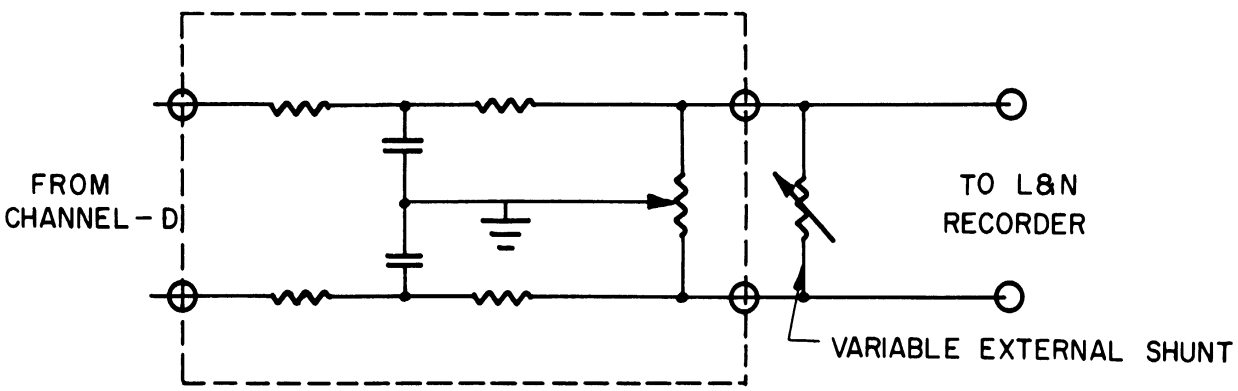


Fig. A-7. Attenuator balance boxes.

INSTRUMENTATION - II

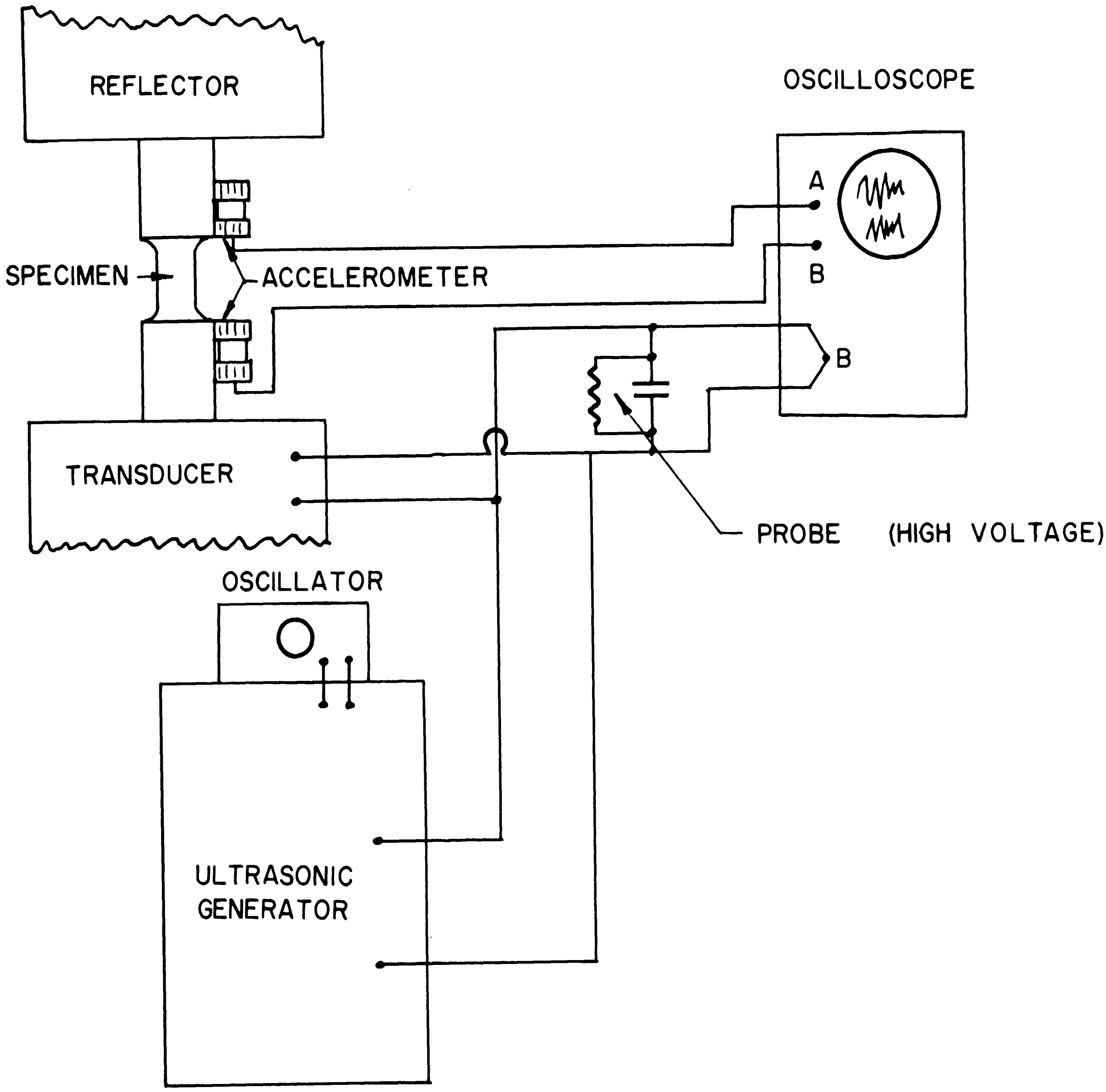
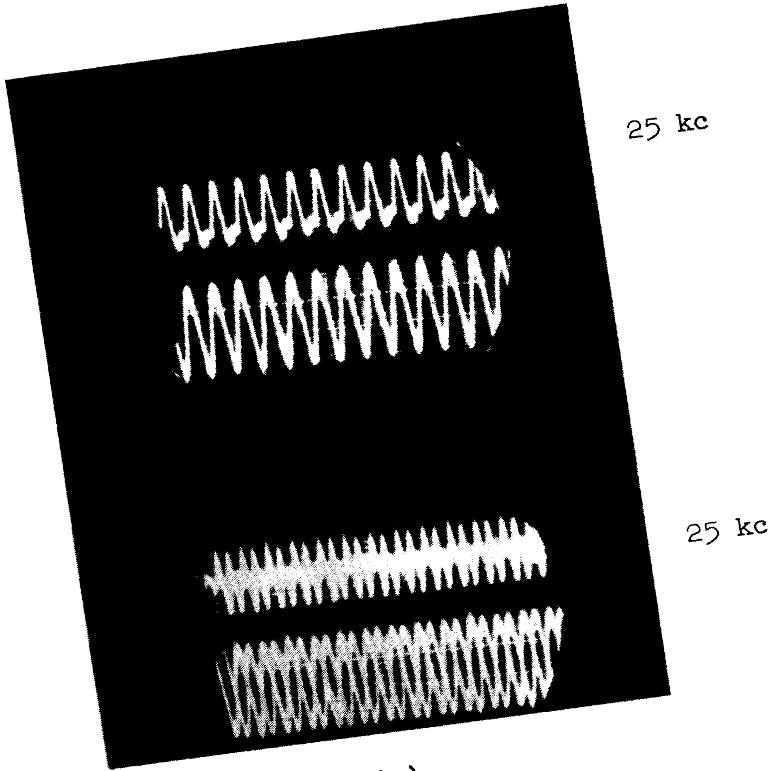
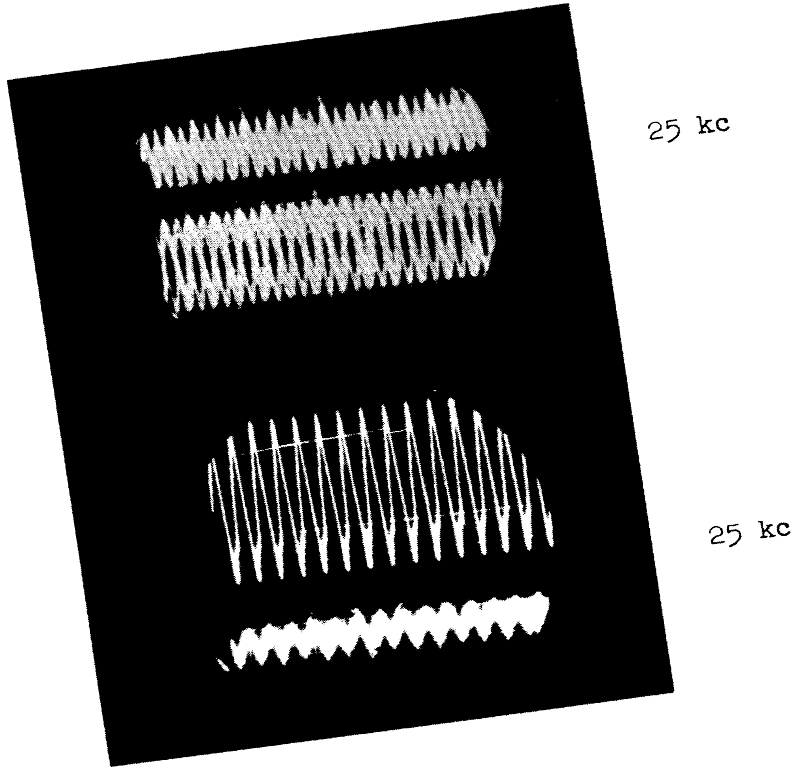


Fig. A-8. Schematic of vibration monitoring circuit.



(a)



(b)

Scale: Accelerometers—2 volts/cm
Strain gage—2 millivolts/cm

Fig. A-9. **Typical oscilloscope traces.** Upper trace is accelerometer output and lower trace is from strain gage on test section. Upper half of (a) shows conditions for maximum stress amplitude as indicated by strain gages. Accelerometer traces gives sume of both accelerometers. Lower half of (a) and upper half of (b) show transduced accelerometer and reflector accelerometer outputs only along with corresponding strain gage record. Lower half of (b) shows that maximum accelerometer output does not correspond to maximum stress.

APPENDIX B

COMMENTS ON THE POSSIBLE USE OF THE "FITZGERALD EFFECT" IN METAL CUTTING OR METAL FORMING

by J. R. Frederick, Ph.D

The "Fitzgerald Effect" is a resonance-type phenomenon. Polycrystaline metals, single crystals, crystalline polymers, and organic crystals shows abrupt increases in their shear compliance at one or more sonic frequencies of excitation.

The phenomenon has been investigated rather extensively by E. R. Fitzgerald since 1957 and he has published several papers on the subject.[1-7]. Reference 7 is a general summary of his efforts. His work has been primarily experimental.

Other workers have also reported this type of behavior in solids.[8-11]

Fitzgerald's work has resulted in some controversy as to whether what he had reported was real or was merely a resonance in his equipment. However, it has turned out that he has been observing a real phenomenon. The mechanisms that cause the effect have not been clearly identified as yet. Various models have been proposed but experimental data to support these models is still lacking.

The model that Dr. Fitzgerald proposes to account for the behavior of polycrystalline metals[7] consists of "small amplitude alternating slip occurring on transitory slip planes with mean lifetimes from 10^{-2} to 10^{-4} seconds." He suggests that this slip is opposed by displacement-dependent, velocity-dependent, and acceleration-dependent stresses along the slip plane. These cause the transitory slip planes to have lifetimes so short that "they do not contribute to the static compliance. Each slip plane, however, will be able to respond to one or more cycles of a low-frequency periodic stress if the plane forms when the alternating stress is near zero. Since the planes are forming and dying constantly, some will always be born at the right time. At higher frequencies the response of the planes will again drop off because of their inertial coefficients until, at ultrasonic frequencies, the dynamic compliance will equal the static compliance."

Fitzgerald suggests that the transient slip planes are caused by the movement of dislocations through the material. However, it is more likely that any resonances involving dislocation movements under applied stresses will have frequencies in the megacycle per second range because of the small size of dislocations. A theory for this has been proposed by Mason[12] and the actual phenomonon has been reported by Granato and Lucke[13] in slightly cold-worked metals in the megacycle per second range. It appears, therefore, that some mechanism other than dislocation resonance is needed, since the Fitzgerald effect occurs at kilocycle frequencies and not in the megacycle range.

A typical example of the results reported in Fitzgerald is shown in Fig. B-1. The sharpness of the resonance is one of the characteristics of the effect.

Fitzgerald finds that the resonance frequencies occur primarily between 150 and 5000 cps. Table B-I shows typical sets of resonant frequencies of various polycrystalline metals.

It does not appear that the Fitzgerald effect is apt to be useful in metal cutting or metal forming applications because of the sharpness of the resonance peaks, and because of the resonant frequencies which are dependent on the stress state and temperature. Furthermore, the peaks would very likely shift around rapidly during a processing operation. A tool or die would have to be driven by a transducer whose frequency was constantly shifting back and forth as it hunts or the maximum resonant peak. This poses a difficult technical problem. "Self-turning" systems do exist, but it is not probable that such systems would be effective in this case because of the multiplicity of the resonances and their sensitivity to processing variables.

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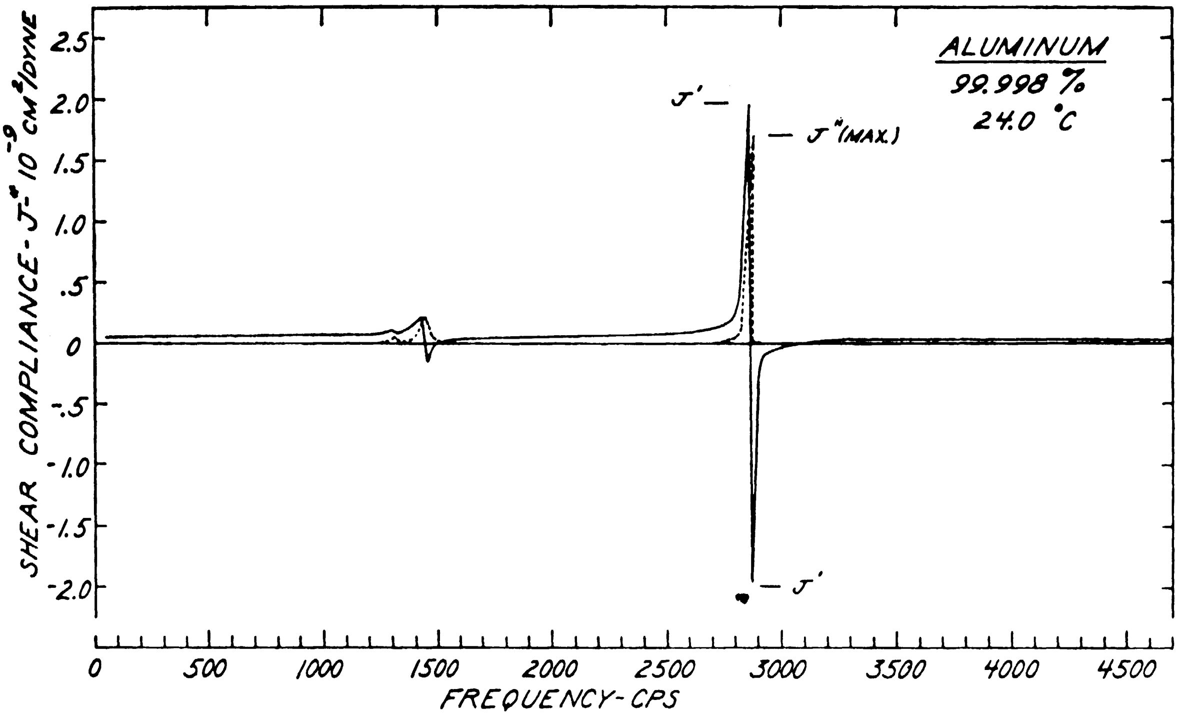

Fig. B-1. Variation of complex shear compliance ($J^* = J' - iJ''$) with frequency for polycrystalline aluminum at 25.1°C (taken from data of Ref. 1).

TABLE B-I

SUMMARY OF EXPERIMENTAL DATA ON MECHANICAL RESONANCE DISPERSIONS IN POLYCRYSTALLINE METALS FROM 100 TO 5000 CPS

Material	T°C	Resonant Frequency, cps	Loss Compliance Maxima or Minima (10^{-9} cm^2/d)
Lead (99.9995%)	23.5	(640 to 691 hr after compression)	
		1150	0.29
		1630	0.04
		1890	0.04
		2640	0.22
		2890	~1
		2910	-0.08
Lead (annealed)	24.1	2905	~2.0
		2920	-0.05
Indium (99.984%)	23.7	1540	0.02
		2830	~5
Aluminum (99.998%)	24.0	1315	0.04
		1435	0.30
		1940	0.04
		2890	~2
		3240	0.02
		3510	0.03
Platinum (99.983%)	24.8	2790	~1.5