SERIAL No. 11

May, 1944 [redacted] NRL Report No. 0-2296

FR-2296

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NAVY DEPARTMENT UNCLASSIFIED

Third Progress Report On

Size Effect in Slow Bend Test on Ni-Cr Steel

(University of North Carolina Progress Report No. 25)

NAVAL RESEARCH LABORATORY
ANACOSTIA STATION
WASHINGTON, D. C.

[redacted]

Classification changed from [redacted]
To UNCLASSIFIED
By authority of Lab. memo. 117/46
File No. Dated 7-1-46

Number of Pages:	Text 12	Tables 5	Figures 16

Authorization: NRL Contract No. N173s-8171

Date of Tests: January, February, March, 1944

Prepared by:

R. M. Trimble
University of North Carolina

P. E. Shearin
University of North Carolina

H. N. Michie
University of North Carolina

Reviewed by:

Ross Gunn, Superintendent
Mechanics & Electricity Division

Distribution Unlimited

Approved by:

A. H. Van Keuren
Rear Admiral, U. S. N.
Director

Approved for
Public Release

Distribution:

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FOREWORD

The organization of results shown in Fig. 15 and Fig. 16 of this report is arranged to show some of the interesting regularities that have emerged from the careful University of North Carolina fracture size effect studies. The relationship between total work density and angle of bend may furnish the basis for a simplified routine size effect measurement. The tendency for size effect to increase generally with brittleness regardless of cause is illustrated in more detail on Fig. 16 than in previous reports. The possibility of exceptions to this general rule remains and the search for such exceptions is continuing.

George R. Irwin

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Report No. 25

To: Drs. Ross Gunn, G. R. Irwin, and A. E. Ruark

By: R. M. Trimble, P. E. Shearin, and H.N.Michie-
University of North Carolina

THIRD PROGRESS REPORT ON SIZE EFFECT IN SLOW BEND TEST ON NI-CR STEEL

ABSTRACT

The report includes data and results of slow bend tests on eight groups of specimens in four Ni-Cr steels. It adds to the report No. 24 (Ref.1) results on the following.

1. Steel 4A443A1; OX direction, tempered bainite and OX direction, tempered martensite.

2. 2" steel plate No. 75907 in both OX and OY directions.

3. Electrolytic cast steel, heat treated and unworked.

Tests on specimens in three directions in 4A443A1 are now complete; two directions in steel 75907, OX and OY; and one direction in the other two steels.

Essential results from Reports 20 and 24 are reproduced here so that this report gives a comprehensive summary of all bend test results obtained up to the present.

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I. NATURE OF THE TESTS.

The specimens were clamped in holders and broken as beams by the application of loads to the holders through ball or roller bearings, at two points equidistant from the center. The holders were in turn supported on ball bearings. The set-up is shown schematically in Fig. 1. The loads were supplied at a rate such that the movement of the loading head was about 0.0002 in. per sec. An interval of at least 5 min. was allowed after each application to permit the load to become essentially stable. During this waiting period the load drops about 0-4 % depending on the stage of the test.

The flow curves for the tests are plotted with reduced bending moment (M/bd^2, where b, d are width and retained depth of specimen, respectively) as ordinate against angle of bend θ. At any load W, $M=f_1(W,\theta)$. Fig. 1 gives this relation for reducing test data as well as deflection of loader, $D=f_2(\theta)$. In earlier tests load and deflection of loader were recorded but more recently the angle of bend has been measured directly by means of an optical lever with telescope, mirrors on specimen holders, and a graduated arc of 2 meters radius.

The degree of accuracy of test loads may best be judged by the following summary of calibration runs with testing rings rated by the Bureau of Standards. The normal capacity of the Riehle testing machine is 100,000 lbs., but the highest loads in the bend tests were in the neighborhood of 40,000 lbs. (for 1-7/8 in. specimens).

LOAD	MAX VARIATION FROM MEAN, %	
	With 10,000 lb. Ring	With 100,000 lb. Ring
2000	0.35	-
4000	0.20	-
6000	0.05	-
8000	0.05	-
10000	0.03	0.15
20000	-	0.09
30000	-	0.07
40000	-	0.03

The arc used for measuring angle of bend is graduated to read directly to 0.001 radian and is recorded by estimation to 0.0001 radian. A small mirror is attached to each holder. The two mirrors are about 2 cm apart and their mean distance from the arc is 2 meters. As the mirrors move downward during a test a small error is introduced due to the fact that their mean position is no longer at the center of the arc. The error is approximately proportional to the angle of bend and, for the

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large bender is very nearly given by the function, e (in %) = $2.5\ \theta$ (in radians). The angle measured by the mirrors is larger than the true angle. For the small bender this error is smaller since the vertical movement of the mirrors is less on the shorter span. The resulting error in total work density is less than half the angular error since the maximum value of M/bd^2 occurs at an angle less than half the terminal angle.

II. THE SPECIMENS

Specimens in various groups are designated OX, OY, or OZ. OX means that the longitudinal axis of the specimen is parallel to the rolling direction or to the longitudinal axis of the original ingot. OY is the transverse direction perpendicular to OX and parallel to the plate faces. OZ is the thickness direction perpendicular to the plate faces.

The notch direction is parallel to OZ for all specimens except those whose axes are parallel to OZ, in which case the notch direction is OY.

Specimen dimensions, in inches, were as follows:

Nominal Length	3.5 ± 0.2	7.75 ±0.3	11.6 ± 0.4
Overall Cross Section	0.4 x 0.4 ±0.005	1.25 x 1.25 ±0.010	1.875 x 1.875 ±0.010
Notch Depth	18 - 22 % of gross depth		
Notch Diameter	0.024 ± .001	0.076 ± .002	0.113 ± 0.002

All sides of specimens were finished by grinding with a wheel of about No. 100 grit, and the notch was lapped into the base of a 90° milling cut with a rotating drill rod a little smaller than finished diameter. The rod was charged with No. 280 and No. 600 carborundum abrasive for large and small specimens respectively and heavy lubricating oil. The finished notch size was not determined from the size of drill rod but from subsequent careful measurements to insure the tolerances given above.

The specimens were not completely broken, for indeed they all bend through 180° without coming apart. The loading was continued until the load fell below 5 % of the maximum at which point the slope of the moment-angle curve is quite small compared with its average value.

III. MATERIAL USED.

The materials covered by the present report are as follows:

1. 18" Bethlehem Plate No. 4A443A1.

Two blocks, about 18" x 13" x 13" and about 12" x 11" x 12"

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respectively, from 18" Bethlehem Plate 4A443A1 were supplied by Naval Research Laboratory, Manufacturer's analysis and mechanical properties are as follows:

	C	Mn	P	S	Si	Ni	Cr
M-End:	.31	.28	.014	.015	.06	3.76	1.86
B-End:	.28	.27	.012	.019	.06	3.75	1.80

Physical properties before re-heat treatment:

	YP	TS	Elong.	RA	Remarks on coupon Fracture
M-End:	77,500	98,000	24.0%	57.3%	Close fiber, laminated.
B-End:	76,500	101,000	22.5%	60.6%	Medium close fiber.

This plate was cross-forged, but the material shows pronounced directional properties in the planes parallel to the plate surfaces. The cutting diagrams, showing how the two blocks were subdivided by the Naval Research Laboratory, are shown in Figs. 2 and 3. The numbers of these subdivisions are shown in the above drawings. Each individual bend specimen is given a number which contains the number of the block from which it was cut i.e. "F2B-1.875", is a 1.875" specimen cut from block F2 .

Metallographic examination at 100 magnification leads to recognition of two distinctly different microstructures. For simplicity these are referred to here as tempered martensite and tempered bainite. Referring to Figs. 2 and 3 the region near the front of the original plate is tempered martensite. Above this is tempered bainite. The boundary between the two is not sharp but extends over about 1" with its center about 3" from the original plate front, so that the boundary lies at about the middle of the large piece D6 in Fig. 2. In Fig. 3 the center of the transition zone is about 3/8" from the top of F 2. This means that 1.875 in. specimens of tempered martensite can be gotten from the bottom of F2. Metallographic examination indicated that the bottom of F 3 was already in the tempered bainite region. However, bend tests in this plate showed a slightly higher work density than did specimens in block F 4. This may indicate that the transition zone extends slightly into F 3 even though this was not detectable in metallographic examinations at 100X. In this report no specimens are included from F 3 nor from the top 1-1/2" of F2; thus the transition zones were avoided.

Macroetchings both here and at N.R.L. show that the region within 4" to 4-1/2" from the face of the original plate is relatively free of large inclusions. In the remainder of the

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material large flattened defects having dimensions up to at least 2-1/2" x 3/16" x 1/16" were observed, though the average length is much less. These defects were parallel to the plate face and their length was in the OX or rolling direction.

2. 2" rolled Steel Plate No. 75907

Two blocks of 2" steel plate Number 75907 both of which were about 12" x 12" x 2" and were numbered respectively 75907A3 and 75907A4 were supplied by the Naval Research Laboratory. The manufacturer's analysis and physical properties are as follows:

C	Mn	P	S	Si	Ni	Cr
.31	.24	.012	.022	.07	3.15	1.17

YP	TS	Elong	RA	Brinell
107,600	127,800	22.0%	64.7%	248
104,300	124,300	22.5%	65.9%	248
Mean 106,000	126,000	22.25%	65.3%	248

Doctor Irwin states, "Plate 75907 probably contains a moderate amount of non-metallics but we can be reasonably certain in this plate that the dirt is not badly segregated, and that the dendritic structure has been thoroughly broken up. These features can be obtained also to a certain degree by choosing various portions of 4A443A1. What cannot be obtained in the 18" plate is the comparative freedom of the 2" plate from high temperature transformation products and the finer grain size".

Cutting diagrams for these two plates are shown in Fig. 4.

3. 2-1/4" Steel Plate from Carnegie Institute of Technology.

Three bars of 2-1/4" steel plate, each approximately 3-1/2" x 2-1/4" x 12", were supplied by the Metals Research Laboratory, Carnegie Institute of Technology and are more fully described by Dr. A. B. Westerman as follows:

"The heat number is 146183. Analysis: 0.30C, 0.20 Mn, 0.012P, 0.026S, 0.05 Si, 3.21 Ni, 1.31 Cr, 0.03 Mo. Brinell hardness: Bar No. 1, 248/253; bar No. 2, 244/251; bar No. 3, 235/246.

"The specimens were heated in a muffle furnace to 1650° F (the furnace was already at temperature when the specimens were placed in it). They came to temperature in about one hour and were held there three hours. They were then quenched in water.

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They were placed in a muffle furnace and tempered while still warm, but below 100°C. The furnace was at the tempering temperature. The total time in the tempering furnace was 4-1/2 hours and the temperature was 1150°F. They were quenched in water from the tempering furnace.

"We have every reason to believe, based upon examination of the tempered structure, that these specimens, like earlier pilot specimens, were martensitic after the first quench. They are, of course, now in a tempered condition and should be substantially free from any martensite."

Studies of size effects in Ni-Cr steels have also been made at Carnegie Institute of Technology (Ref.2). The above described material was studied here in order to determine size effects in a material of similar composition and supposedly cleaner than materials so far tested here.

4. Cast Steel From Electrolytic Iron

One ingot of cast steel made from electrolytic iron was supplied by the Naval Research Laboratory. The ingot was about 12" long and tapered from about 3" x 3" at one end to about 2" x 2" at the other end. The analysis and heat treatment, supplied by Dr. George Irwin, are as follows:

C	Mn	Si	P	S	Al	Va	Ni	Cr
.28	.27	.20	.004	.005	.03	.024	3.13	1.30

Chilled mold;

3 hours at 1800°F; air cooled;

3 hours at 1600°F; oil quench.

Temper 1.5 hours at 1000°F. Gave 303 BHN.

Temper 3 hours at 1100°F. Gave 268 BHN.

The material was not worked after these treatments.

IV. RESULTS

1. Nature of the Cracking Process. Visual observations of the notch surface during the progress of the test were made by means of a scanning device equipped with a microscope of low power (about 10x) and a small incandescent light of high power. These observations yielded significant qualitative facts concerning crack formation and propagation. The appearance of the notch before the initiation of the main crack was distintly different for different materials. Usually, for specimens from the tempered-bainite region of the 18" steel, small cracks, presumably caused by inclusions or other weaknesses, are the first

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visual signs of distress. The first of these could be seen very soon after the beginning of plastic deformation of the specimen. The number of these cracks may become quite large before there is any indication as to where the main crack will commence. The main crack is usually initiated by the growth of one of the larger of these small cracks, and then it extends by passing progressively through other small cracks. The "lips", or ends of the notch, usually remain intact until the crack is continuous through the center. As a rule, one of the lips which happens to contain an unfavorable array of sources of weakness, breaks through well ahead of the other lip. It is usually possible to predict which lip will go first, by the pattern of defects or cracks appearing in the notch, even before the main crack is formed.

The onset of cracking is noticeably different in the 2" material No. 75907 and the 2-1/4" steel plate from C.I.T. In specimens from these materials the first indication of distress in the notch is evidenced by a general dullness of the surface, followed by a pronounced roughening. The roughening then gradually arranges itself into rather clearly defined ridges parallel to the length of the notch. In the valleys between ridges fine cracks eventually start. As loading continues these cracks join to form the main crack, the latter frequently jumping from one valley to the adjacent one. As a rule the main crack starts at the center and progresses towards the ends or lips of the notch. The lips continue to hold until the crack at the center is definitely open and continuous. Finally the crack breaks through both lips at approximately the same time.

The total increment of gross strain from the initiation of the main crack until it extends completely across the specimen is much less in the 2" and 2-1/4" steels than in the tempered bainite of the 18" steel.

For specimens in that region of the 18" steel described as tempered martensite the cracking process is somewhat similar to that in the 2" and 2-1/4" steels, the crack developing very rapidly once it starts.

The cast electrolytic steel showed defects before the main crack started, and its behavior was somewhat similar to that of the tempered bainite.#Rather loud noises of unmistakable specimen origin are usually heard in the last stages of breaking the 1.875 in. specimens, and are sometimes heard in the 0.4 in. specimens, and indicate that the breaking process is not a smooth gradual one. The most striking example was that of 1.875 in. specimens in the OZ direction of tempered bainite (Specimens F1A and F1B Fig. 7.) In each of these two specimens the first loud noise (approximately the loudness of a 22 calibre rifle) was heard shortly after the crack broke through the last lip. A number of other sounds were heard during the remainder of the test. After the specimens were broken apart, the fracture surfaces showed a prominent banded structure indicating that each loud noise was due to a sudden extension of the crack over a region represented by one of these bands.

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The occurence of sudden fracture is simply an indication that the potential energy stored in the specimen, the holders, and all other elastic parts of the machine is sufficient to supply the energy needed for a finite plastic deformation, since the surface energy of the newly formed crack is negligible. The interesting point is that the sudden fracture occurs in the largest OZ specimens, which show the smallest values of work - density and final angle of bend.

In each of the curves of Figs. 5 to 14 the position on the curve at which the crack is continuous across the notch is indicated for each specimen. In Fig. 5, showing the results for 4A443A1, tempered bainite in the OX direction, it will be noted that, especially for the 0.4 In. specimens, the crack is continuous very close to the maximum. For most of the other specimens the crack is not continuous until a point well beyond the maximum is reached.

2. MOMENT ANGLE CURVES AND WORK DENSITIES.

Measured loads were converted into reduced moments (M/bd^2) by means of the relations in Fig. 1, and the reduced moments plotted against angle of bend as seen in Figs. 5 to 14.* The areas under these curves out to the 5 % ordinate give work densities, in ft. lbs. per cu. in., as recorded in Tables I to III. The conventional volume involved in these work densities is that of a parallelepiped whose edges are b, d, and d.

Figs. 8, 9, 12, 13 and 14, show flow curves for the means of specimen size groups in the different materials; the effect of specimen size; both in amount (the area) and in behavior (the shape), is easily observed.

Tables I-III give work densities for individual specimens in material not previously reported upon. Three values of work density are shown: viz.(1) W_1 the work density from the start of the test, represented by the area under the flow curve from the origin to the maximum ordinate; (2) W_2 that from maximum ordinate to the terminal ordinate at 5 % of maximum moment, and (3) W, the sum of W_1 and W_2 or total work density. The alternative method of computing work densities, described in Report 24, namely, determining W, as the area under the flow curve had the specimen been unloaded from the maximum, has not as yet been applied to this body of data. Obviously the total work density, W is not affected. The table also shows the ratios of the three work densities.

Table IV summarizes the data for individual specimens in group means and includes, for comparison, the earlier results on 4A443A1 OX and OY specimens and on 2-1/4 in. plate, previously reported in Report 24.

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* Figs 6, 7, 8 were used in essentially their present form in Report No. 24 and a discussion of the "old notch" curves appears in the report.

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3. Relation Between W and Final Angle of Bend

Table V gives, size effect values (such as $W_{0.4}/W_{1.875}$) for different sizes of specimens in all materials, and reductions (%) in work density accompanying increase in size. Curiously perhaps, the spread in the percentage reductions due to changing from the 0.4 in. specimen to the 1.25 in. specimen is 21.4 %, whereas the corresponding value for 0.4 in. and 1.875 in. specimens is only 11.7 %.

The materials may be classified roughly, relative to each other, by plotting total work density (W) against terminal angle of bend(that at 5 % or 10 % of maximum moment). Fig. 15 shows these graphs for the angles at 10 % since a few specimens were not carried quite to the 5 % mark. The 5 % plottings show the same trends but the lines are not quite so steep.

It appears from this figure that for a given material(and for a given orientation of the specimens, in a material which is not isotropic) the total work density measured in this test is essentially a linear function of terminal angle of bend; and that the slope of the graph, (ft.lbs. per cu. in. per radian) might be a rough measure of "brittleness" or of "toughness". Thus steel 4A443A1 (OZ) has the least steep slope; 75907 OX and OY and Carnegie steel, all essentially the same slope and steepest of all.

Size effects, expressed as ratios of means of total work densities of size groups, appear to follow roughly the trend of "brittleness" values, i.e. as work density per radian increases size effects decrease.

Other comparisons on this basis are interesting. For example, 4A443A1 (OX) specimens in tempered bainite and in tempered martensite have work densities which are not materially different (see Table IV) for 0.4 in. specimens. Their work densities per radian, however, vary by 20.1 %.

Another interesting observation involves the comparison of total work density values for specimens in tempered bainite and in tempered martensite. From Table IV the following is repeated:

		Bainite		Martensite		
Size	Direction	Mean of	W	Mean of	W	W_M/W_B
0.4	OX	4	1635.9	4	1612.5	98.6 %
1.875	OX	2	672.6	2	855.4	127.2%

[redacted]

It would appear from this that total work density would not distinguish tempered bainite from tempered martensite if comparative specimens of about 0.4 in. were used, but for a considerably larger size (1-7/8") the difference is marked (about 27%). The amount of bend (terminal) is greater for tempered bainite however and the increase in work density per radian (Table V) of tempered martensite over tempered bainite is 18.7%, Carnegie 2-1/4" steel (OX) and steel 75907 (OY) have roughly the same work density per radian and total work density in the 0.4 in. size and from this alone it might be concluded that their physical behaviors in the bend test were the same; but on comparing their total work densities in the 1.875 in. size 75907 (OY) falls below Carnegie (OX) by 41.7%.

V. SUMMARY AND CONCLUSION

1. **Materials.** Table V and Fig. 15 provide a condensed account of the results of slow-bend tests on geometrically similar specimens of four Ni-Cr steels, at surface hardness levels in the range 235-268 Brinell. One material was available in large blocks having tempered martensite at the surface and tempered bainite of considerable uniformity in the body of the blocks. These could be tested separately so effectively we have results on five materials.

2. **The Specimens,** square in cross section, have substantially the proportions of the bars used in Izod impact tests but the notches are different, to allow careful lapping and control of the notch dimensions. The specimen sizes are designated by b, the width, or notch length, (which is 0.4", 1.25" and 1.875" for the three sizes employed), also by the direction of the long axis of the specimen. The designations OX, OY, OZ refer to the length, width, and thickness of the original bar or plate.

3. **Qualitative Study of Crack Formation.** The initial cracks in the notch, which join together later to form the main crack, appear at an early stage in the bending process because of the hindrance to flow associated with the notch. They may be quite numerous, over a hundred being observed in some cases. A detailed study of their distribution and growth would doubtless yield information on the number and size of the dangerous inclusions in the metal, but such a study, to be valuable and convincing, would require the expenditure of great time and effort. Here we limit ourselves to the statement that the roughening pattern and hair-crack pattern in the notch shows definite differences from one material to another. We believe, on very general grounds, that there is a correlation between the number of these cracks, the area of notch surface, and the work required to sever the specimen, but we do not believe the correlation is sufficiently good to warrant an extensive study. It seems much more important to study the texture of the finished fracture surface, and such an investigation is under way.

4. **Method of Indicating Size Effects.** A curve showing load versus deflection, or a curve of bending moment M versus angle θ is drawn for each specimen. In this report all results

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are reduced to the latter basis. The curves of M/bd^2 versus θ were drawn, where b is specimen width and d retained depth. If there were no size effect, and no variation from specimen to specimen these curves would coincide. The area under such a curve is the work required to break the specimen, divided by a volume bd^2, and is simply called work-density, W. Now since there is a size effect, W depends on specimen size and either a ratio, such as $W_{0.4}/W_{1.875}$ or a percentage difference such as 100 $(W_{0.4}-W_{1.875}/W_{0.4})$ may be taken as a measure of size effect.

5. Effect of Specimen Orientation. Orientation effects in tensile specimens of material 4A443A1 have been discussed in Report 20(Ref. 3) They show up very clearly in the slow bend test as we can see from Table IV. Since the size effect ratios are different for the three principal directions it is clear that the effect of orientation on total work depends on the size of the specimens studied.

6. Size Effects. Fig. 16 shows considerable differences in the general trend of the total work, as a function of size, for the various materials studied. The accuracy of the work measurements is more than sufficient to bring out differences between individual specimens and the uncertainty of the ordinates in Fig. 16 is substantially controlled by the spread of the results for individual specimens which is usually between 1.0 and 7.5 %(average deviation from the mean).

The size effects portrayed cannot sufficiently be described by a single work ratio such as $W_{0.4}/W_{1.875}$ or by the average slope of the curves. From the discussion in the text, it appears that the work density per radian is substantially constant for all specimen sizes of a given material, tested in a given orientation. This quantity may be a satisfactory measure of size effect in these Ni-Cr steels, but it is best to reserve judgment, remembering that the curves themselves furnish the detailed picture of the decrease in work-density as the size increases.

It is clear that further increase of size would result in further decrease of work-density W, for all the material studied.

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Table I. Work Densities in Ft.Lb./Cu.In. From Moment-Angle Curves For 18 In. Steel 4A443A1, OX Direction

Specimen		Work Density			W_1/W	W_2/W	W_2/W_1
Size	No.	W_1	W_2	W	%	%	%
		Specimens From Tempered Bainite					
0.4"	F6A	752.4	841.5	1593.9	47.2	52.8	111.8
	F6B	808.8	863.7	1672.5	48.4	51.6	106.8
	F6C	760.8	889.7	1650.5	46.1	53.9	116.9
	F6D	719.6	907.3	1626.9	44.2	55.8	126.1
	Mean	760.4	875.5	1635.9	46.5	53.5	115.1
1.25"	F4A	554.2	431.5	985.7	56.2	43.8	77.9
	F4B	532.2	424.6	956.8	55.6	44.4	79.8
	F4C	574.2	416.5	990.7	58.0	42.0	72.5
	Mean	553.5	424.2	977.7	56.6	43.4	76.6
1.875"	F6A	422.8	284.4	707.2	59.8	40.2	67.2
	F6B	367.8	270.3	638.1	57.6	42.4	73.5
	Mean	395.3	277.3	672.6	58.8	41.2	70.1
		Specimens from Tempered Martensite					
0.4"	F2A	780.5	849.1	1629.6	47.9	52.1	108.8
	F2B	749.0	874.7	1623.7	46.1	53.9	116.8
	F2C	621.0	923.7	1544.7	40.2	59.8	148.7
	F2D	675.3	976.5	1651.8	40.9	59.1	144.6
	Mean	706.5	906.0	1612.5	43.8	56.2	128.2
1.875"	F2A	551.6	369.7	921.3	59.9	40.1	67.0
	F2B	432.8	356.7	789.5	54.8	45.2	82.4
	Mean	492.2	363.2	855.4	57.4	42.6	74.7

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TABLE II. Work Densities in Ft.Lb./Cu.In.From Moment-Angle Curves for 2 In. Rolled Steel No.75907

Specimen Size	Specimen No.	Work Density W1	Work Density W2	Work Density W	W1/W %	W2/W %	W2/W1 %
Specimen Direction OX							
0.4"	1A3	625.3	949.6	1574.9	39.7	60.3	151.9
	3A3	617.8	911.6	1529.4	40.4	59.6	147.5
	4A3	653.2	832.0	1485.2	44.0	56.0	127.3
	5A3	658.3	885.6	1543.9	42.6	57.4	134.5
	6A3	626.6	894.2	1520.8	41.2	58.8	142.7
	Mean	636.2	894.6	1530.8	41.6	58.4	140.6
1.25"	1A3	495.2	428.1	923.3	53.6	46.4	86.5
	2A3	493.6	456.2	949.8	52.0	48.0	92.4
	3A3	496.4	499.6	996.0	49.8	50.2	100.6
	Mean	495.1	461.3	956.4	51.8	48.2	93.2
1.875"	A3	448.7	378.9	827.6	54.2	45.8	84.4
Specimen Direction OY							
0.4"	1A4	498.4	514.1	1012.5	49.2	50.8	103.2
	2A4	556.9	510.4	1067.3	52.2	47.8	91.7
	3A4	561.8	542.5	1103.3	50.9	49.1	96.6
	4A4	573.0	467.9	1040.9	55.0	45.0	81.7
	5A4	517.5	583.6	1101.1	47.0	53.0	112.8
	6A4	546.8	558.9	1104.7	49.5	50.5	102.2
	Mean	542.4	529.6	1071.0	50.6	49.4	98.0
1.25"	1A4	307.8	206.2	514.0	59.9	40.1	67.0
	2A4	370.7	210.7	581.4	63.6	36.4	56.8
	3A4	316.8	221.6	538.4	58.8	41.2	69.9
	Mean	331.8	212.8	544.6	60.8	39.2	64.6
1.875"	1A4	282.5	160.8	443.3	63.7	36.3	56.9
	2A4	339.6	175.3	514.9	66.0	34.0	51.6
	Mean	311.1	168.0	479.1	64.9	35.1	54.2

TABLE III. Work Densities in Ft. Lb./Cu.In. From Moment-Angle Curves For Electrolytic Cast Steel, Heat Treated, Unworked

0.4"	1E1	427.9	635.1	1063.0	40.8	59.2	148.5
	2E1	374.3	592.6	966.9	38.7	61.3	158.3
	3E1	116.5	333.5	450.0	25.9	74.1	286.2
	4E1	326.7	670.7	997.4	32.8	67.2	205.3
	Mean	311.4	558.0	869.4	35.8	64.2	179.2
1.25"	1E1	193.7	253.1	446.8	43.4	56.6	130.7

[redacted]

TABLE IV. SUMMARY OF MEAN WORK DENSITIES FOR ALL MATERIALS.

MATERIAL	Direction	Number of tests	Mean Work Density			W_1/W %	W_2/W %	W_2/W_1 %
			W_1	W_2	W			
0.4 In. Specimens								
4A443Al Bainite	OX	4	760.4	875.5	1635.9	46.5	53.5	115.1
	OY	3	675.8	603.3	1279.1	52.8	47.2	89.8
	OZ	4	451.2	406.8	858.0	52.6	47.4	90.4
Martensite	OX	4	706.5	906.0	1612.5	43.8	56.2	128.2
75907, 2 in. Rolled Steel	OX	5	636.2	894.6	1530.8	41.6	58.4	140.6
	OY	6	542.4	529.6	1071.0	50.6	49.4	98.0
Carnegie 2-1/4"	OX	4	578.5	574.7	1153.2	50.1	49.9	100.0
Cast, unworked	OX	4	311.4	558.0	869.4	35.8	64.2	179.2
125.in. Specimens								
4A443Al Bainite	OX	3	553.5	424.2	977.7	56.6	43.4	76.6
	OY	2	421.9	309.9	731.8	57.6	42.4	75.5
	OZ	3	256.8	191.6	444.8	57.8	42.2	73.7
75907, 2 in. Rolled Steel	OX	3	495.1	461.3	956.4	51.8	48.2	93.2
	OY	3	331.8	212.8	544.6	60.8	39.2	64.6
Cast, unworked	OX	1	193.7	253.1	446.8	43.4	56.6	130.7
1.875 Specimens								
4A443Al, Bainite	OX	2	395.3	277.3	672.6	58.8	41.2	70.1
	OY	2	288.8	254.1	542.9	53.2	46.8	87.9
	OZ	2	175.1	146.7	321.8	55.7	44.3	83.2
Martensite	OX	2	492.2	363.2	855.4	57.4	42.6	74.7
75907, 2 in Rolled Steel	OX	1	448.7	378.9	827.6	54.2	45.8	84.4
	CY	2	311.1	168.1	479.1	64.9	35.1	54.2
Carnegie 2-1/4"	OX	3	404.6	274.2	678.8	59.6	40.4	67.7

[redacted]

TABLE V. Work Density Per Radian and Effect Of Specimen Size On Total Work Density.

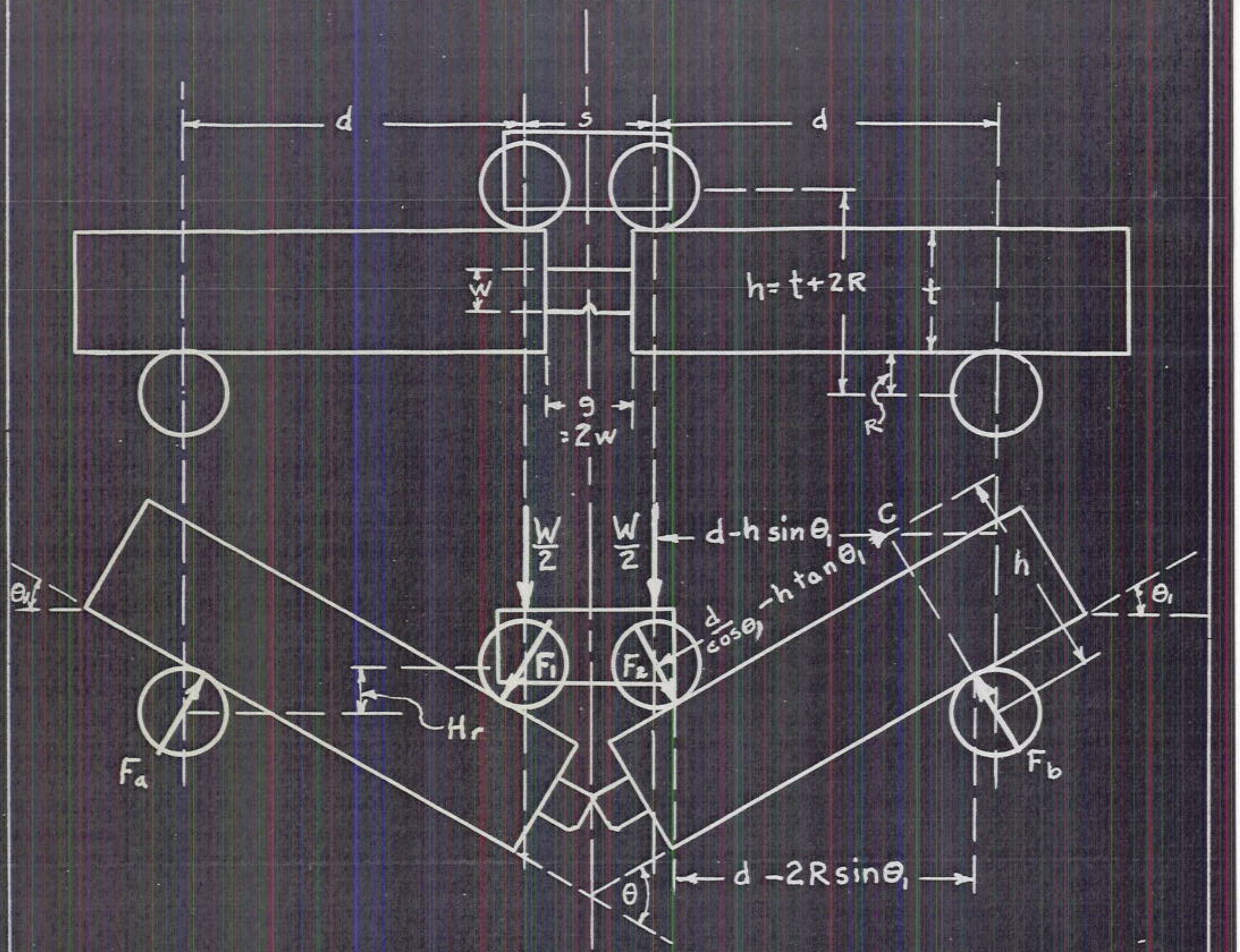
Work Density Values in Ft.Lb. per cu. in.

Material	Dir	Work Density Per Radian	$\frac{W0.4}{W1.25}$	$\frac{W0.4}{W1.875}$	Decrease in Work Density (%)	
					0.4-1.25	0.4-1.875
4A443A1-18 in. Bainite	OX	1365	1.67 ±.03	2.43 ±.13	40.2	58.9
Bainite	OY	1315	1.75 ±.08	2.34 ±.12	42.8	57.2
Bainite	OZ	1200	1.93 ±.05	2.67 ±.05	48.2	62.5
Martensite	OX	1620		1.88 ±.15		47.0
72907 -2 in Rolled Steel	OX	1740	1.60 ±.04	1.85 ±.06	37.5	45.9
	OY	1720	1.97 ±.08	2.24 +.05	49.2	55.2
Carnegie 2-1/4 in 146183	OX	1750		1.70 ±.07		41.1
Cast, unworked	OX	1530	1.95		48.6	

In this table values of $\Delta S/S$ (e.g ± .03) have been computed from the relation

$$\frac{\Delta S}{S} = \sqrt{\left(\frac{\Delta W_a}{W_a}\right)^2 / N_a - 1 \quad + \left(\frac{\Delta W_b}{W_b}\right)^2 \quad / N_b - 1}$$

where W is total work density. a and b represent small and large specimen size, respectively.



$H_r = h\cos\theta_1 - (d - h\sin\theta_1)\tan\theta_1$ $\qquad W/2 = F_2\cos\theta_1\,;\ \theta = 2\theta_1$

$= -d\tan\theta_1 + h(\cos\theta_1 + \sin\theta_1\tan\theta_1)$ $\qquad$ Moment, M:

Deflection, D: $\qquad M = F_2\left(\frac{d}{\cos\theta_1} - h\tan\theta_1\right)$

$D = d\tan\theta_1 + h(1 - \cos\theta_1 - \sin\theta_1\tan\theta_1)$ $\qquad M = \frac{Wd}{2}\left[\frac{1 - (h/d)\sin\theta_1}{1 - \sin^2\theta_1}\right]$

$D = d\tan\theta_1 - h(\sec\theta_1 - 1)$

Approx. Travel of upper roller on block: $(s/2)(\sec\theta - 1) + (w + R)\tan\theta_1$

" " " lower " " " : $(s/2 + d)(\sec\theta - 1) + (w - R)\tan\theta_1$

In practice $t = w$, approximately.

FIG. 1.

TITLE Geometry, Slow-Bend Tester.
DRAWN BY A.E. Ruark DATE Dec. 1943
Traced, H.N. Michie.
ACC. NO. 193 SCALE —

DECLASSIFIED

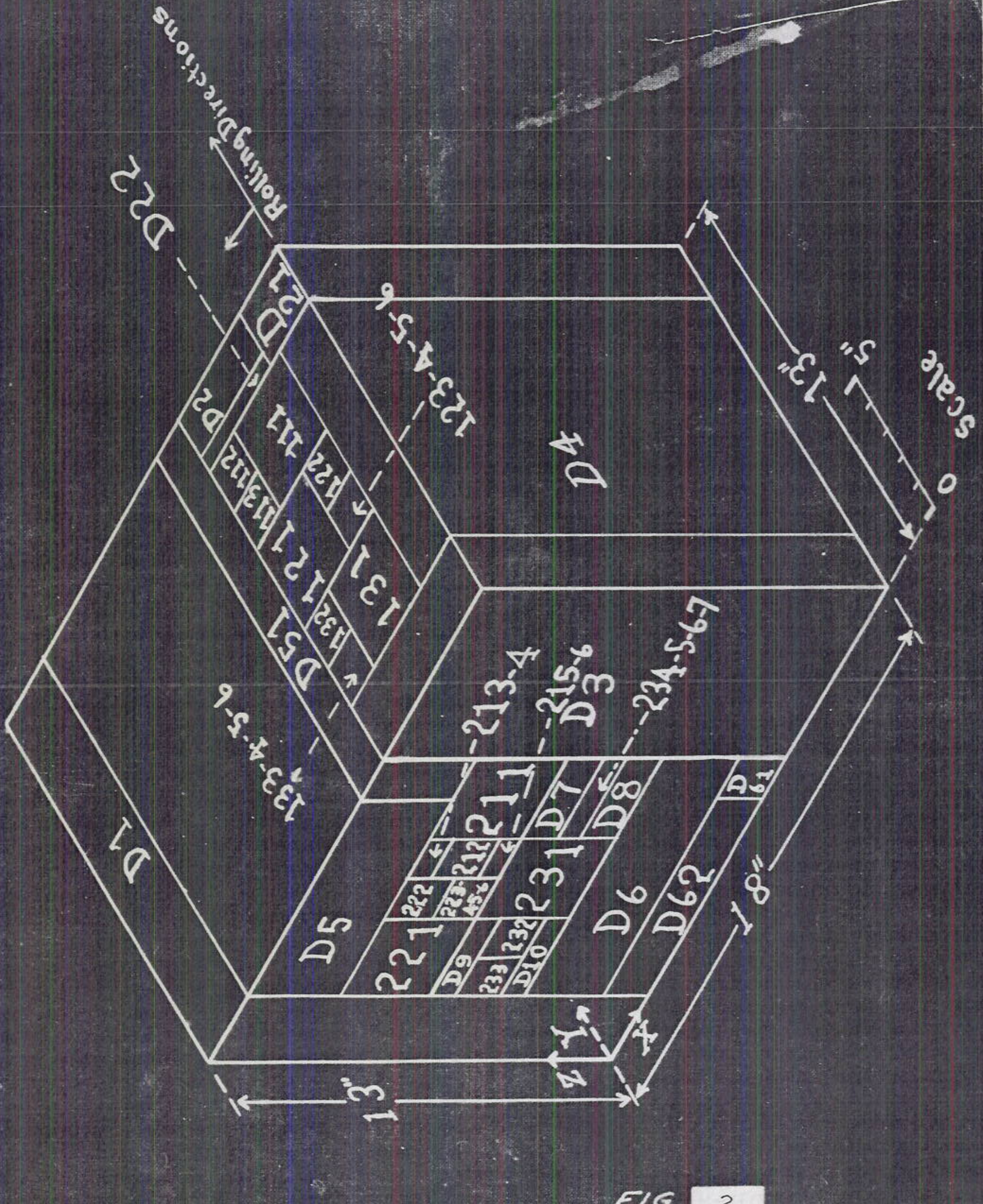
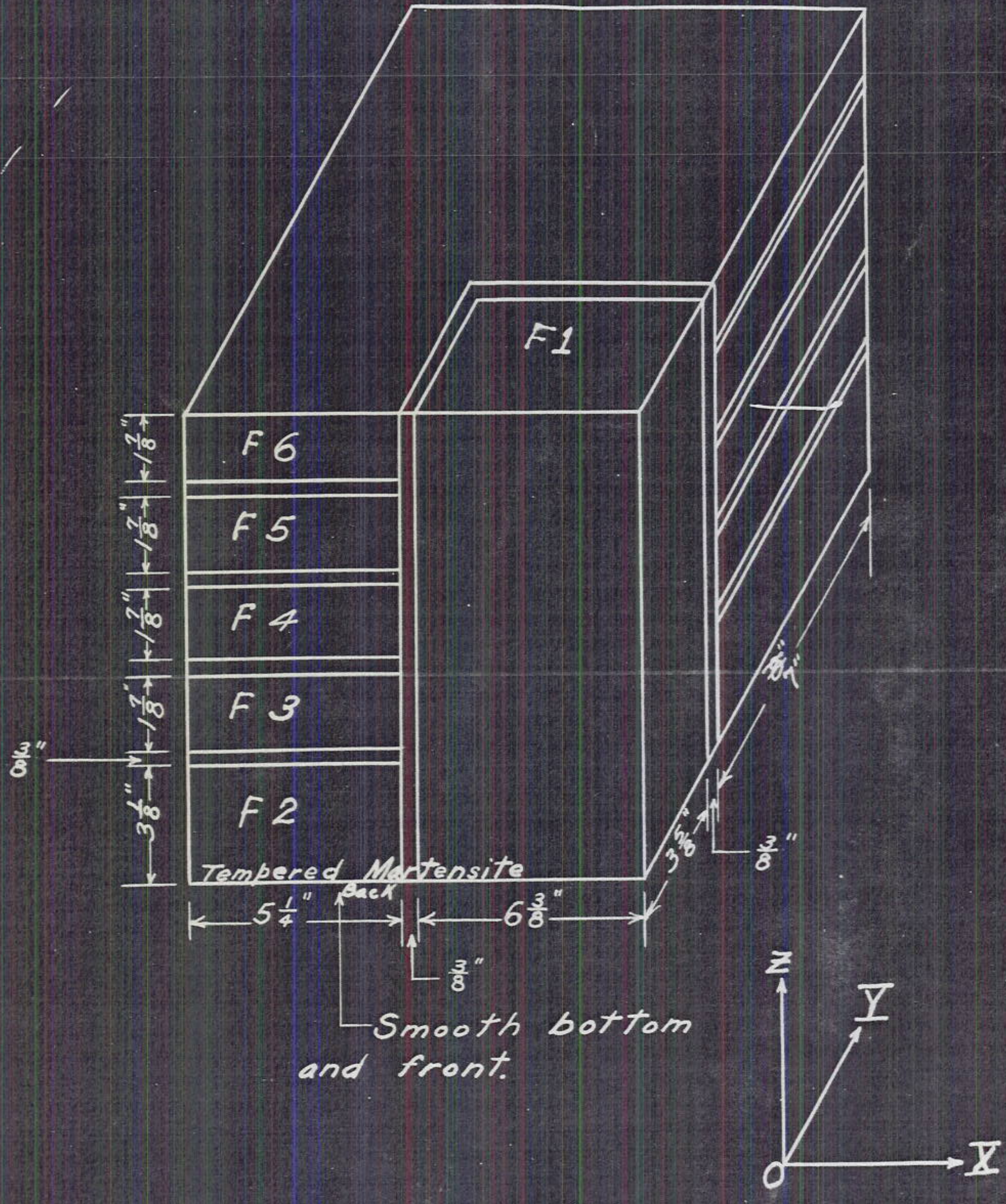


FIG. 2.

TITLE Block Cut From Original 18" Cube
Of 18" Steel A 4A443
DRAWN BY James Russell DATE June 12, 1942.
ACC. NO. N101 SCALE -

Back of original Plate at Bottom.
Other Outside Surfaces of Block Shown
are Flame-cut. All Subdividing Done
With Saw.

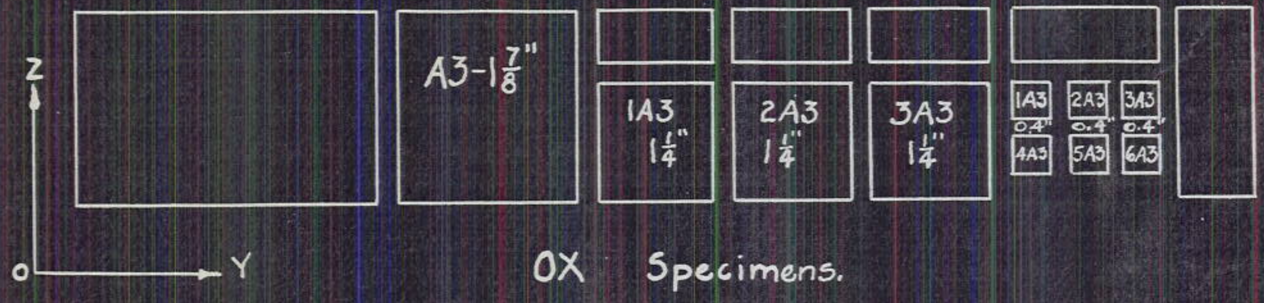
Checked, Arthur Ruark.



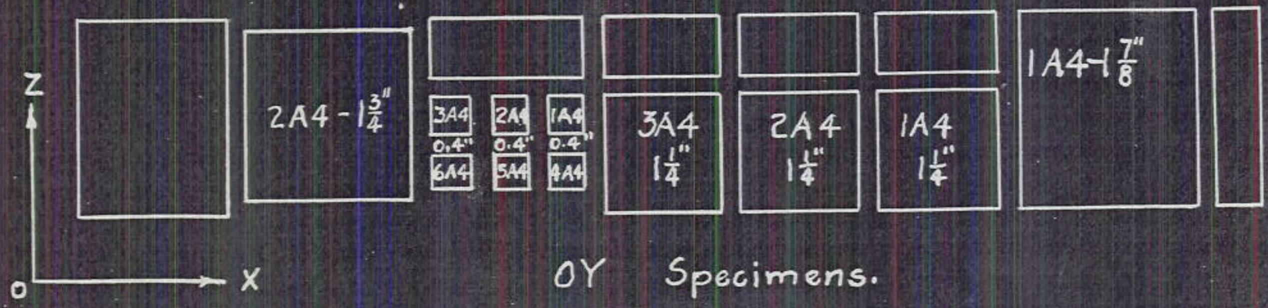
Effective 12" x 11" x 12"

FIG. 3.

TITLE	CUTTING DIAGRAM FOR 13½" x 13½" x 13½" BLOCK OF 18" STEEL 4A443A1.
DRAWN BY P.E.S.	DATE 6/3/43
ACC. NO. 184.	SCALE



OX Specimens.

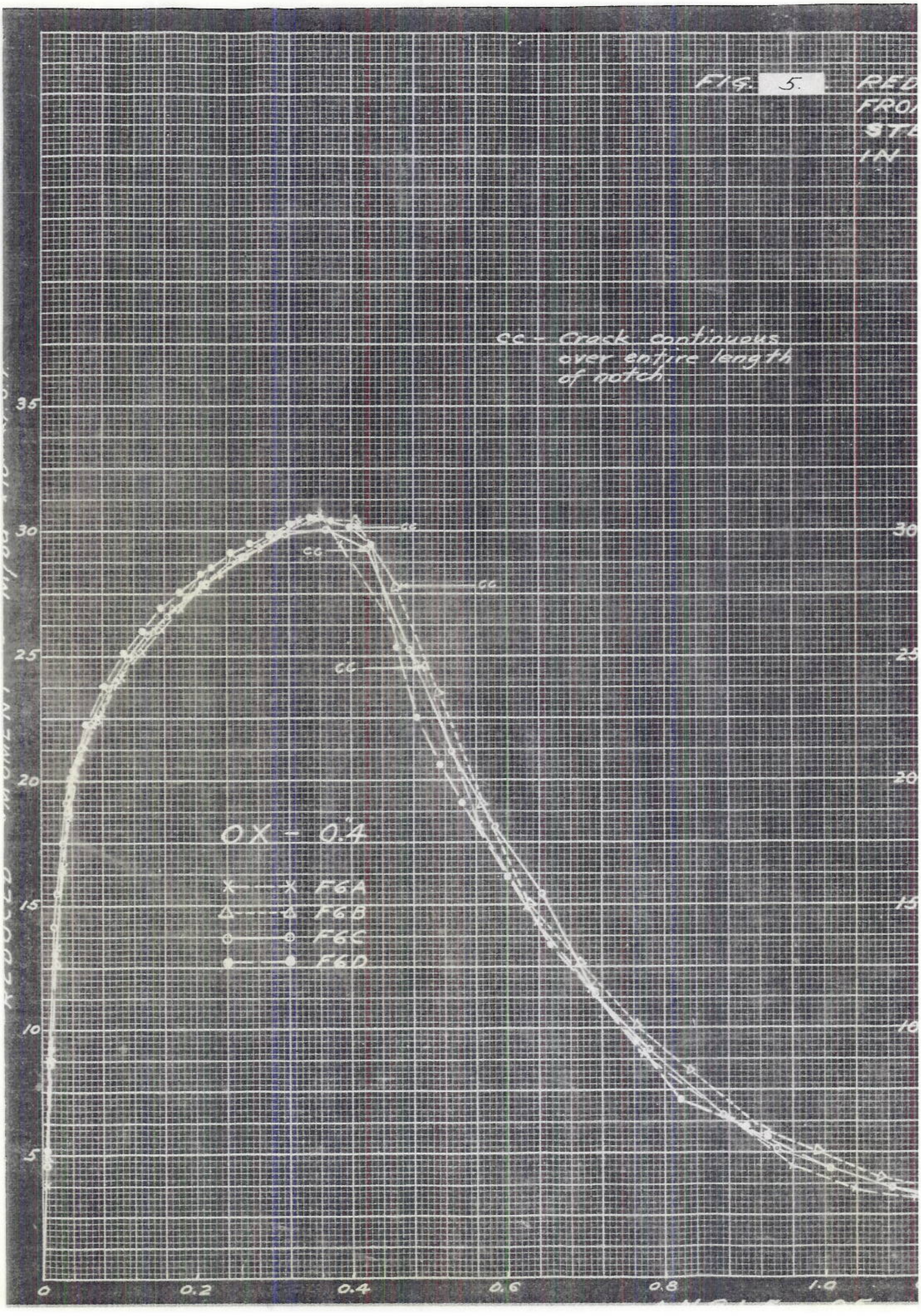


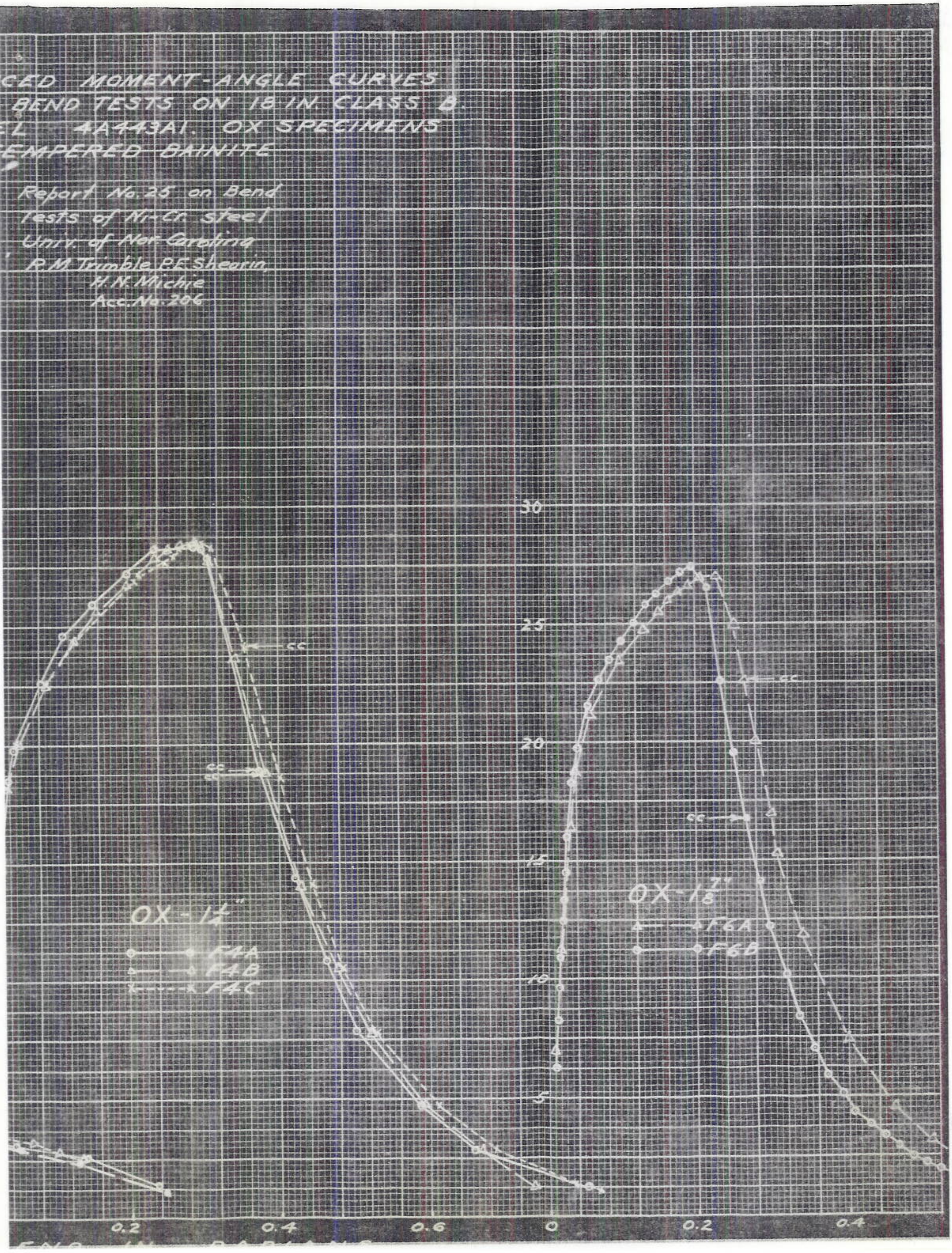
OY Specimens.

FIG. 4

TITLE Cutting Diagrams For 2"
Rolled Steel No. 75907 A3 & A4.
DRAWN BY P.E. Shearin DATE Dec. 1943.
Traced By H.N. Michie.
ACC. NO. 218 SCALE 1" = 2"

FIG. 5.


RED
FRO
STE
IN
cc - Crack continuous over entire length of notch
cc
cc
cc
cc
OX - 0.4
F6A
F6B
F6C
F6D
REDUCED MOMENT M/bd
35
30
25
20
15
10
5
0
0.2
0.4
0.6
0.8
1.0
ANGLE OF


CED MOMENT-ANGLE CURVES
BEND TESTS ON 18 IN. CLASS B.
EL 4A443A1. OX SPECIMENS
EMPERED BAINITE
Report No. 25 on Bend
Tests of Ni-Cr. steel
Univ. of Nor Carolina
R.M. Trimble, P.E. Shearin,
H.N. Michie
Acc. No. 206
30
25
20
15
10
5
cc
cc
cc
cc
OX-1¼"
F4A
F4B
F4C
OX-1⅞"
F6A
F6B
0.2
0.4
0.6
0
0.2
0.4

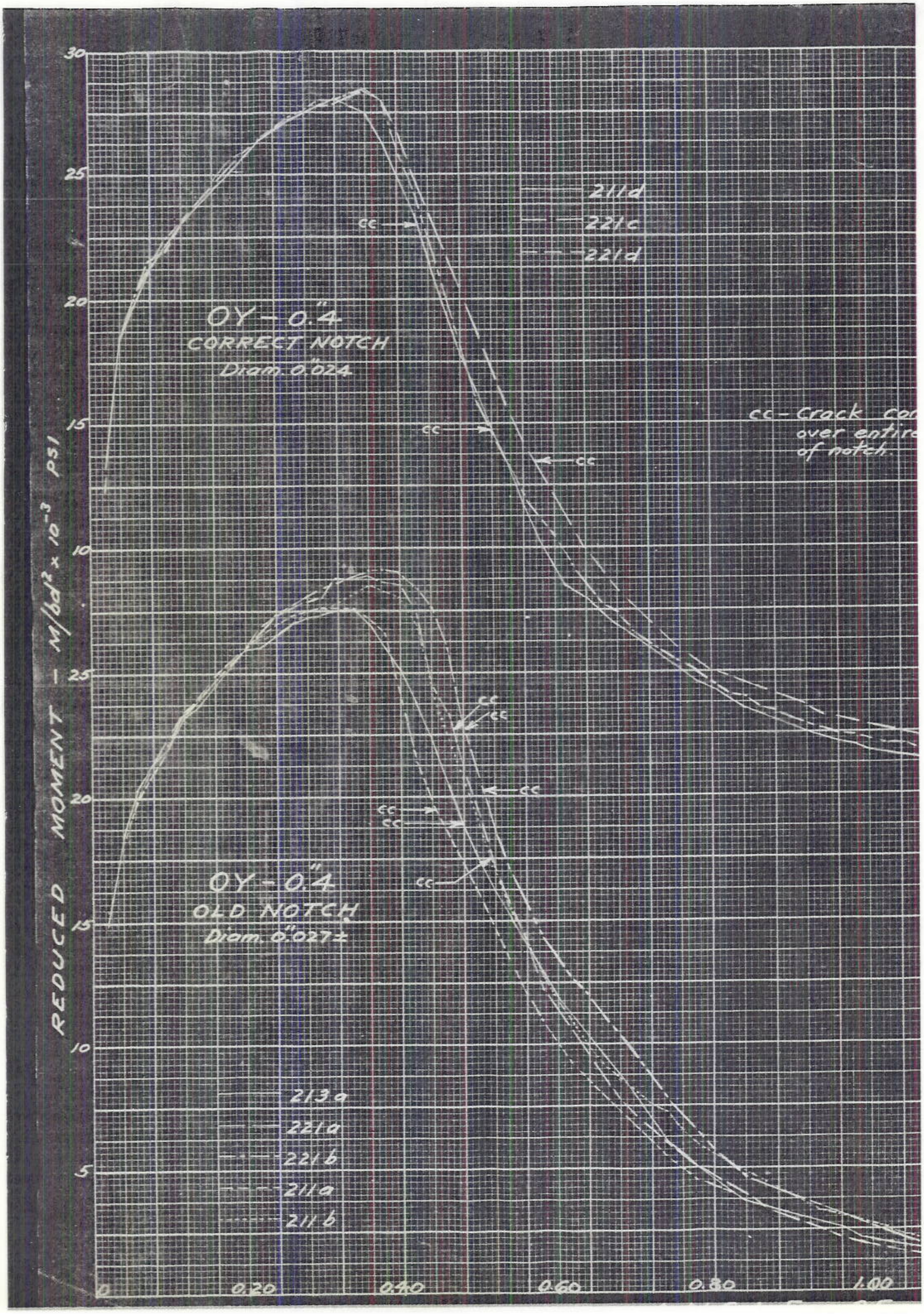
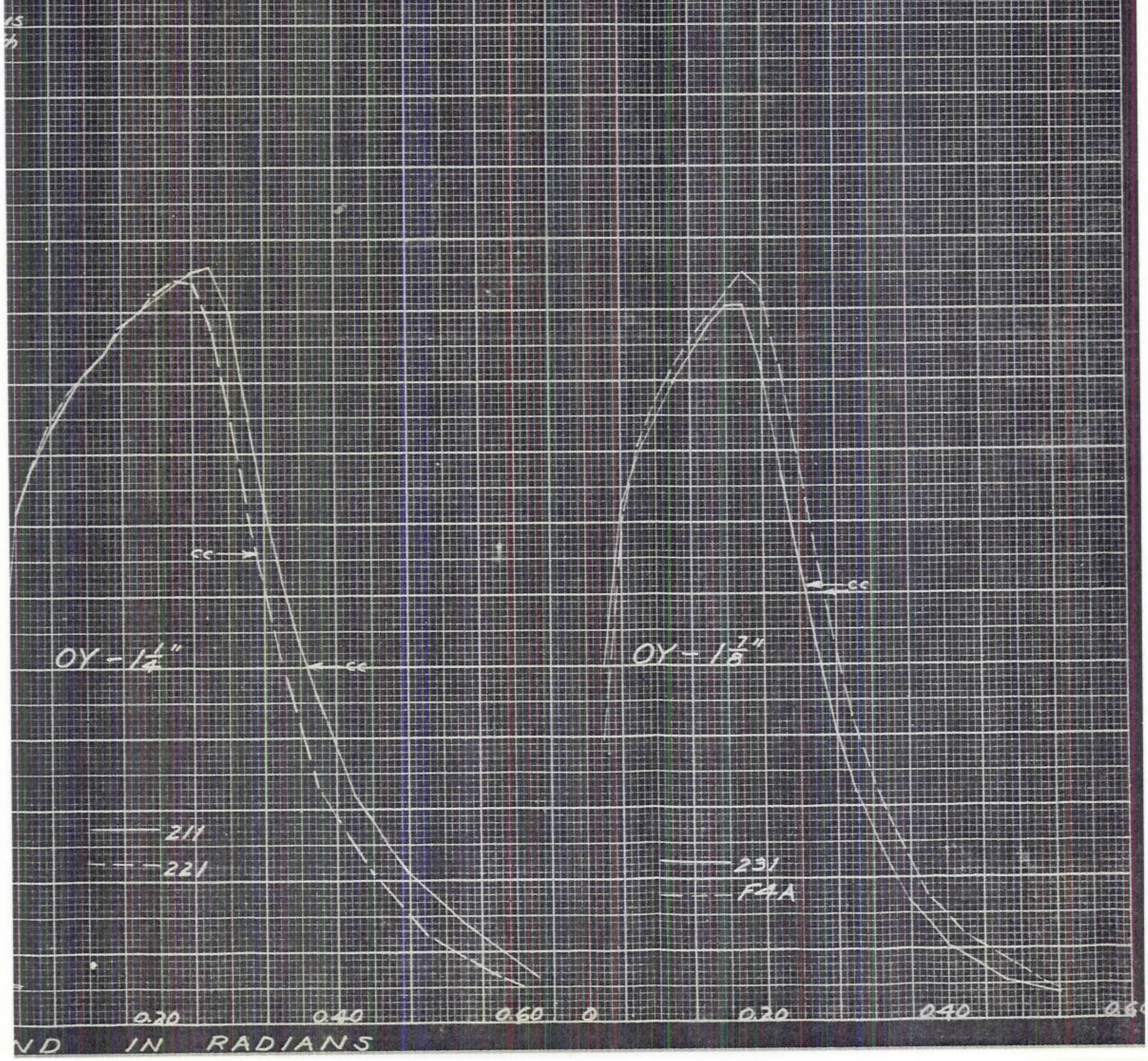

REDUCED MOMENT - M/bd² × 10⁻³ PSI
30
25
20
15
10
25
20
15
10
5
0
0.20
0.40
0.60
0.80
1.00
211d
221c
221d
OY - 0.4"
CORRECT NOTCH
Diam. 0.024"
cc
cc
cc
cc - Crack co
over entir
of notch.
cc
cc
cc
cc
cc
cc
OY - 0.4"
OLD NOTCH
Diam. 0.027"±
213a
221a
221b
211a
211b

FIG. 6. REDUCED MOMENT-ANGLE CURVES FROM BEND TESTS ON 18 IN. CLASS B STEEL 4A443A1. OY SPECIMENS IN TEMPERED BAINITE.

Report No. 25 on Bend
Tests of Ni-Cr. Steel
Univ. of Nor. Carolina
R.M. Trimble, P.E. Shearin
H.N. Michie
Acc. No. 207



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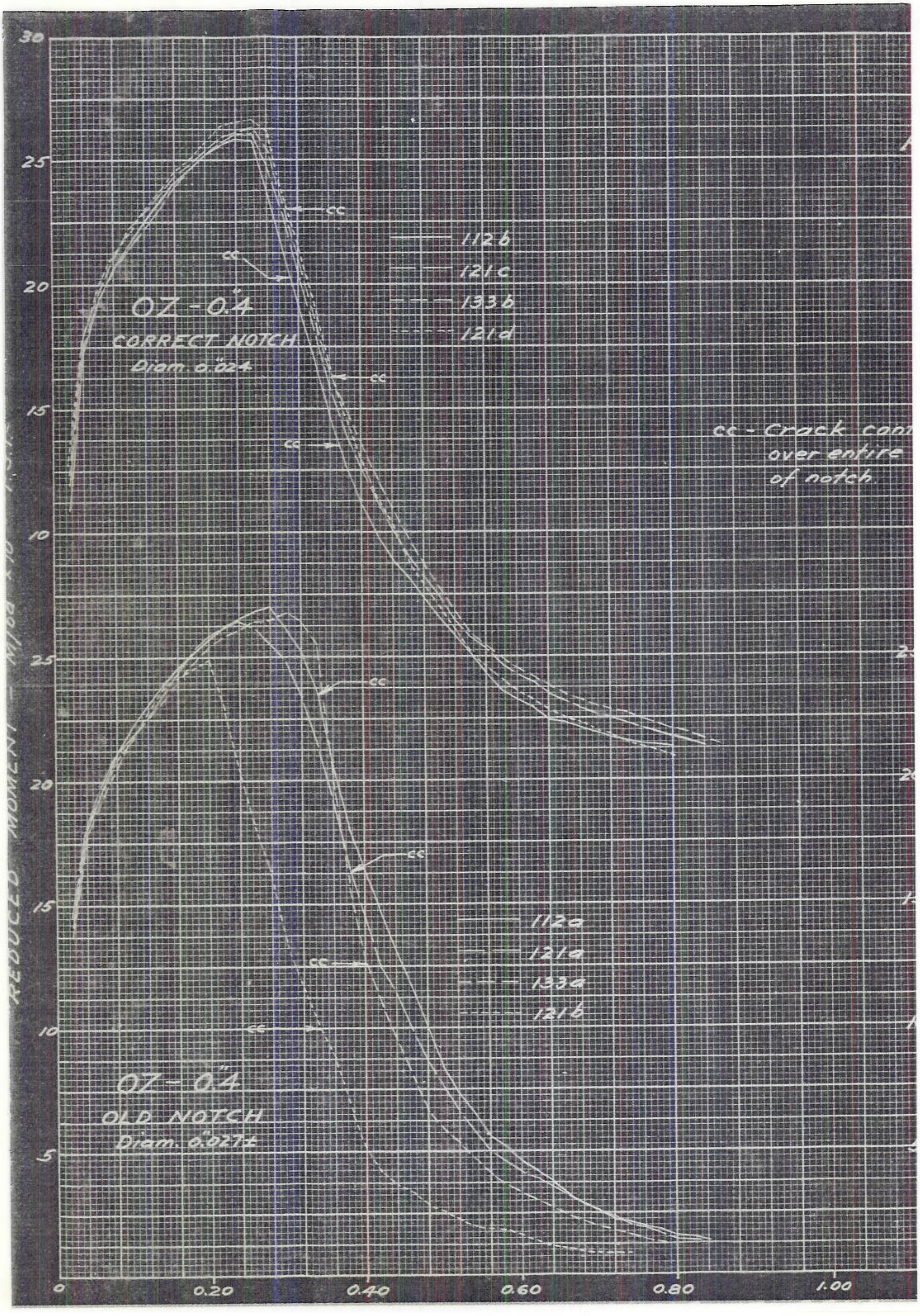
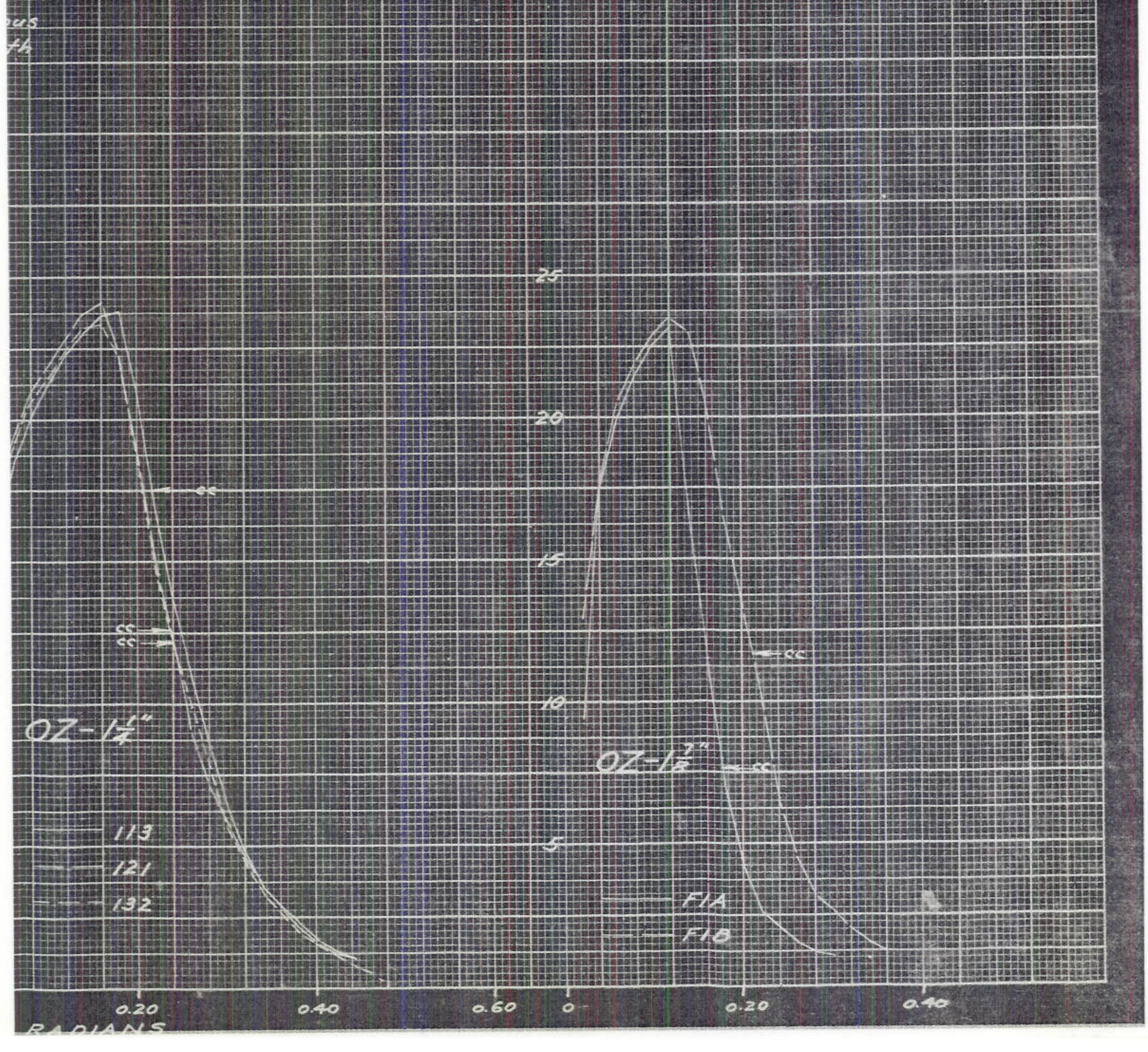
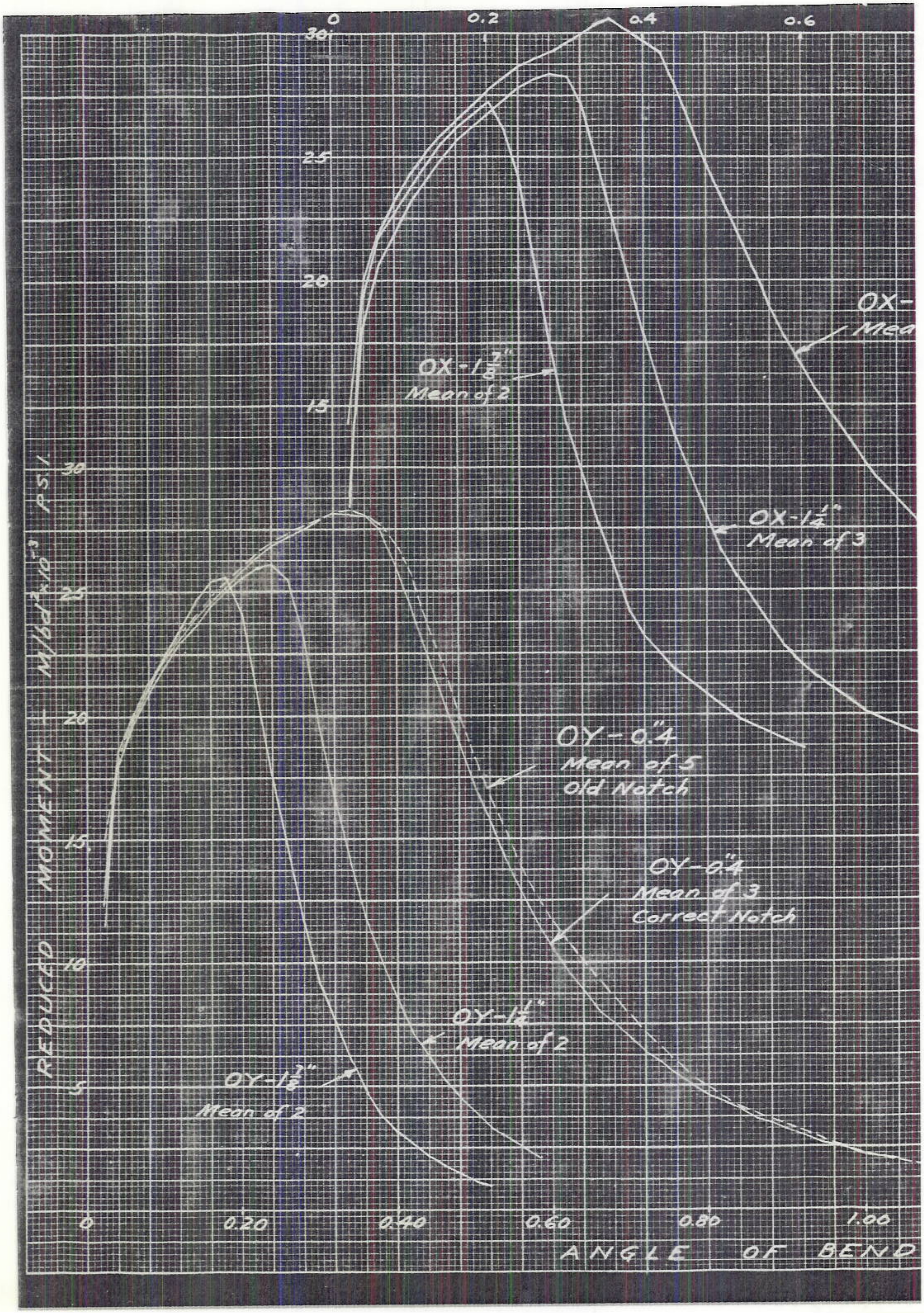


DECLASSIFIED

7 REDUCED MOMENT-ANGLE CURVES FROM BEND TESTS ON 18-IN. CLASS B STEEL 4A443A1. SPECIMEN DIRECTION OZ, IN TEMPERED BAINITE

Report No. 25 on Bend Tests of Ni-Cr steel. Univ. of N.C.
R. M. Trimble, P.E. Shearin
H.N. Michie
Acc. No. 208




0
0.2
0.4
0.6
30
25
20
15
OX-
Mea
OX-1 7/8"
Mean of 2
OX-1 1/4"
Mean of 3
30
25
20
15
10
5
REDUCED MOMENT M/bd² × 10⁻³ P.S.I.
OY-0.4"
Mean of 5
Old Notch
OY-0.4"
Mean of 3
Correct Notch
OY-1 1/4"
Mean of 2
OY-1 7/8"
Mean of 2
0
0.20
0.40
0.60
0.80
1.00
ANGLE OF BEND

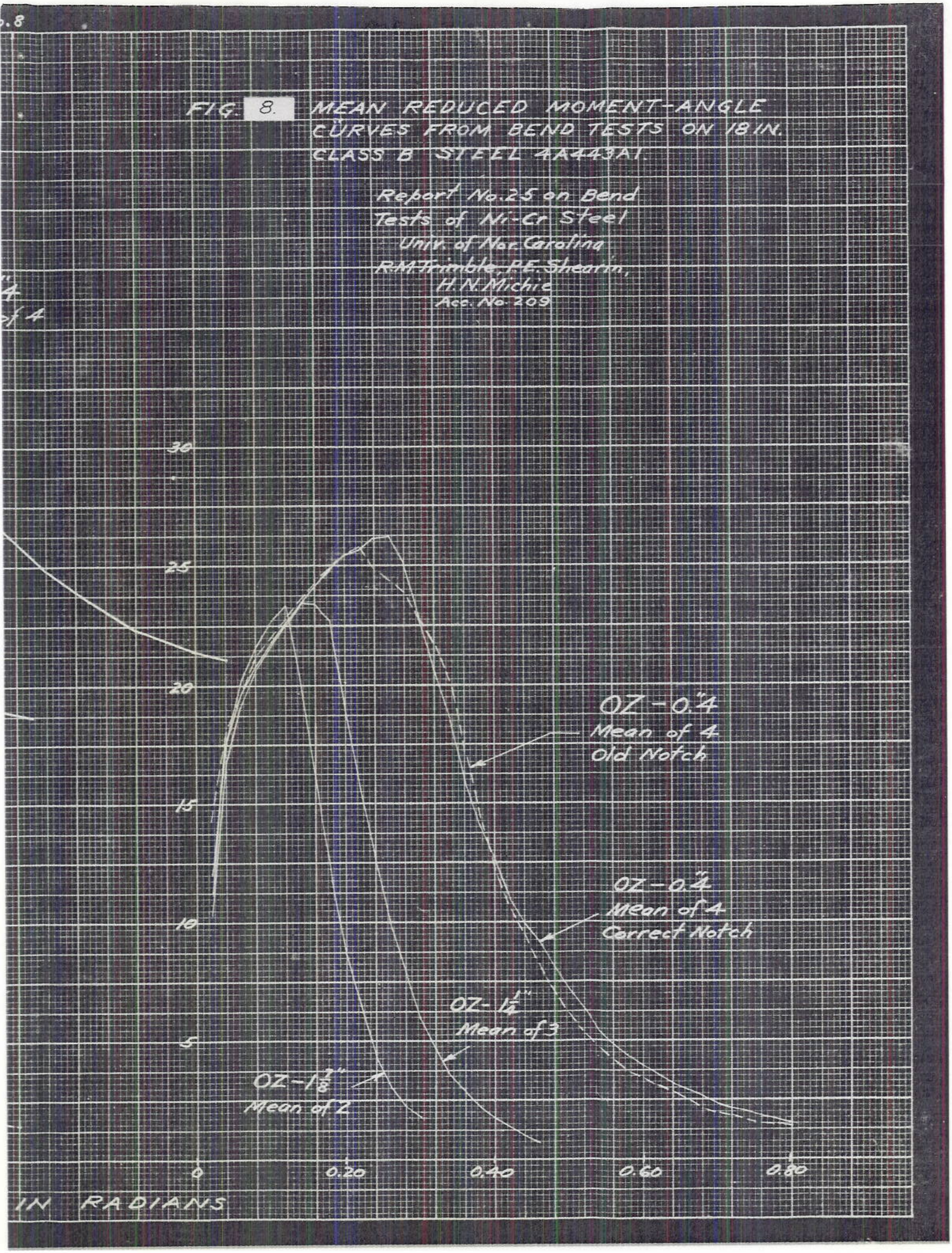


FIG. 8. MEAN REDUCED MOMENT-ANGLE CURVES FROM BEND TESTS ON 18 IN. CLASS B STEEL 4A443A1.

Report No. 25 on Bend
Tests of Ni-Cr Steel
Univ. of Nor. Carolina
R.M. Trimble, P.E. Shearin,
H.N. Michie
Acc. No. 209

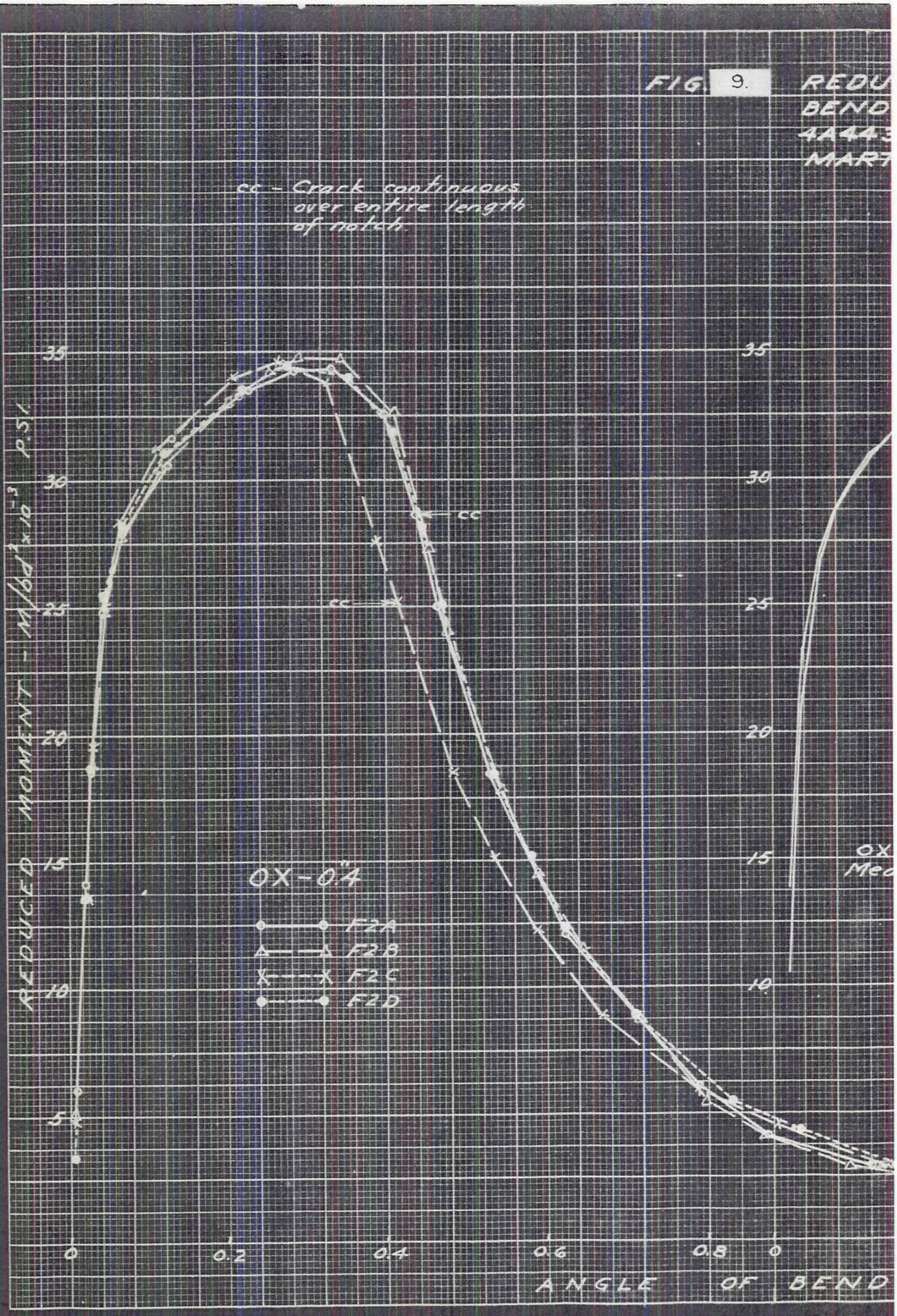
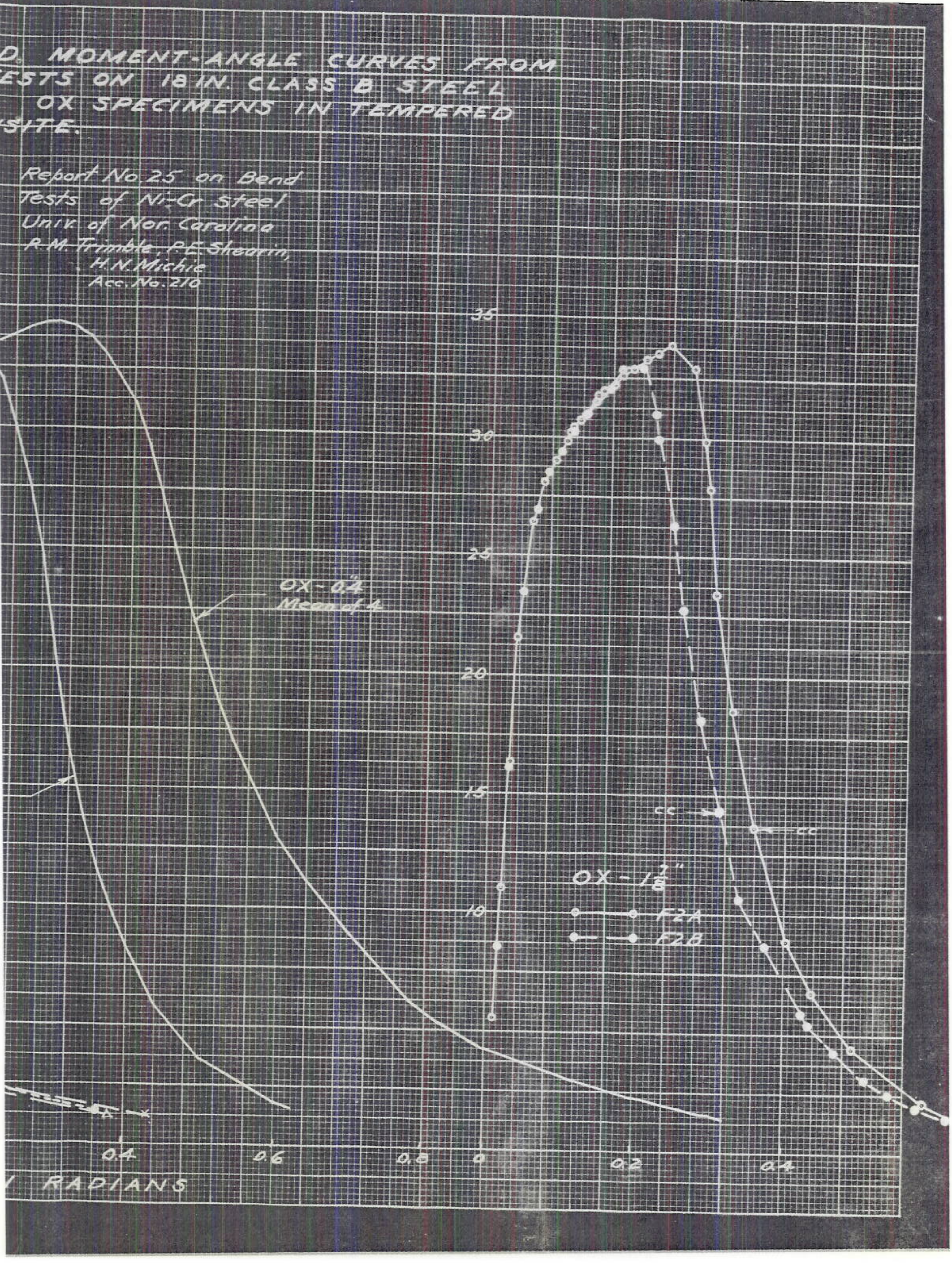


FIG. 9. REDU
BEND
4A443
MART



D. MOMENT-ANGLE CURVES FROM
ESTS ON 18 IN. CLASS B STEEL
OX SPECIMENS IN TEMPERED
SITE.

Report No 25 on Bend
Tests of Ni-Cr Steel
Univ. of Nor. Carolina
R.M. Trimble, P.E. Shearin,
H.N. Michie
Acc. No. 210

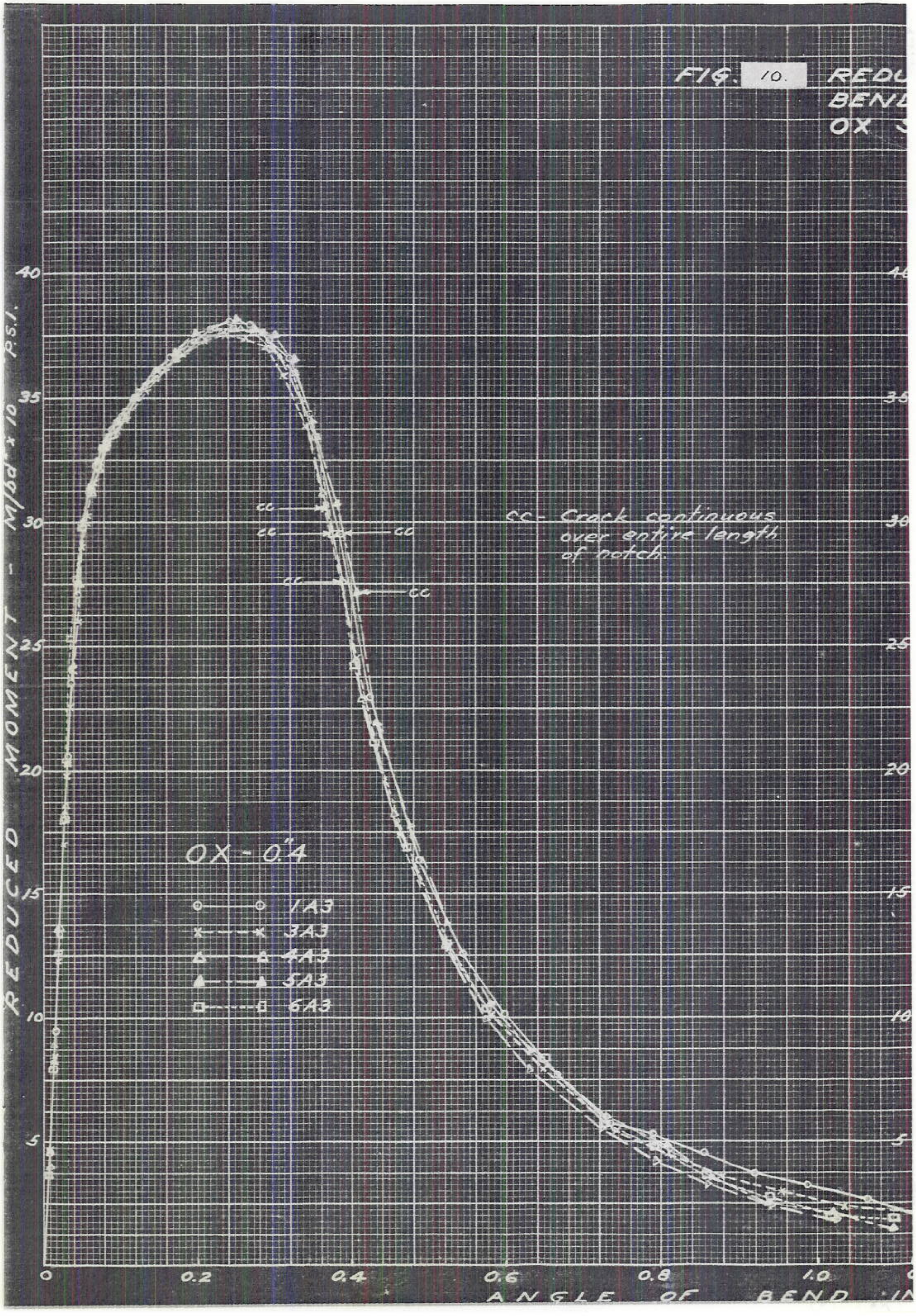
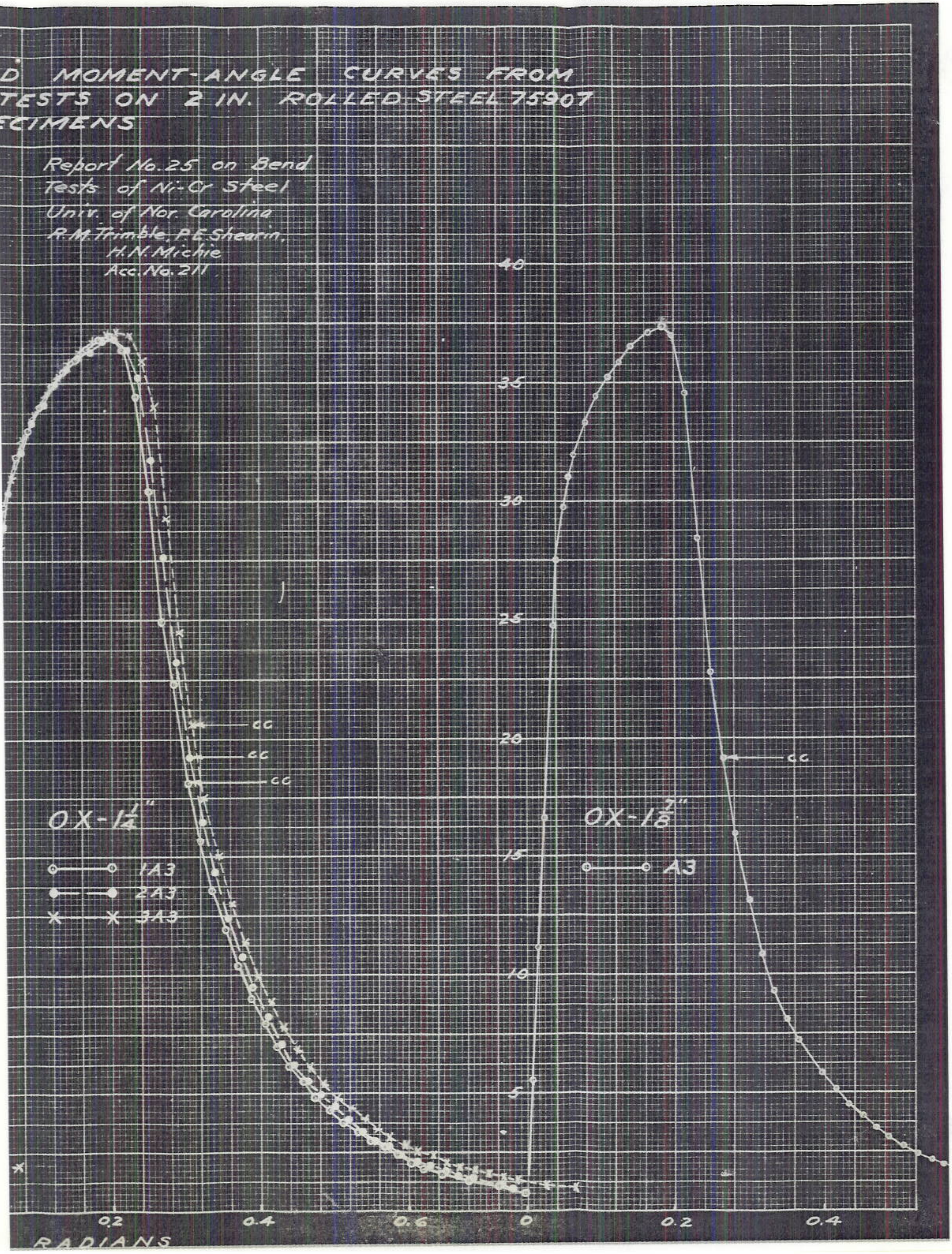


FIG. 10. REDU
BEND
OX

DECLASSIFIED



D MOMENT-ANGLE CURVES FROM
TESTS ON 2 IN. ROLLED STEEL 75907
ECIMENS

Report No. 25 on Bend
Tests of Ni-Cr Steel
Univ. of Nor. Carolina
R.M. Trimble, P.E. Shearin,
H.N. Michie
Acc. No. 211

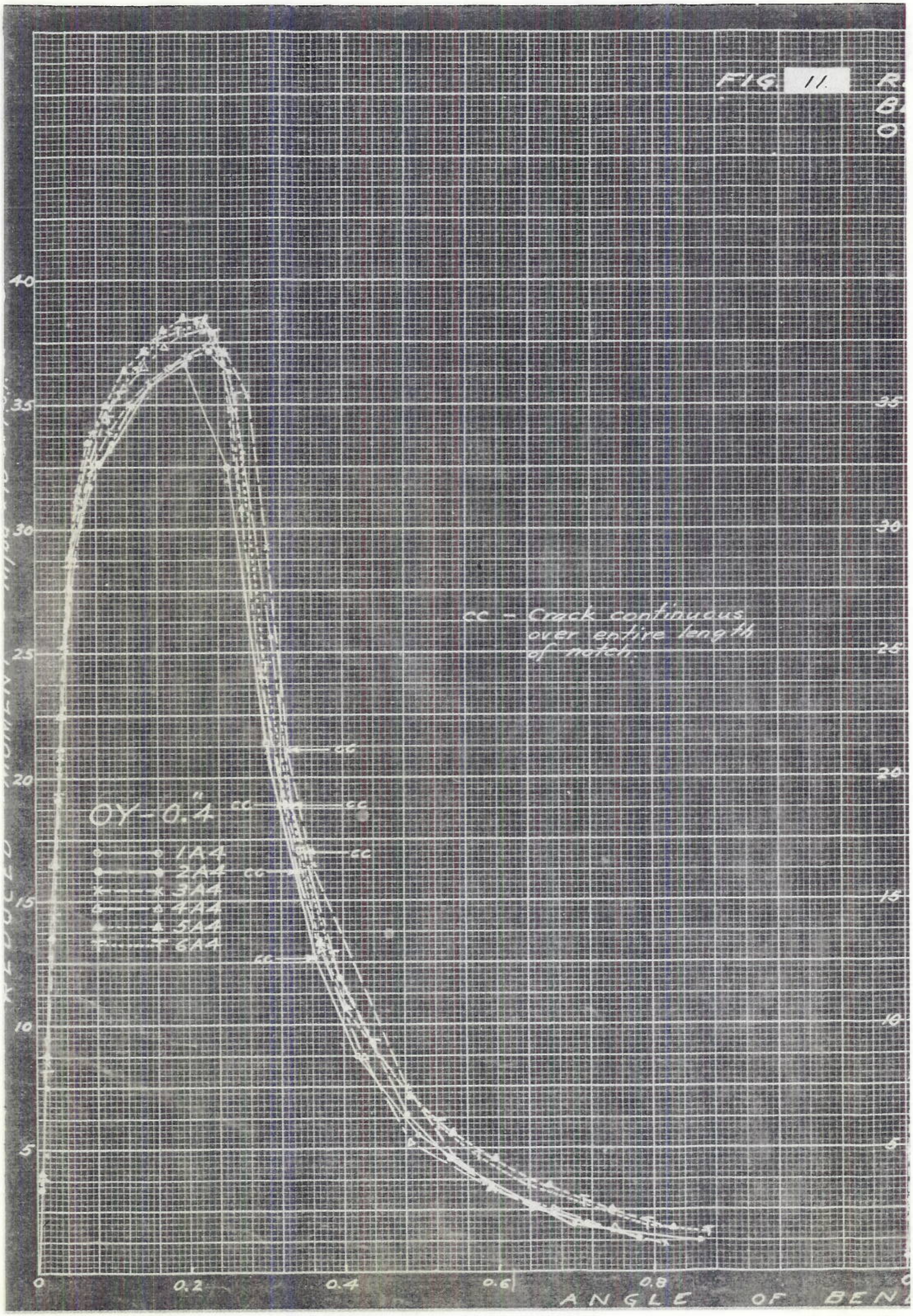
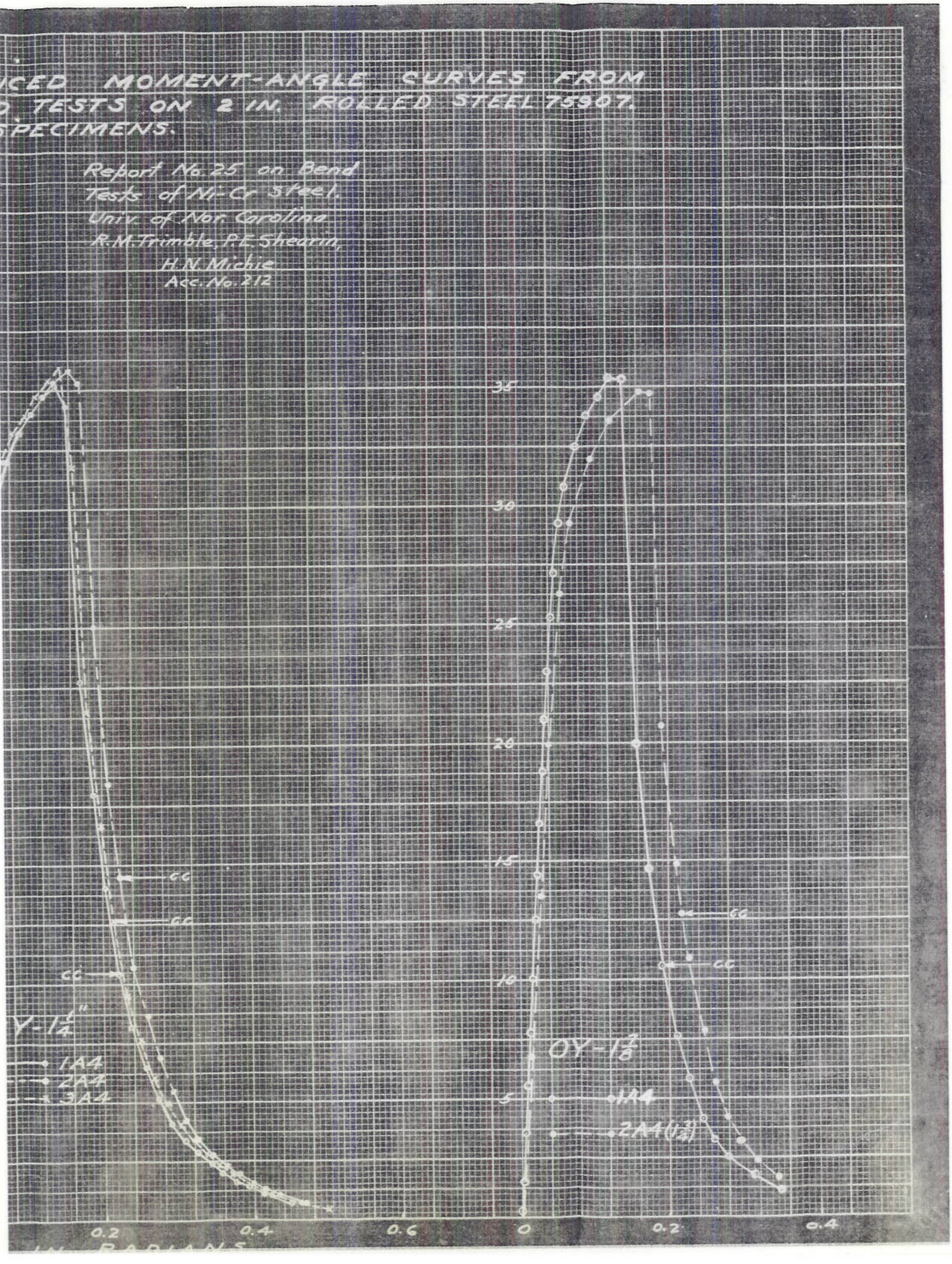


FIG. 11.

cc – Crack continuous over entire length of notch.
OY-0.4"
1A4
2A4
3A4
4A4
5A4
6A4
cc
cc
cc
cc
cc
cc
REDUCED MOMENT
ANGLE OF BEN
0
0.2
0.4
0.6
0.8
5
10
15
20
25
30
35
40

DECLASSIFIED



DECLASSIFIED

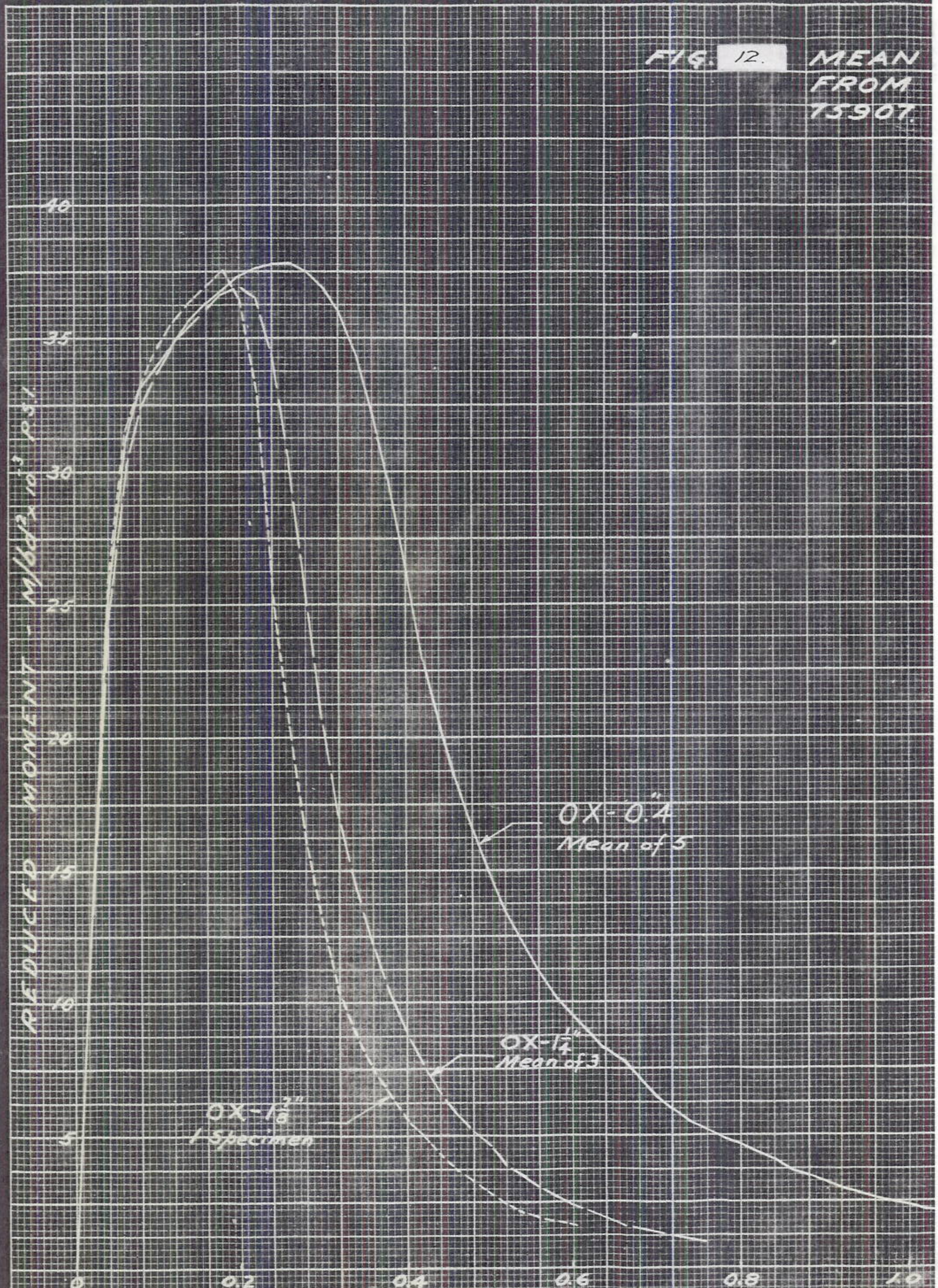
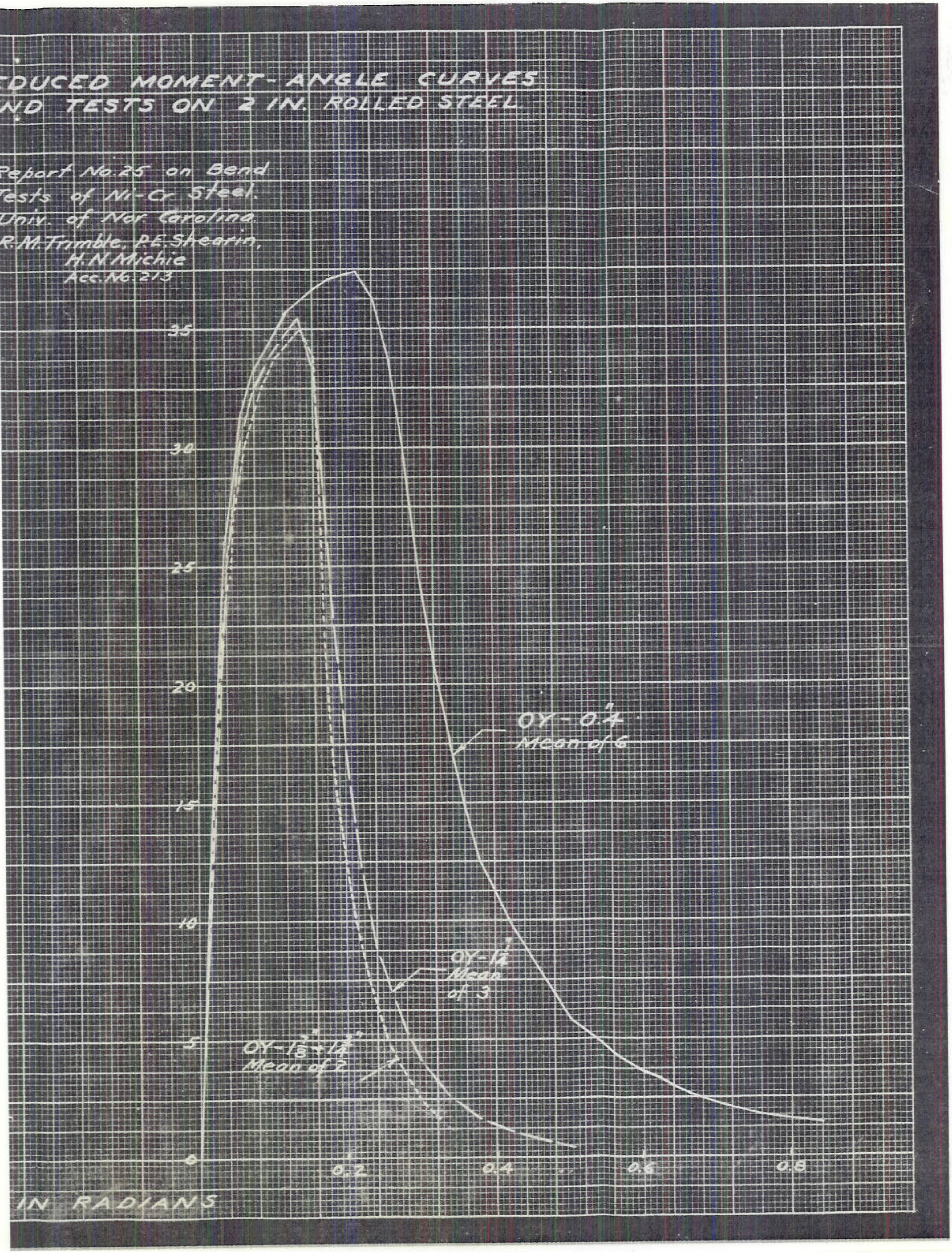


FIG. 12. MEAN FROM 75907.


EDUCED MOMENT-ANGLE CURVES
ND TESTS ON 2 IN. ROLLED STEEL
Report No.25 on Bend
Tests of Ni-Cr. Steel.
Univ. of Nor. Carolina
R.M.Trimble, P.E.Shearin,
H.N.Michie
Acc.No.213
35
30
25
20
15
10
5
0
0.2
0.4
0.6
0.8
IN RADIANS
OY-0.4"
Mean of 6
OY-1¼"
Mean
of 3
OY-1⅜"+1¾"
Mean of 2

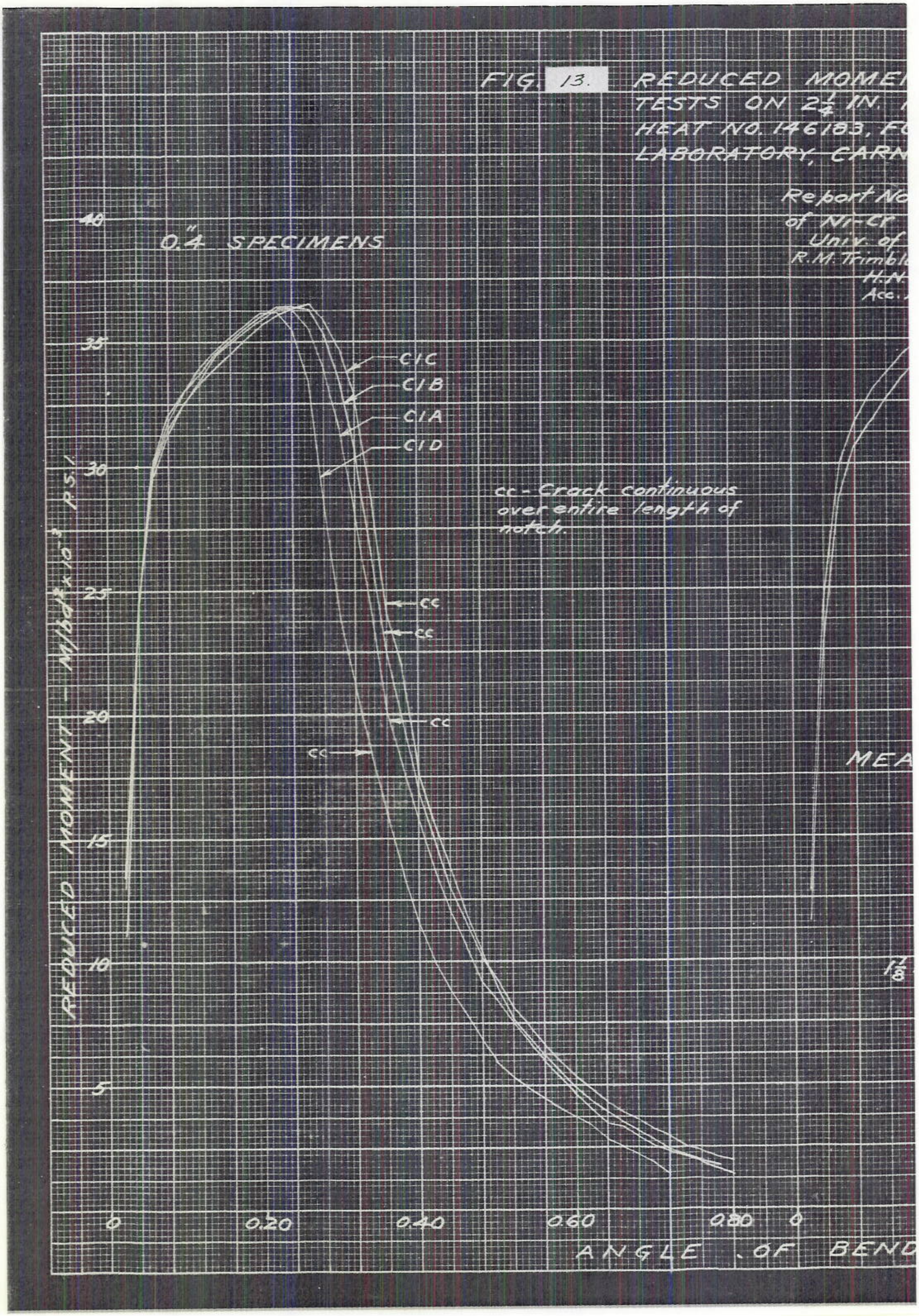
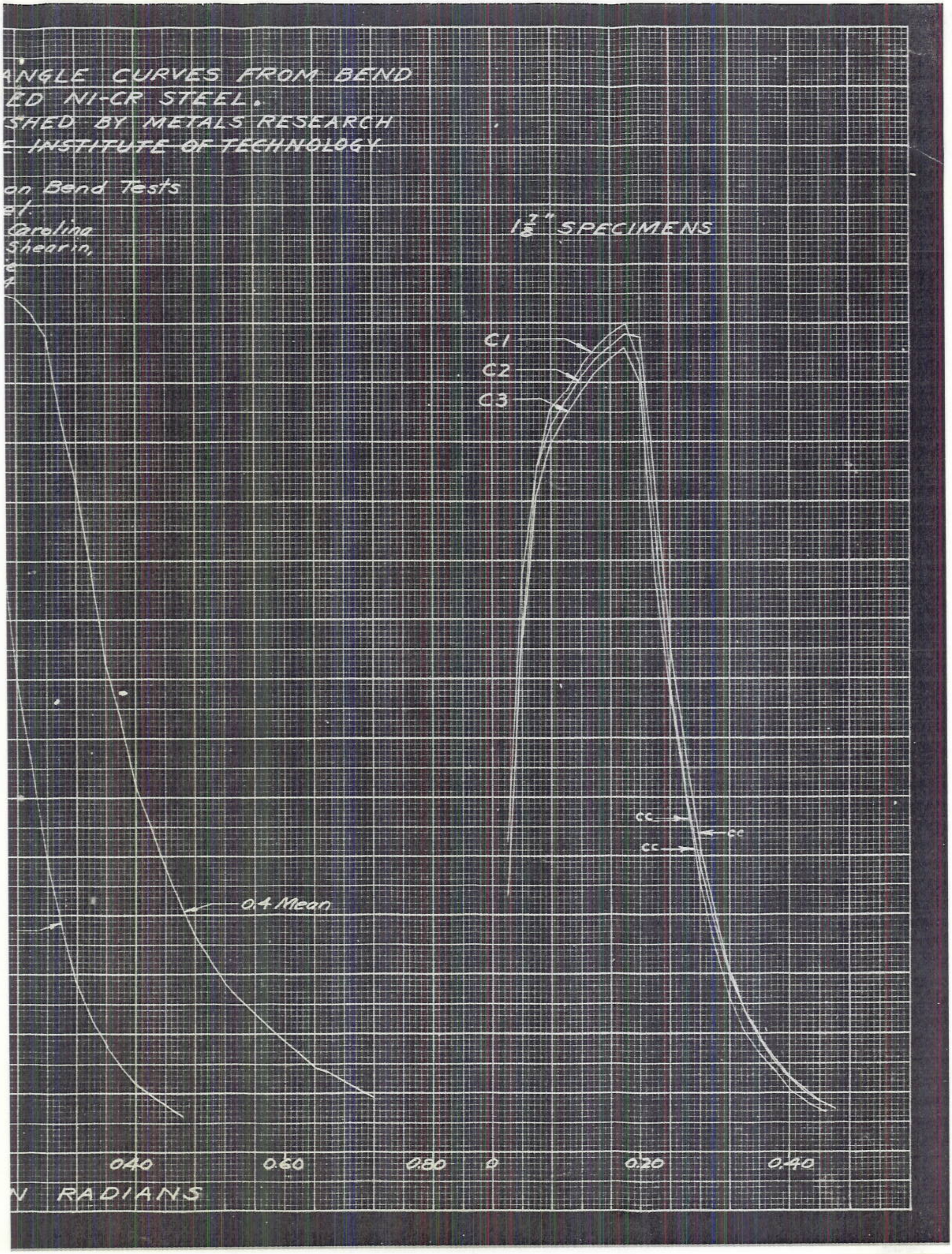


FIG. 13. REDUCED MOME
TESTS ON $2\frac{1}{4}$ IN.
HEAT NO. 146183, F
LABORATORY, CARN

Report No
of Ni-Cr
Univ. of
R.M. Trimbl
H.N.
Acc.

cc - Crack continuous over entire length of notch.



ANGLE CURVES FROM BEND
ED NI-CR STEEL.
SHED BY METALS RESEARCH
E INSTITUTE OF TECHNOLOGY

on Bend Tests
el.
Carolina
Shearin,
e
4

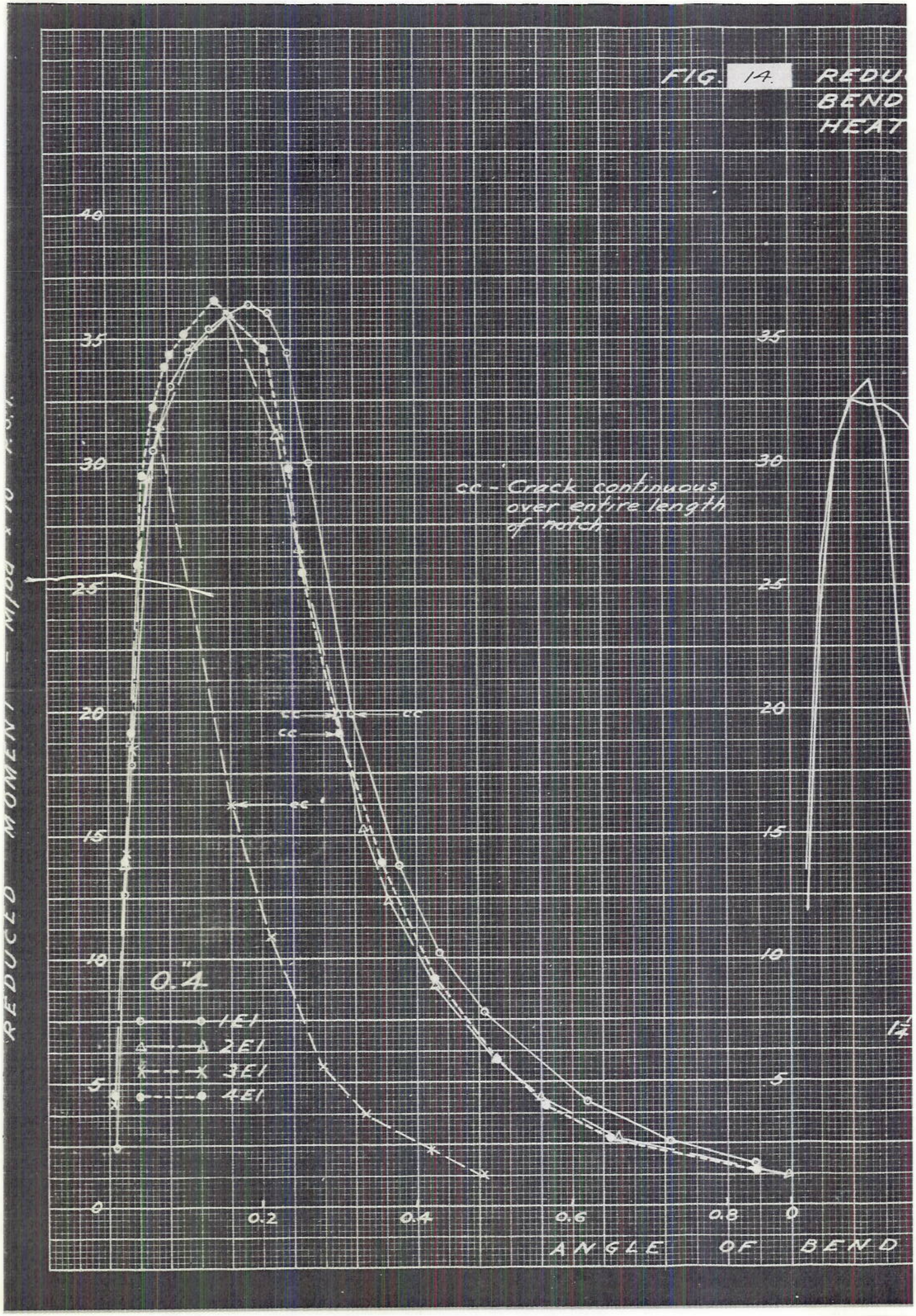
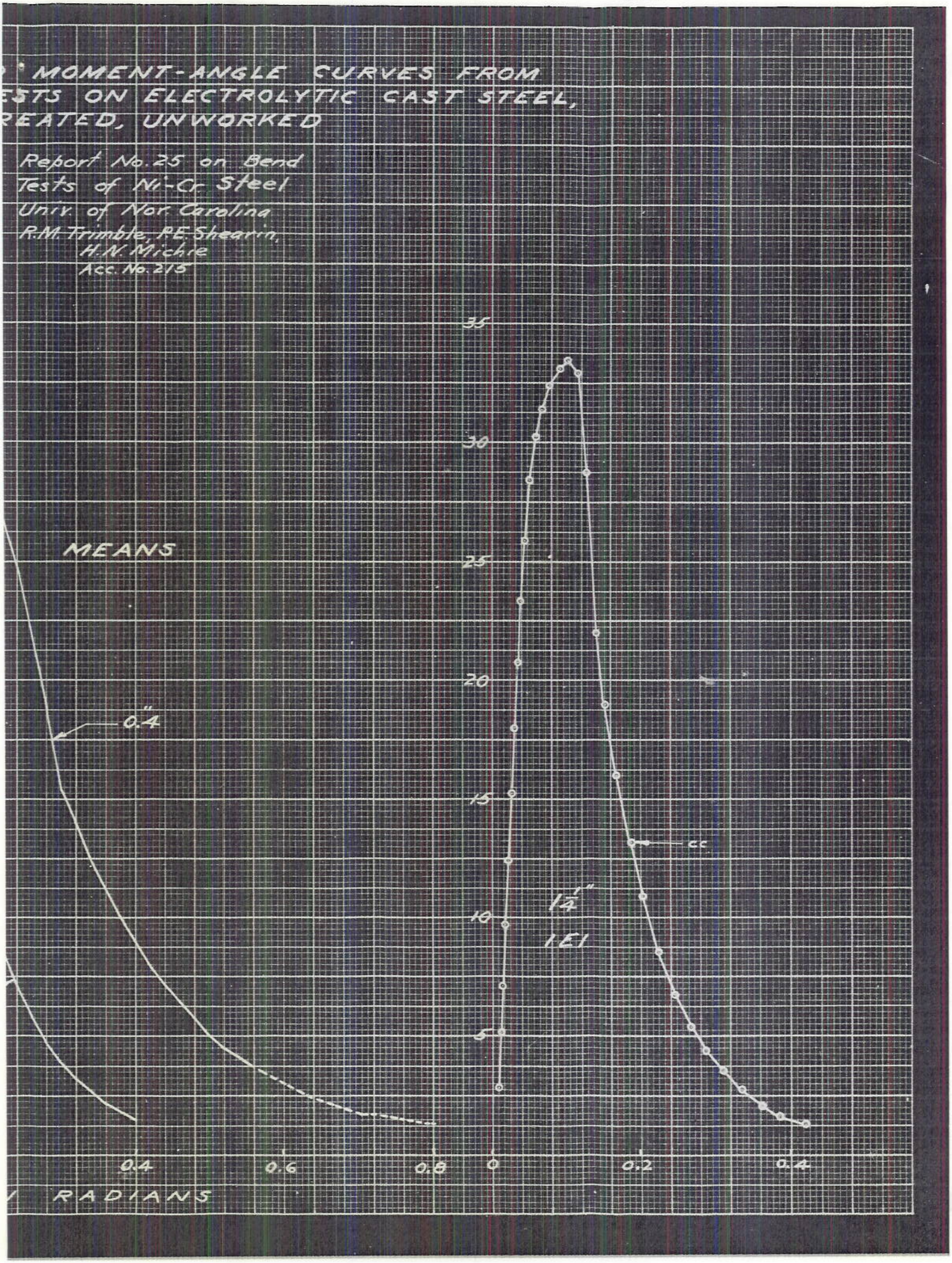
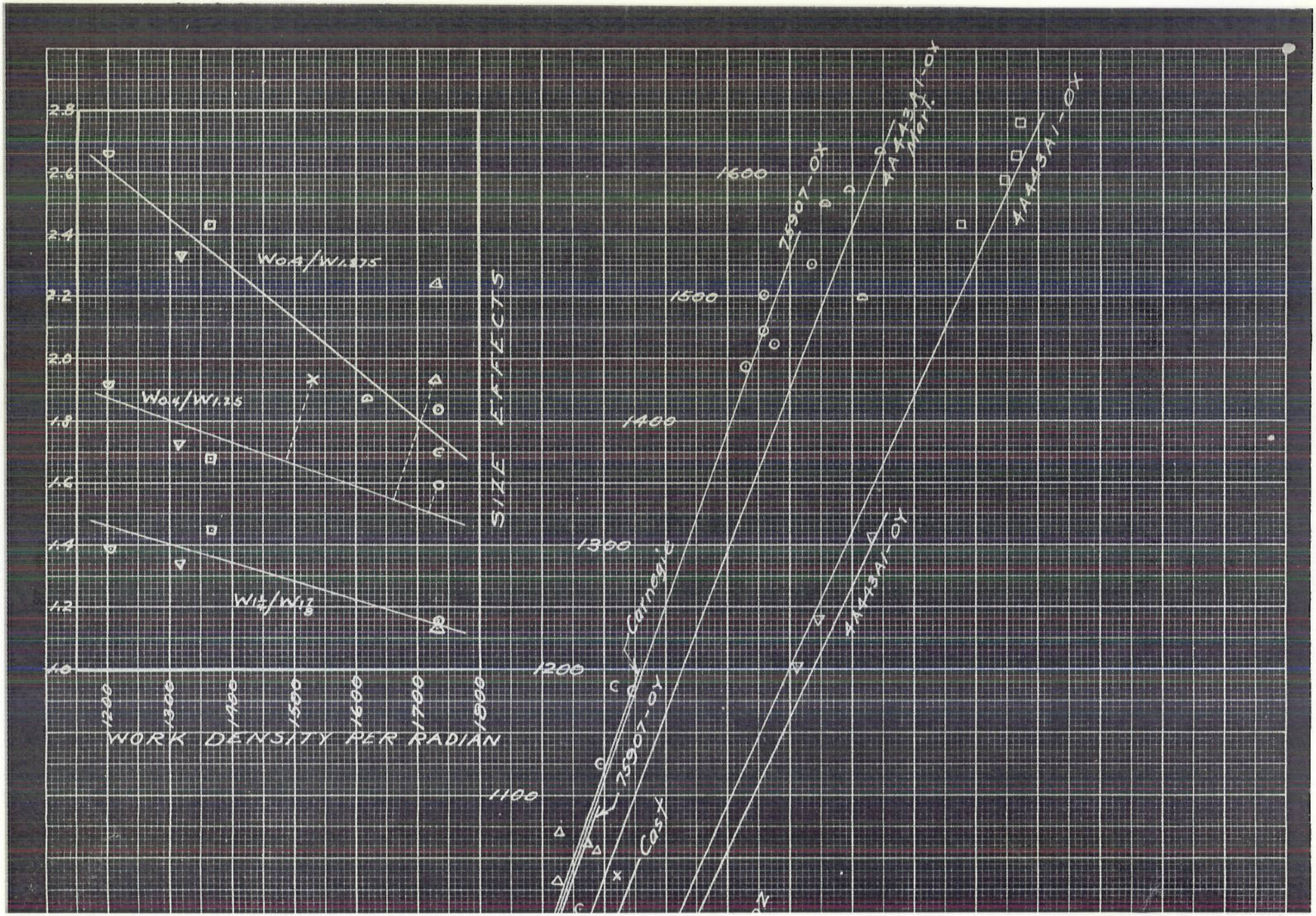


FIG. 14. REDU
BEND
HEAT


MOMENT-ANGLE CURVES FROM
ESTS ON ELECTROLYTIC CAST STEEL,
REATED, UNWORKED
Report No. 25 on Bend
Tests of Ni-Cr Steel
Univ. of Nor. Carolina
R.M. Trimble, P.E. Shearin,
H.N. Michie
Acc. No. 215
MEANS
0.4"
35
30
25
20
15
10
5
cc
1¼"
1E1
0.4
0.6
0.8
0
0.2
0.4
RADIANS


SIZE EFFECTS
WORK DENSITY PER RADIAN
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
1200
1300
1400
1500
1600
1700
1800
W0A/W1.375
W04/W1.25
W1¼/W1⅞
1100
1200
1300
1400
1500
1600
75907-OX
4A443A1-OX
Mart.
4A443A1-OX
4A443A1-OY
Carnegie
75907-OY
Cast

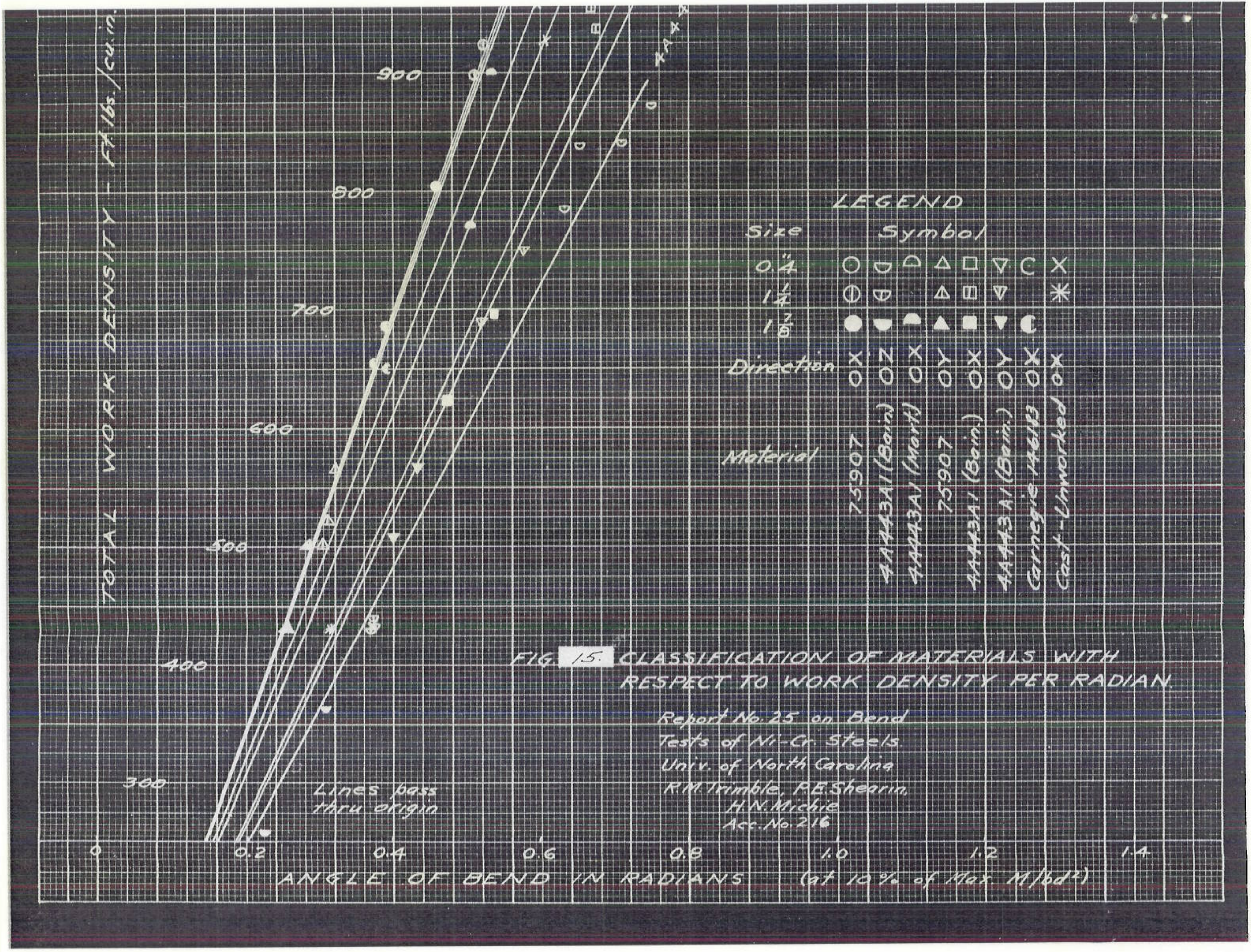


FIG. 15. CLASSIFICATION OF MATERIALS WITH RESPECT TO WORK DENSITY PER RADIAN.

Report No. 25 on Bend
Tests of Ni-Cr. Steels.
Univ. of North Carolina
R.M. Trimble, P.E. Shearin,
H.N. Michie
Acc. No. 216

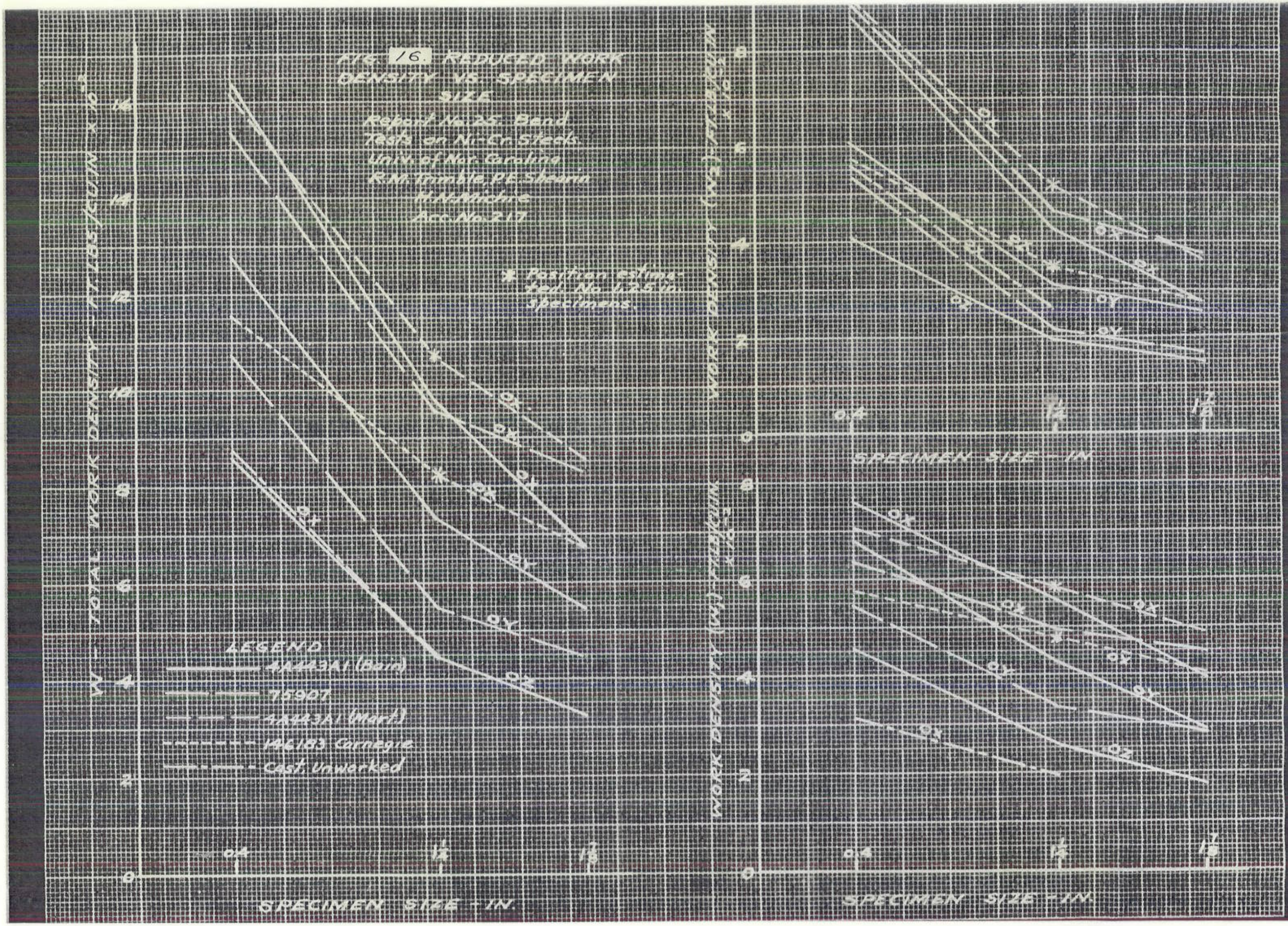


FIG. 16. REDUCED WORK DENSITY VS. SPECIMEN SIZE

Report No. 25. Bend Tests on Ni-Cr. Steels
Univ. of Nor. Carolina
R.M. Trimble, P.E. Shearin
H.N. Mitchie
Acc. No. 217

* Position estimated. No 1.25 in. specimens.

DECLASSIFIED

REPORT NO. 0-2298

Date 29 May 1944

FR-2298

SECRET

Report on

INFLUENCE OF ELECTRIC FIELD ON AERODYNAMIC DRAG COEFFICIENT

DECLASSIFIED by NRL Contract
Declassification Team
Date: 11 AUG 2016
Reviewer's name(s): A. THOMPSON, P. HANNA
Declassification authority: NAVY DECLASS MANUAL, 11 DEC 2012, 02 SERIES

by

Ross Gunn

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