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METALLURGY DIVISION SPECIAL ALLOYS SECTION

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PROPERTIES OF QUENCHED AND TEMPERED HTS PLATE

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by

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Approved for Public Release

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NRL Problem No. M95
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ABSTRACT

Steels of the HT grade of Specification 48S5 are used for ship construction in the as-rolled condition and as such possess relatively low resistance to impact at low temperatures (high transition temperature). In an effort to improve their tensile and notch toughness characteristics steels of this analysis were quenched and tempered and the results of tensile and notched bar tests show that yield strengths of 70,000 p.s.i. are obtainable in most of the steels at tempering temperatures in the vicinity of 1000°F and that the transition temperature is lowered about 70°C (158°F) at this yield strength level. Nick-bend weldability tests on the heat treated material show an improvement in fracture characteristics over the as-rolled steel but a slight loss in the ductility as measured by the angle at maximum load.

Introduction

1. The investigation of the properties of quenched and tempered hi-tensile steel was authorized by BuShips letter JJ46-1-(25)(334) of 9 November 1945.

Statement of Problem

2. Steel of the HT grade of Specification 48S5 is used in the construction of ships in the as-rolled, or "as-received" condition. An interest in obtaining higher levels of yield strengths and improved notch toughness characteristics without sacrifice in weldability prompted the investigation of the uenched and tempered properties of this particular grade of Navy steel.

Known Facts and Theoretical Considerations

3. It is generally known that heat treatment (quenching and tempering) will im rove the mechanical properties of steels and that tempering at high tempering temperatures results in low-temperature toughness (low transition temperature). However, quantitative data on steels of the HT analysis are lacking.

Narrative of Original Work Done at this Laboratory

4. Eleven steels of varying thicknesses were selected to cover composition ranges above, below and within the specification limits of the HT type steel. Their chemical analyses are shown in Table 1. These steels were quenched and tempered to four hardness levels produced by tempering two hours at 600, 800, 1000 and 1200°F. The mechanical properties, low-temperature impact, and welded properties were determined.

Methods

5. For all tests except those on weldability plates measuring 6" x 8" were uenched from 1650°F. in a jig to ensure constant quench conditions throughout the investigation. This jig is shown in Plate 1. The water enters the bottom and then passes through two displaced screens in order to ensure lamellar flow over the entire depth of the jig. The water flow is measured by a manometer attached to a pitot tube at the water inlet.

6. A distance equal to the plate thickness was sawed off the four edges of the plates after heat treatment and before sawing out the tensile specimen blanks. This was done to eliminate "edge effect". Individual blanks from each steel were then tempered two hours at 600, 800, 1000 and 1200°F. and water-quenched from these tempering temperatures.

7. The transverse tensile properties were obtained by using the strip-type tensile specimen shown in Plate 2 since a conventional .505" diameter round specimen machined from the center of a quenched and tempered plate would not include the hardened areas of the plate. The strip-type specimen was chosen because it includes the entire thickness of the heat treated plate. Yield strengths were obtained at 0.2 percent offset.

8. The impact studies were made using the Charpy V-notch type specimen cut longitudinally to the direction of rolling. The notches were machined perpendicular to the plate surfaces. Preliminary studies on the effect of notch location (Plate 3) showed that this type of notch location produced the most reproducible impact strengths and fracture types.

9. The notches of representative specimens from each steel were examined at 50X and compared with a template of the notch. It was found that notch radii varied only slightly and in no cases were notch contours sufficiently disturbed to warrant rejection of the specimen.

10. Transition temperature curves were obtained for the steels in the "as-received" and in the quenched and tempered conditions. Four tempering temperatures, 600, 800, 1000 and 1200°F. were used and the tempering treatment was followed by a water quench. About thirty impact specimens were broken for each curve, duplicate specimens being broken at each testing temperature. At temperatures where a spread in impact values was noticed, five or six specimens were broken. The averages of the readings were plotted on the curves. The deviation from the average for all specimens in all series broken in the brittle range near the "knee" of the transition curve was $\pm$ 8 percent and increased to $\pm$ 16 percent at temperatures midway between the high and low energy levels.

11. The specimens broken at temperatures above room temperature were heated in baths of hot water or hot oil. Temperatures below room temperature were obtained using either alcohol and dry ice or isopentane and liquid air. All specimens were held within 2°C. of the testing temperature for a minimum of 5 minutes and then at

the testing temperature for a minimum of 3 minutes before quickly removing them from the bath to the Amsler impact testing machine for breaking. The estimated time for transfer from the bath to the moment of impact was 6 seconds.

12. Charpy specimens from each of the steels were treated to determine their susceptibility to temper brittleness. Samples of four of the heat treated steels were air-cooled after tempering 2 hours at 800°F. The temperature range of the onset of brittleness was obtained. For the remaining steels samples which had been originally water quenched from the tempering temperature of 1000°F. were reheated to 1000°F and allowed to furnace cool. All the specimens in this group were broken at 0°C. and their energy levels and fracture characteristics compared with the original series broken at the same temperature.

13. For evaluating weldability plates measuring 8" x 12" were water-quenched from 1650°F. in a commercial quenching tank and then tempered at 1200°F. for two hours followed by a water quench. These plates were then subjected to the standard NRL Nick-Bend Test procedure (1). Airco 78E welding rods, 3/16", in diameter, were used at 175 amperes, 26½ volts, reverse polarity and 6" travel per minute. The weld bead was deposited transverse to the direction of rolling. Duplicate specimens of welded and unwelded plates in both the as-received and heat treated condition were broken. Load-deflection curves were recorded for each specimen and compared with the series of standards shown on Plate 4.

Data Obtained and Discussion

14. The tensile properties and representative photomicrographs (the latter taken near the surface of the plates) of the eleven steels are shown in Plates 5 through 15. It is evident that those steels having an analysis above and close to the maximum in the present 48S5 Specification will give yield strengths above 70,000 p.s.i. after quenching and tempering at temperatures up to 1000°F. Two exceptions to this are steels No. 396 and No. 527 whose yield points fall below 70,000 p.s.i. at tempering temperatures of 1000 and 800°F., respectively. It is believed that these steels did not respond properly to the heat treatment even though their chemical analyses are such that good response is indicated. Those steels below the specification did not respond to heat treatment and will require a more drastic quench than given them in this investigation.

15. Six of the steels, namely 492, 577, 394, 396, 494 and 333

exhibit anamalous yield strength behavior as affected by tempering temperature. The yield strengths for these steels appear to be lower at the lower tempering temperatures than would normally be expected. Another series of bars was pulled to check this behavior and produced the same results.

16. The notched bar impact test results are given in Plates 17 through 28. An attempt was made to isolate the temperature of the onset of brittleness to a temperature range of about 10°C. Accordingly each curve is presented with two letters, D and B. These letters represent, respectively, the temperature of the last appearance of a completely ductile fracture and the temperature of the first appearance of a partially brittle fracture. The improvement in transition temperature as a result of quenching and tempering at 1000 or 1200°F. amounts to an average lowering of about 70°C. (158°F.). An attempt to correlate chemical analysis, hardness, tensile strength and other variables with transition temperature failed. This was ascribed to such unknown factors as process variables, age and strain hardening rates, variations in hardenability, etc. Table 3 gives a compilation of the data showing the change in the temperature of the onset of brittleness. This is given by a range of temperatures, the first temperature being the temperature of the last completely ductile fracture, the second being the first appearance of a partially brittle fracture. The next column gives the average of this range and the last column the temperature at which an impact value of 15 foot-pounds is attained.

18. The results of the temper brittleness series (Table 4) show that only one of the eleven steels, No. 577, is temper brittle. This is evident from the upward shift of about 21°C. (70°F) in transition temperature for the air-cooled specimens compared with the specimens water-quenched from the tempering temperature. The remaining steels show no embrittlement due to furnace or air-cooling after the draw. However, the tempering temperature of 800°F which was used on four of the steels may have been too low to indicate any susceptibility to temper brittleness.

19. The results of the Nick-Bend tests are given in Table 2. In the unwelded condition the bend characteristics of the heat treated plate specimens generally show higher maximum loads than the as-received specimens. The angle at maximum load is slightly reduced, however, indicating a slight loss in ductility. The failure types are in some cases improved by heat treatment.

20. The as-received plates after welding show serious losses in ductility and changes in failure types. If the angle at maximum

load is used as the criterion for evaluating weldability, the quenched and tempered material is slightly inferior to the as-received material. However, the failure type must also be considered in this evaluation. Heat treatment of the material has obviously lowered the temperature of transition from ductile to brittle failure and, therefore, guards against the occurrence of a brittle failure as influenced by other features such as notch conditions, geometry of the structure, increased strain rates and a decrease in the temperature at which the structure is used.

Conclusions and Recommendations

22. Quenching and tempering of steels of an analysis covered by Specification 48S5, HT grade, improves the yield and tensile strengths. A yield of 70,000 p.s.i. is obtainable in most of the steels when tempering temperatures as high as 1000°F. are used. The transition temperature is lowered about 70°C. (158°F) when tempering temperature of 1000 or 1200°F are used. Certain welded properties of the heat treated plates are slightly inferior to those of the welded as-received plates, but the heat treated plates exhibit improved failure types and fracture characteristics.

23. It is recommended that additions of other alloying elements in small percentages, such as nickel or molybdenum, be added to the basic 48S5 composition for the purpose of improving the hardenability to facilitate "through hardening" and better uniformity of structure throughout the plate thickness. It is felt that this will ensure maximum physical properties in the plates.

Acknowledgement

24. The authors wish to express their gratitude to George G. Luther and W. Eugene Ellis for direction and assistance in making the weldability tests.

Table 1

Chemical Analyses

Steel No.	Nominal Thickness In.	C	Mn	Si	P	S	Cr	Ni	Mo	Cu	V	Ti*	Al*
594	1¼	0.16	1.21	0.32	0.028	0.04	0.09	0.16	0.02	0.15	0.04	0.014	0.005
492	1¼	0.16	1.28	0.30	0.020	0.020	0.08	0.08	0.02	0.10	0.005	0.015	0.02
601	1¼	0.15	0.88	0.19	0.028	0.038	0.08	0.20	0.015	0.07	0.028	0.012	0.01
577	1	0.17	0.99	0.22	0.017	0.015	0.04	0.10	0.02	0.13	0.03	0.005	0.01
394	1-1/8	0.17	1.30	0.23	0.031	0.023	0.21	0.03	0.005	0.04	0.005	0.028	0.023
396	1	0.16	1.37	0.24	0.020	0.027	0.19	0.07	0.005	0.015	0.005	0.03	0.023
527	1	0.17	1.30	0.22	0.016	0.026	0.05	0.03	0.01	0.02	0.005	0.05	0.01
531	1	0.17	1.52	0.36	0.028	0.026	0.08	0.07	0.01	0.16	0.005	0.02	0.019
494	7/8	0.22	1.57	0.24	0.024	0.02	0.20	0.21	0.01	0.20	0.005	0.017	0.01
504	1	0.14	1.20	0.24	0.023	0.033	0.03	0.05	0.01	0.02	0.005	0.02	0.01
333	1	0.18	1.12	0.17	0.017	0.025	0.04	0.12	0.02	0.22	0.005	0.005	0.015

* Total Ti
Acid Soluble Al

Table 2

Nick-Bend Test Results

Steel No.	Specimen Condition	Maximum Load-Lbs.	Angle at Max. Load Degree	Failure Type	Remarks
	As Rec'd - Plate	27,250	71	A1	
	As Rec'd - Plate	26,400	63.5	A1	
	As Rec'd - Welded	22,975	24	C2	Brittle Fracture
	As Rec'd - Welded	21,750	18	C2	Brittle Fracture
594	HT* - Plate	29,600	55	A1	
	HT* - Plate	30,125	57	A1	
	HT* - Welded	26,000	23	A1	
	HT* - Welded	25,050	19	A1	
	As Rec'd - Plate	28,050	66	A1	
	As Rec'd - Plate	27,900	66	A1	
	As Rec'd - Welded	26,725	43	B2	
492	As Rec'd - Welded	26,200	38	B2	
	HT - Plate	29,650	61.5	A1	
	HT - Plate	29,550	64.5	A1	
	HT - Welded	27,950	31	A1	
	As Rec'd - Plate	27,460	59	B2	Brittle Fracture
	As Rec'd - Plate	27,500	63	B1	
	As Rec'd - Welded	24,700	37	B2	Borderline C2 Failure
601	As Rec'd - Welded	23,750	30	B2	" "
	HT - Plate	30,250	61.5	A1	
	HT - Plate	30,200	65.5	A1	
	HT - Welded	25,350	34	A1	
	HT - Welded	25,050	35	A1	
	As Rec'd - Plate	16,800	66	A1	
	As Rec'd - Plate	17,550	68.5	A1	
	As Rec'd - Welded	17,125	46.5	B2	Brittle Fracture
	As Rec'd - Welded	17,600	44.5	B2	Brittle Fracture
577	HT - Plate	18,860	59	A1	
	HT - Plate	18,890	58	A1	
	HT - Welded	17,450	26.5	A1	
	HT - Welded	18,250	34.5	A1	

*HT = Heat Treated: 1650°F - 1 hr. per inch - WQ
1200°F - 2 hrs - WQ

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Table 2 (Cont'd.)

Steel No.	Specimen Condition	Maximum Load-Lbs.	Angle at Max. Load Degree	Failure Type	Remarks
	As Rec'd - Plate	21,975	60	B1	
	As Rec'd - Plate	22,250	63.5	A1	
	As Rec'd - Welded	19,350	21	A2	
394	As Rec'd - Welded	17,425	12	A2	
	HT - Plate	22,425	54	A1	
	HT - Plate	22,575	52.5	A1	
	HT - Welded	19,600	16	A1	
	HT - Welded	20,600	17	A1	
	As Rec'd - Plate	20,725	88	B1	
	As Rec'd - Plate	20,775	84.5	A1	
	As Rec'd - Welded	18,000	33	B2	Brittle Fracture
396	As Rec'd - Welded	18,360	37.5	A2	Ductile Fracture
	HT - Plate	19,710	57	A1	
	HT - Plate	19,410	58.5	A1	
	HT - Welded	20,175	26.5	A2	
	HT - Welded	19,450	26	A2	
	As Rec'd - Plate	16,650	67	A1	
	As Rec'd - Plate	16,750	68.5	A1	
	As Rec'd - Welded	16,000	40.5	A1	Borderline A2 Failure
	As Rec'd - Welded	15,525	35	A1	" "
527	HT - Plate	18,910	58	A1	
	HT - Plate	18,510	57	A1	
	HT - Welded	16,450	25	A1	
	HT - Welded	17,000	26.5	A1	
	As Rec'd - Plate	17,000	67.5	A1	
	As Rec'd - Plate	16,550	67.5	A1	
	As Rec'd - Welded	14,750	23.5	A2	
	As Rec'd - Welded	13,750	16.5	A2	
531	HT - Plate	19,460	57	A1	
	HT - Plate	19,440	58	A1	
	HT - Welded	15,100	11	A2	
	HT - Welded	15,600	13.5	A2	

Table 2 (Cont'd.)

Steel No.	Specimen Condition	Maximum Load-Lbs.	Angle at Max. Load Degree	Failure Type	Remarks
494	As Rec'd - Plate	15,350	62	B2	Brittle Fracture
	As Rec'd - Plate	15,475	62	A1	
	As Rec'd - Welded	11,750	14	C1	Brittle Fracture
	As Rec'd - Welded	13,050	21	C1	Brittle Fracture
	HT - Plate	15,550	52.5	A1	
	HT - Plate	15,790	52	A1	
	HT - Welded	13,300	14.5	A1	
	HT - Welded	12,600	9	A1	
504	As Rec'd - Plate	15,550	67.5	A1	
	As Rec'd - Plate	15,450	67	A1	
	As Rec'd - Welded	16,000	42	B2	
	As Rec'd - Welded	16,125	43	B2	
	HT - Plate	17,150	68	A1	
	HT - Plate	17,100	58	A1	
	HT - Welded	15,575	35	A1	
	HT - Welded	15,000	31	A1	
333	As Rec'd - Plate	16,175	74.5	A1	
	As Rec'd - Plate	17,000	76	A1	
	As Rec'd - Welded	14,850	37	B1	Borderline C1 Failure, Brittle Fracture
	As Rec'd - Welded	15,100	38	B1	" " "
	HT - Plate	17,700	52.5	A1	
	HT - Plate	17,840	52.5	A1	
	HT - Welded	16,700	31.5	A1	
	HT - Welded	15,600	25	A1	

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Table 3

Transition Temperature Data

Steel No.	Quenched 1650°F Tempered @	Temperature Range of Onset of Brittleness °C	Average °C	Average °F	Temperature at 15 ft.-lb. Level °C	Temperature at 15 ft.-lb. Level °F
594	As Rec'd	65 to 53	59	138	10	50
594	600°F	39 to 29	34	93	-55	-67
594	800°F	0 to-10	- 5	23	-70	-94
594	1000°F	-20 to-29	-24	-11	-65	-85
594	1200°F	-10 to-19	-14	7	-60	-76
492	As Rec'd	55 to 45	50	122	-21	- 6
492	600°F	28 to 18	23	73	-38	-36
492	800°F	11 to 5	7	45	-60	-76
492	1000°F	-15 to-25	-20	- 4	-88	-126
492	1200°F	-22 to-30	-26	-15	-72	-97
601	As Rec'd	47 to 36	41	106	9	48
601	600°F	22 to 10	16	61	-50	-58
601	800°F	15 to 0	7	45	-57	-71
601	1000°F	25 to 10	17	63	-65	-85
601	1200°F	10 to 0	5	41	-48	-54
577	As Rec'd	42 to 34	38	100	-45	-49
577	600°F	0 to-10	-5	23	-72	-97
577	800°F	-10 to-22	-15	5	-75	-103
577	1000°F	-30 to-40	-35	-31	-80	-112
577	1200°F	-15 to-20	-17	2	-88	-126
394	As Rec'd	70 to 62	66	151	5	41
394	600°F	80 to 70	75	167	-3	27
394	800°F	14 to 9	12	54	-34	-29
394	1000°F	-11 to-16	-13	9	-57	-71
394	1200°F	- 9 to-16	-12	10	-55	-67
396	As Rec'd	71 to 64	67	153	-12	10
396	600°F	36 to 27	31	88	-27	-17
396	800°F	19 to 9	14	57	-47	-53
396	1000°F	0 to-10	-5	23	-51	-60
396	1200°F	0 to-14	-7	19	-57	-71

Table 3 (Cont'd.)

Steel No.	Quenched 1650°F Tempered @	Temperature Range of Onset of Brittleness °C	Average °C	Average °F	Temperature at 15 ft.-lb. Level °C	Temperature at 15 ft.-lb. Level °F
527	As Rec'd	50 to 44	47	117	-20	- 4
527	600°F	70 to 59	64	147	- 9	16
527	800°F	55 to 45	50	122	-30	-22
527	1000°F	25 to 15	20	68	-57	-71
527	1200°F	9 to -2	3	37	-55	-67
531	As Rec'd	24 to 10	16	61	-39	-38
531	600°F	80 to 66	73	163	- 3	27
531	800°F	10 to 0	5	41	-40	-40
531	1000°F	-22 to-35	-28	-18	-74	-101
531	1200°F	-32 to-42	-37	-35	-90	-130
494	As Rec'd	80 to 71	66	151	-15	5
494	800°F	25 to 16	20	68	-54	-65
494	1000°F	-20 to-30	-25	-13	-75	-103
494	1200°F	-31 to-42	-36	-33	-89	-128
504	As Rec'd	55 to 46	50	122	-29	-22
504	600°F	9 to 0	4	39	-66	-87
504	800°F	0 to-11	-5	23	-76	-105
504	1000°F	-11 to-20	-16	3	-76	-105
504	1200°F	-15 to-25	-20	-4	-90	-160
333	As Rec'd	53 to 47	50	122	3	37
333	600°F	68 to 57	62	144	-35	-31
333	800°F	51 to 42	46	115	-15	5
333	1000°F	23 to 13	18	64	-22	- 8
333	1200°F	39 to 26	32	90	-38	-36

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Table 4

Temper Brittleness Data

Heat Treatment

1650°F --- WQ
1000°F --- 2 hrs.---WQ
1000°F --- FC

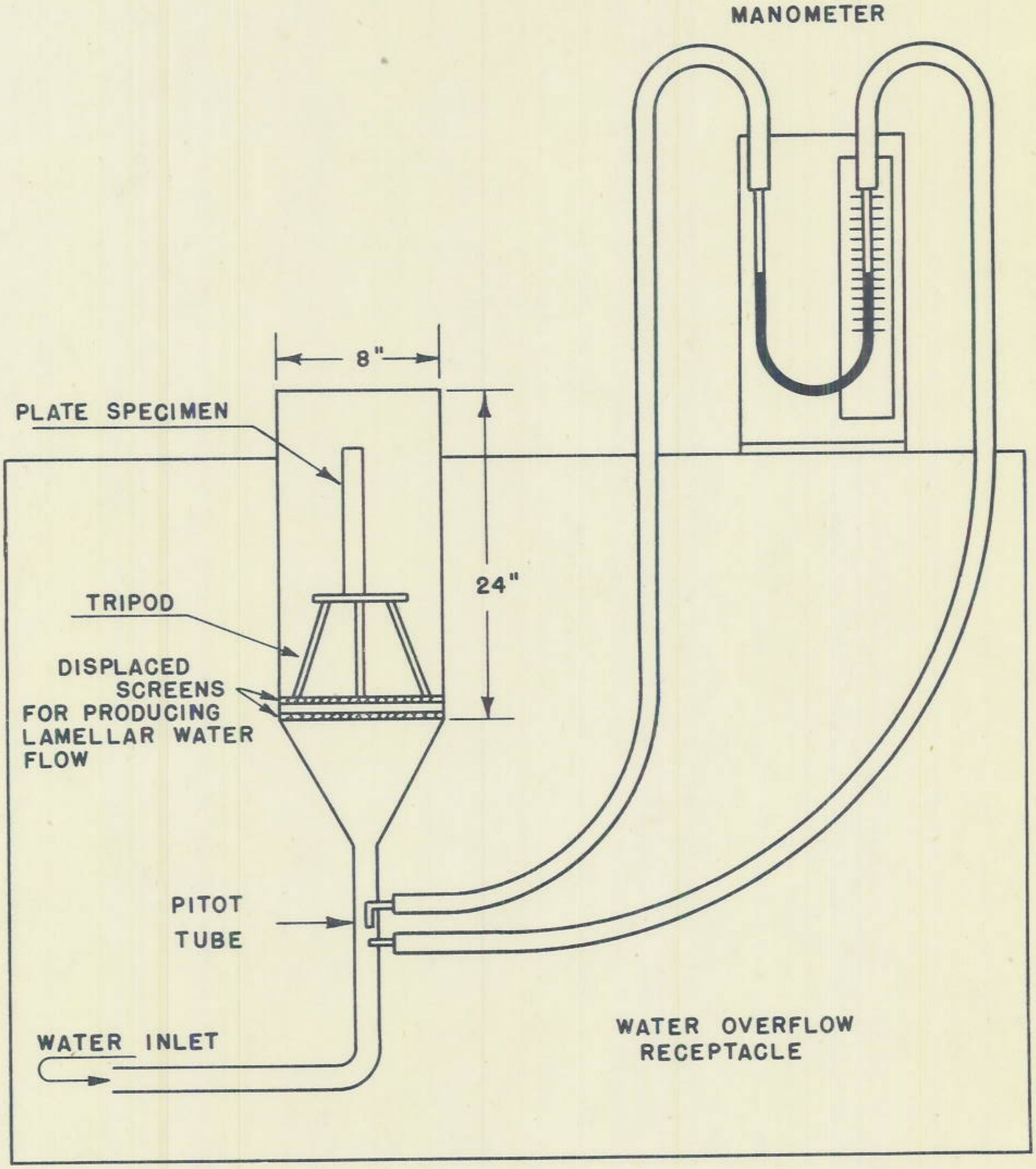
Steel Number	Impact Ft.-Lbs*	Fracture	Test Temp.°C
492	105	Ductile	0
504	137	Ductile	0
531	66	Ductile	0
394	69	Ductile	0
494	95	Ductile	0
527	97	Ductile	28
396	102	Ductile	0

Heat Treatment

1650°F --- WQ
800°F --- 2 hrs---AC

Steel Number	Temp. Range of Onset of Brittleness °C	Energy Level Ft-Lbs
594	-18 to -22	73
577	14 to 6	109
601	6 to - 4	75
333	24 to 14	75

* Average of three specimens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8"
PLATE SPECIMEN
24"
TRIPOD
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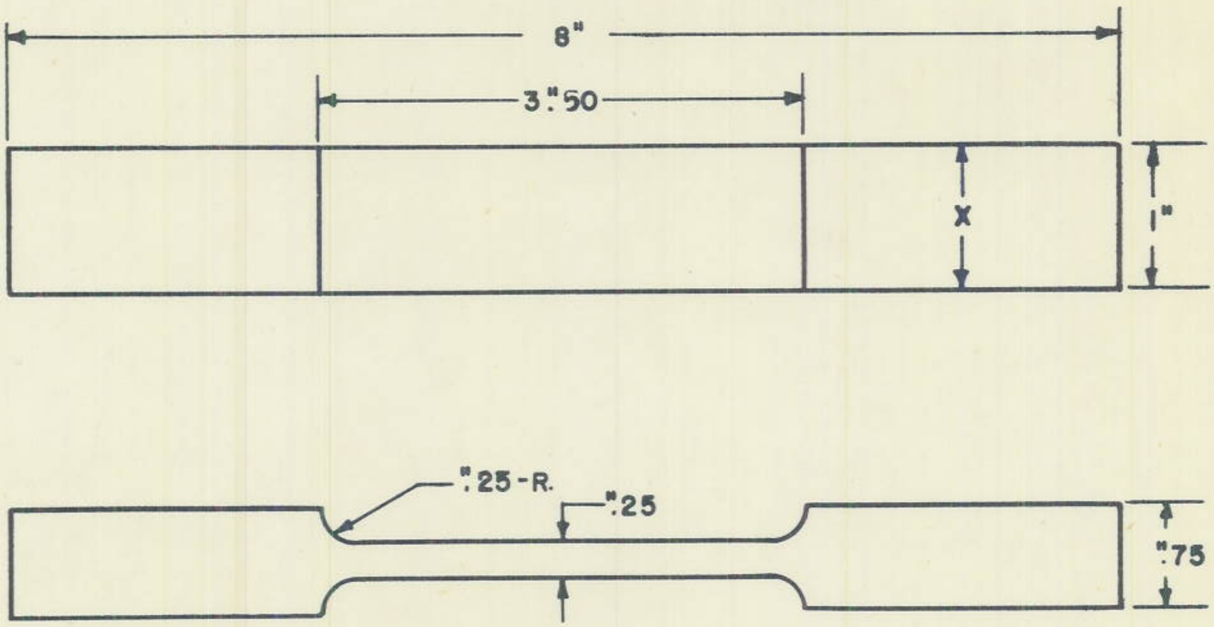
TUBE
WATER INLET
WATER OVERFLOW
RECEPTACLE

TENSILE TEST SPECIMEN



NOTE: DISTANCE "X" = PLATE THICKNESS

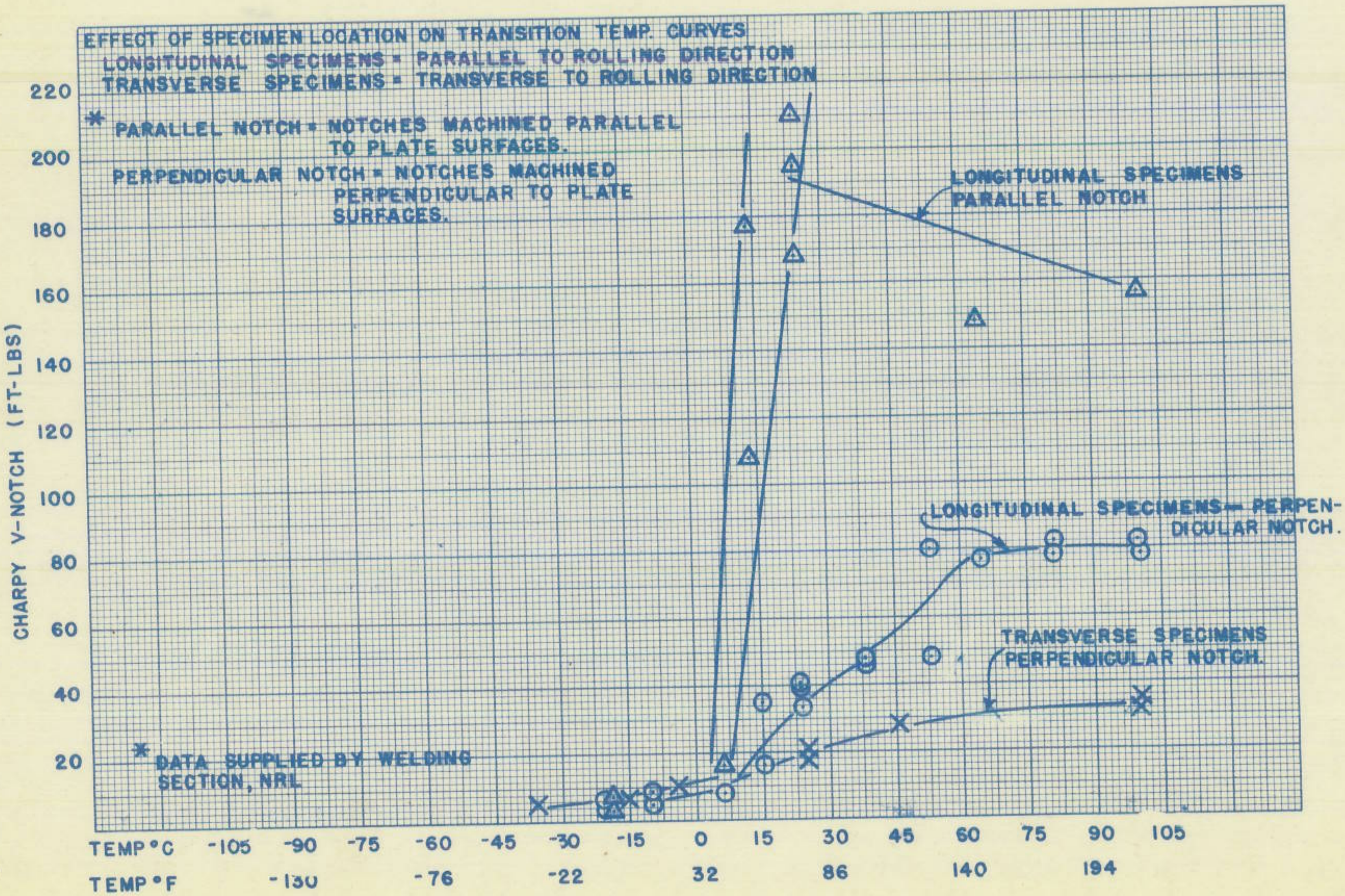


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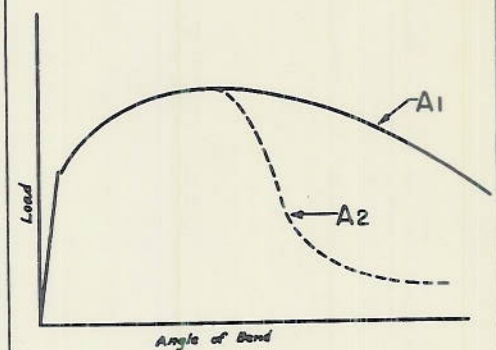
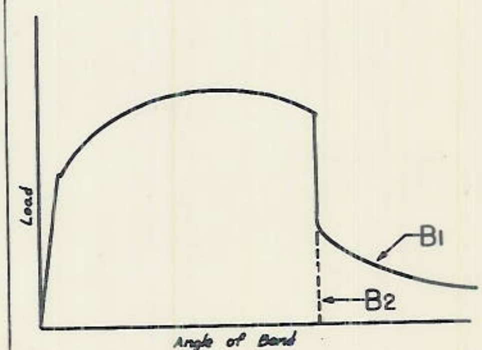
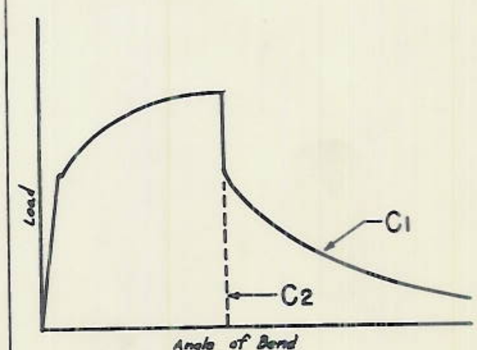
PLATE 3

TYPES OF NICK BEND FAILURES

TYPE	SUB TYPE	DESCRIPTION	TYPICAL STRESS STRAIN CURVES
A		PROGRESSIVE FAILURE UNTIL LOAD DROPS TO LESS THAN 50%.	
	1	GRADUAL DECREASE IN LOAD AS ANGLE IS INCREASED.	
	2	RAPID PROGRESSIVE FAILURE. LOAD DROPS AT LEAST 50% BEFORE ANGLE HAS INCREASED 10° BEYOND MAXIMUM LOAD.	
B		PROGRESSIVE FAILURE FOLLOWED BY INSTANTANEOUS* FAILURE BEFORE LOAD DROPS 50%.	
	1	INSTANTANEOUS* FAILURE CAUSES LOAD TO DROP TO NO LESS THAN 500 POUNDS.	
	2	INSTANTANEOUS* FAILURE CAUSES LOAD TO DROP TO LESS THAN 500 POUNDS.	
C		INSTANTANEOUS * FAILURE AT MAXIMUM LOAD. LOAD DROPS AT LEAST 10%.	
	1	INSTANTANEOUS* FAILURE CAUSES LOAD TO DROP TO NO LESS THAN 500 POUNDS.	
	2	INSTANTANEOUS* FAILURE CAUSES LOAD TO DROP TO LESS THAN 500 POUNDS.	

*APPRECIABLE DROP IN LOAD WITH NEGLIGIBLE INCREASE IN ANGLE (USUALLY AUDIBLE)

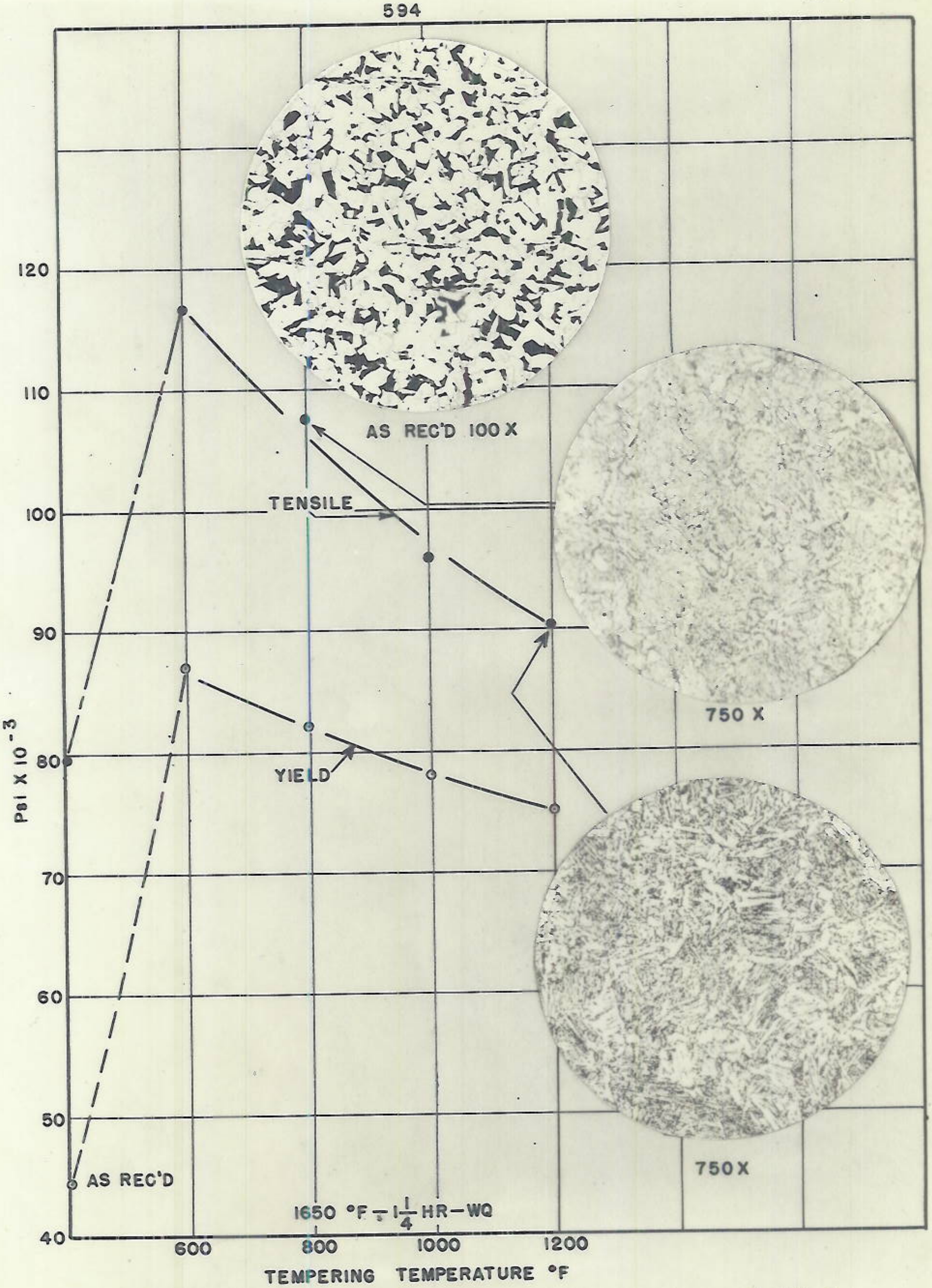


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PLATE 5

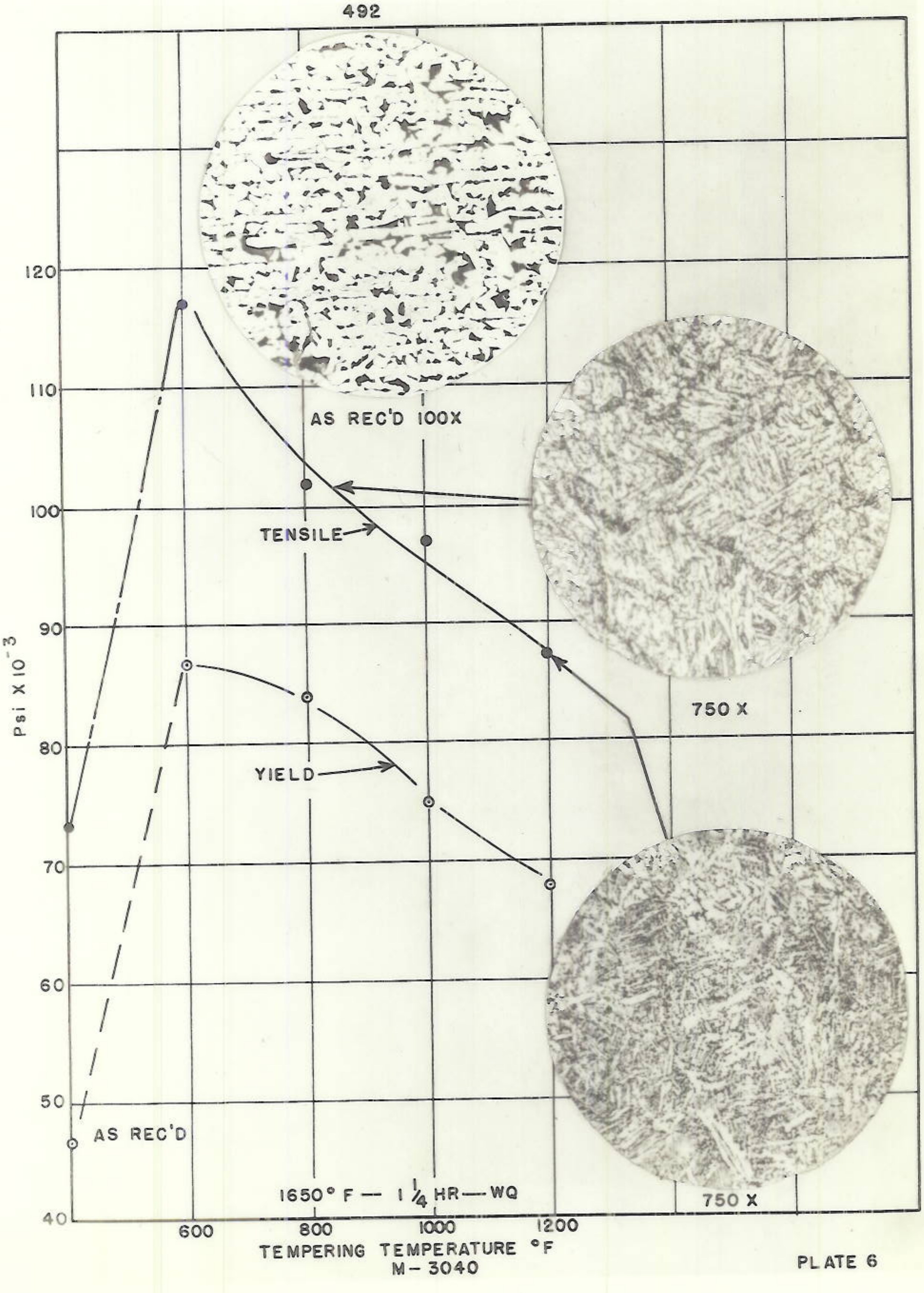

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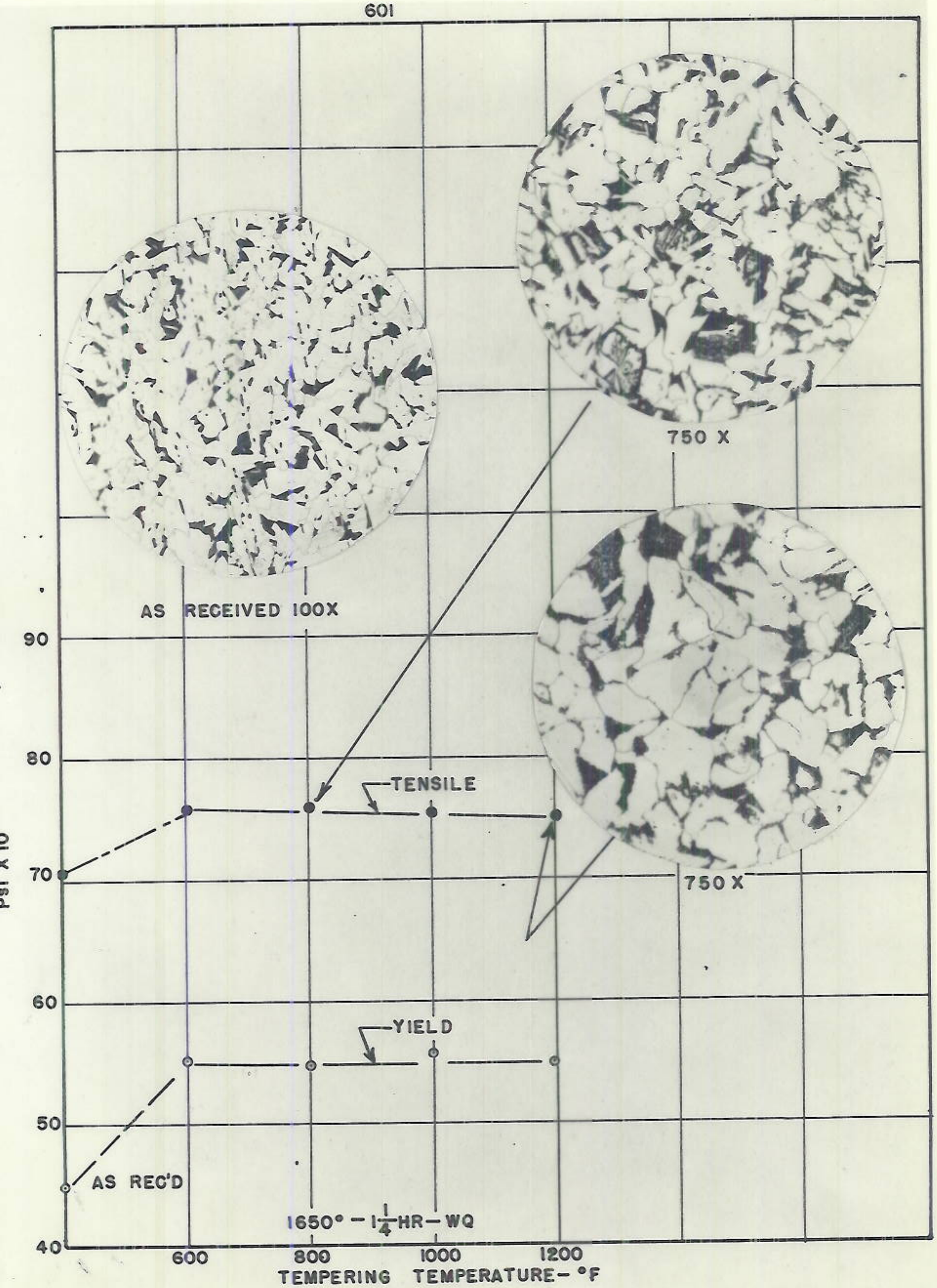
PLATE 6

601



M-3040

PLATE 7

UNCLASSIFIED

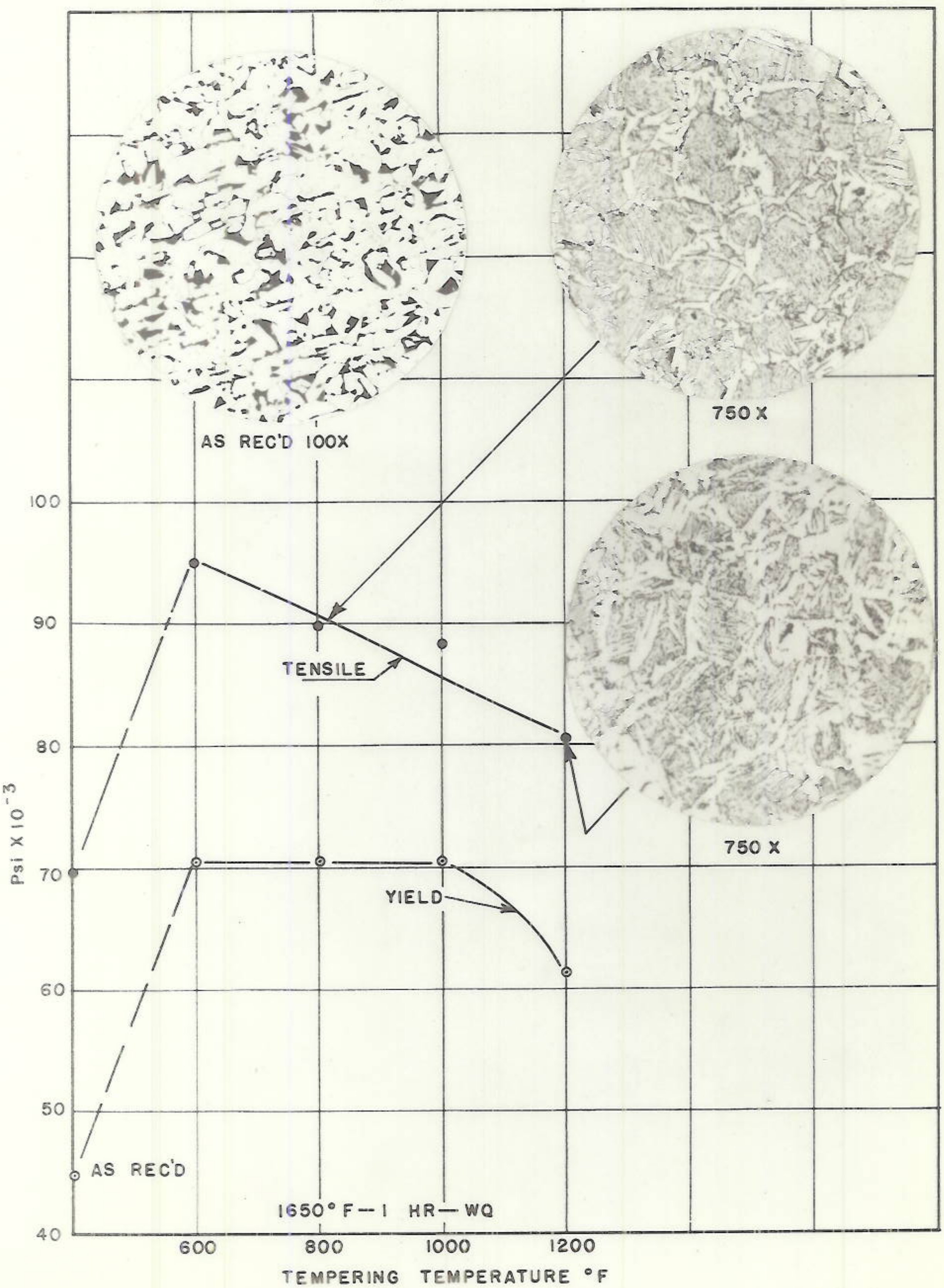


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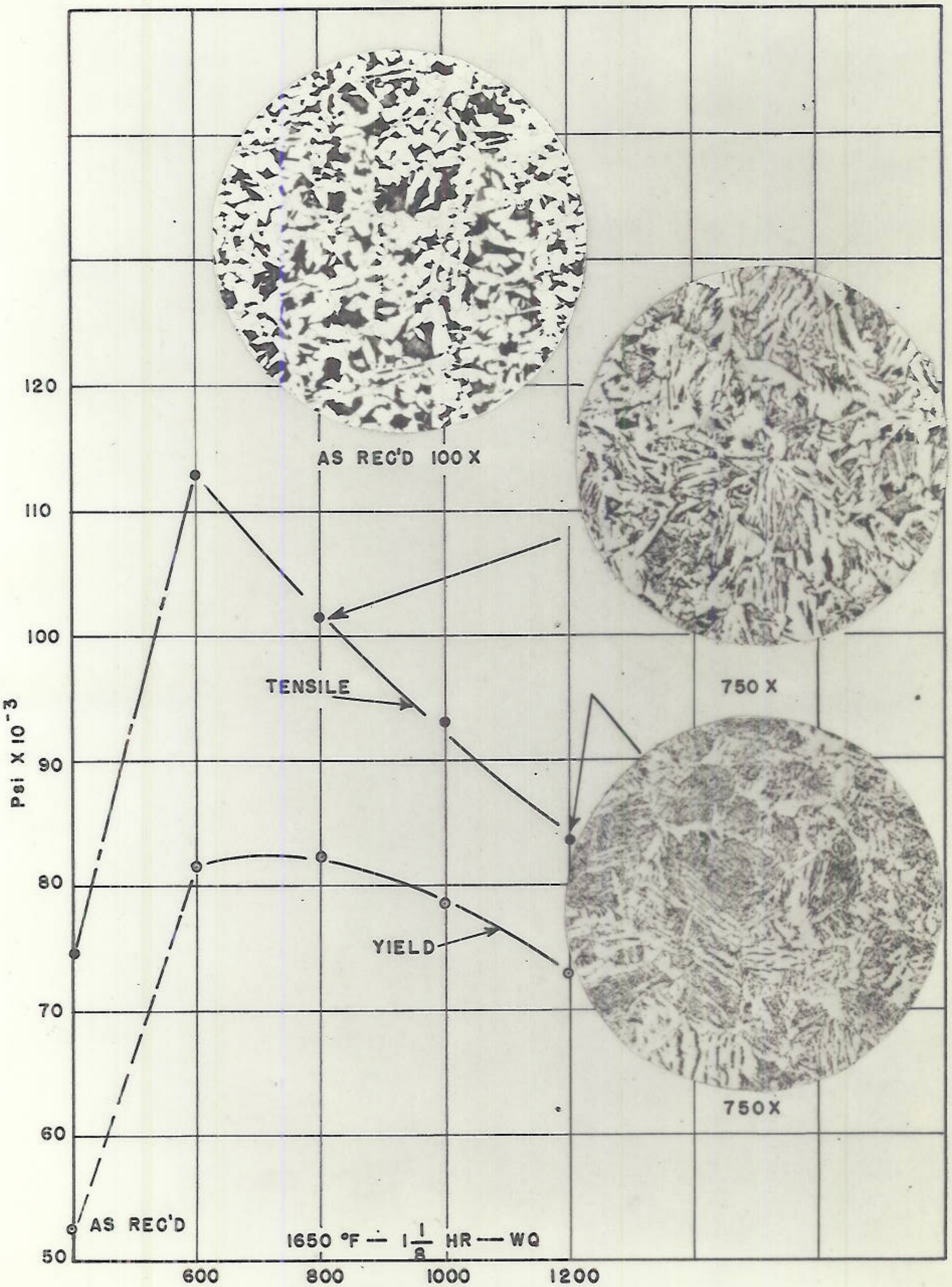
PLATE 8



M- 3040

PLATE 9

UNCLASSIFIED

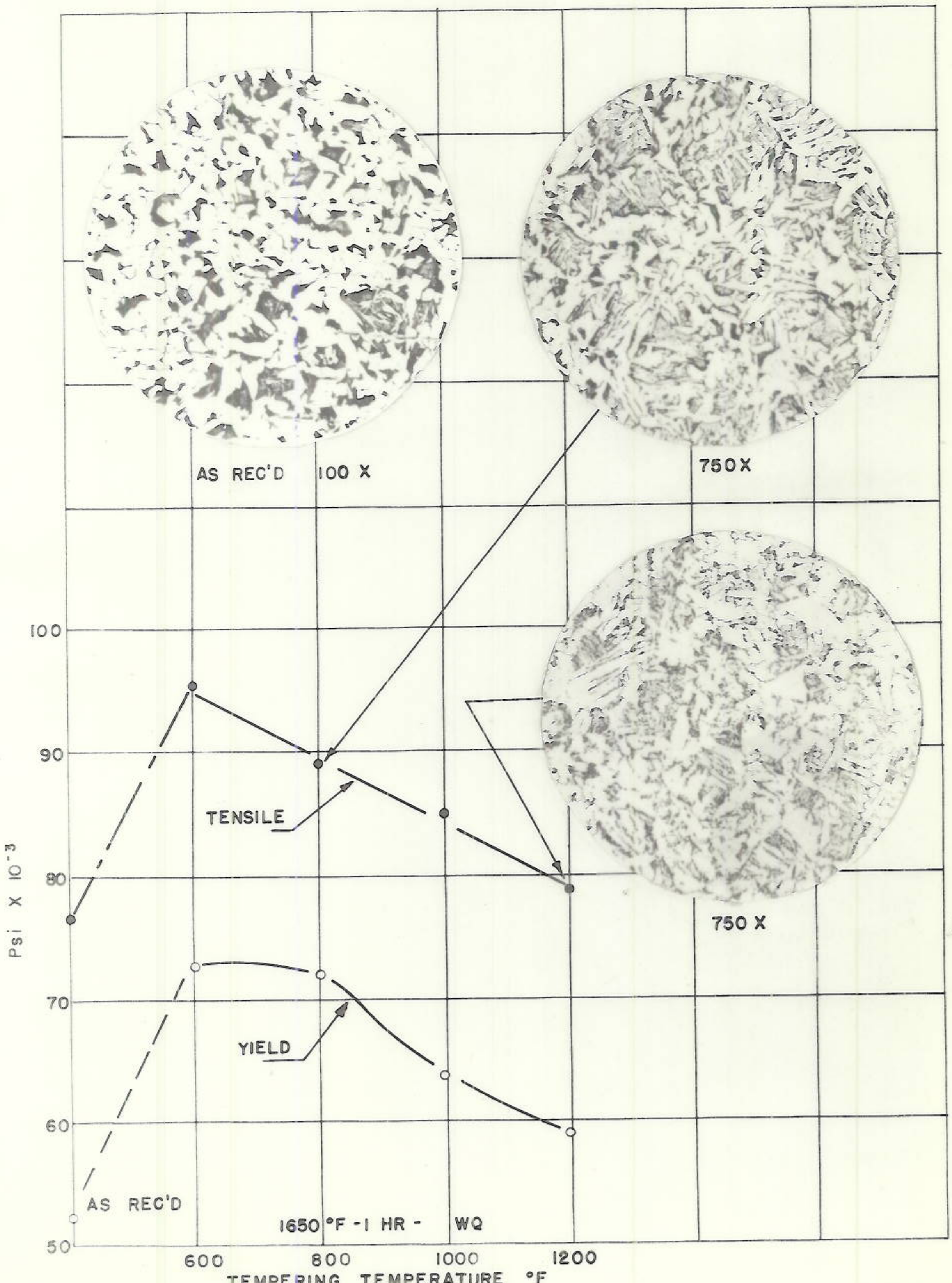


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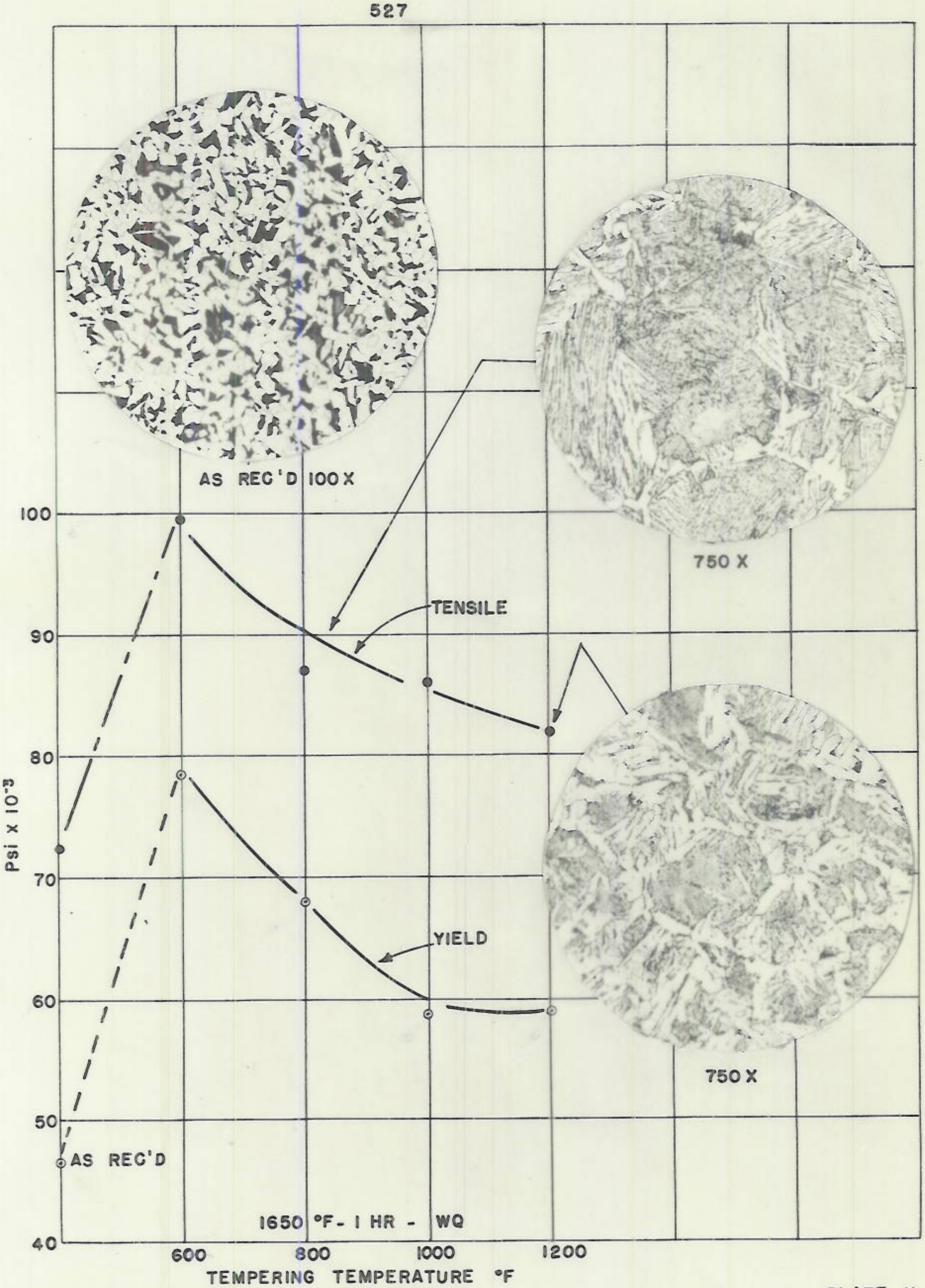
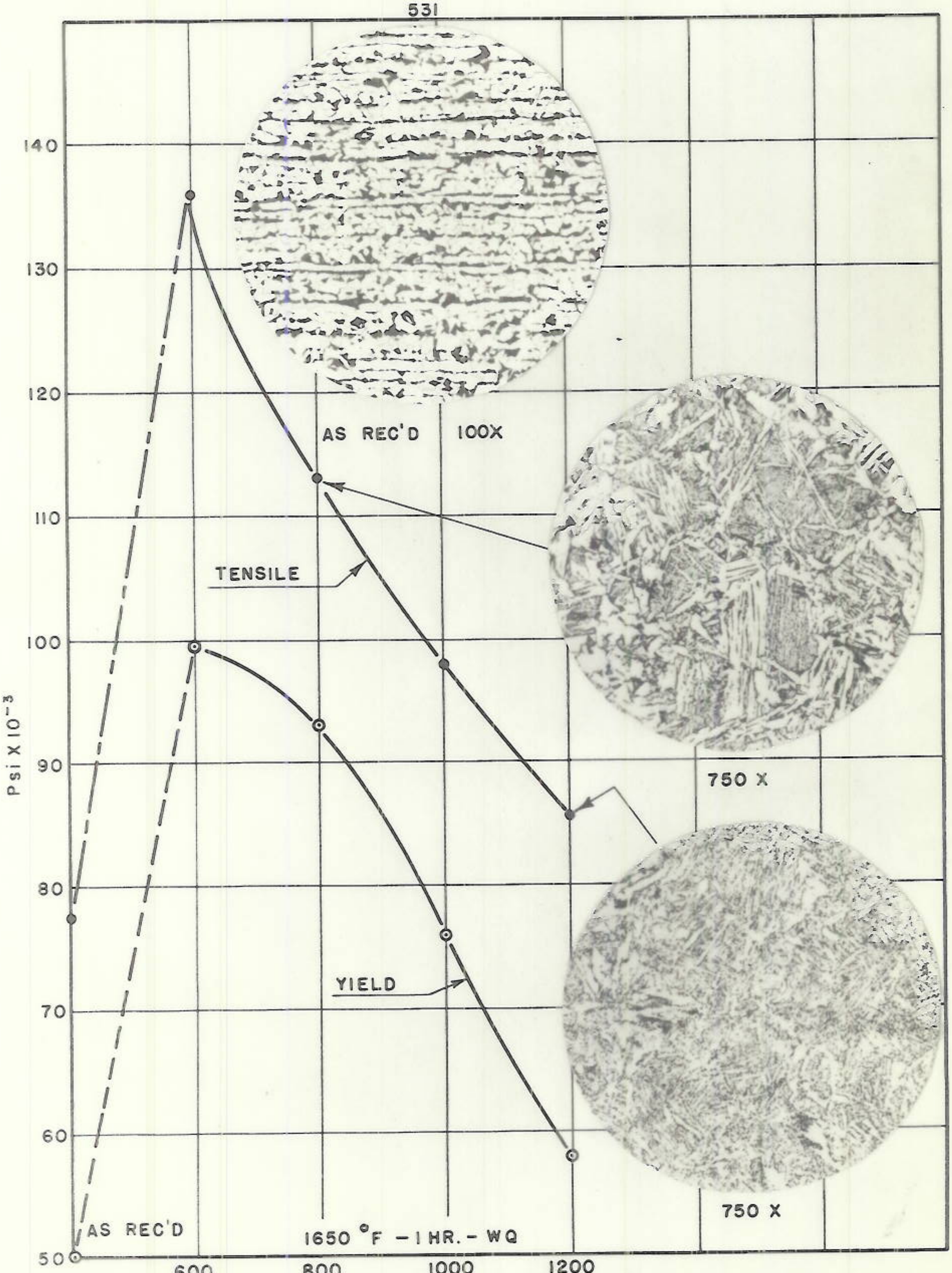
PLATE 10



M - 3040

PLATE II

UNCLASSIFIED



M - 3040

PLATE 12

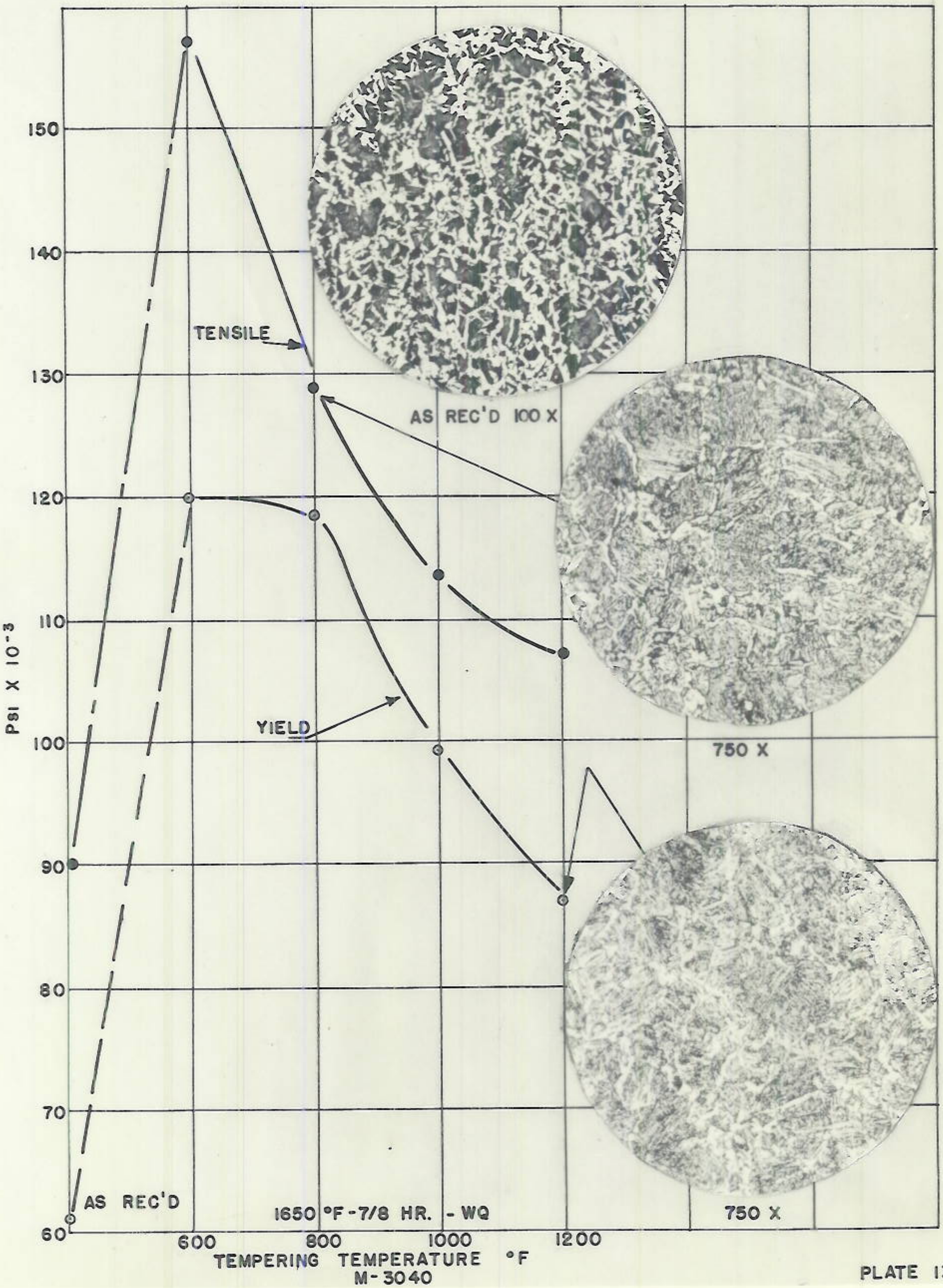
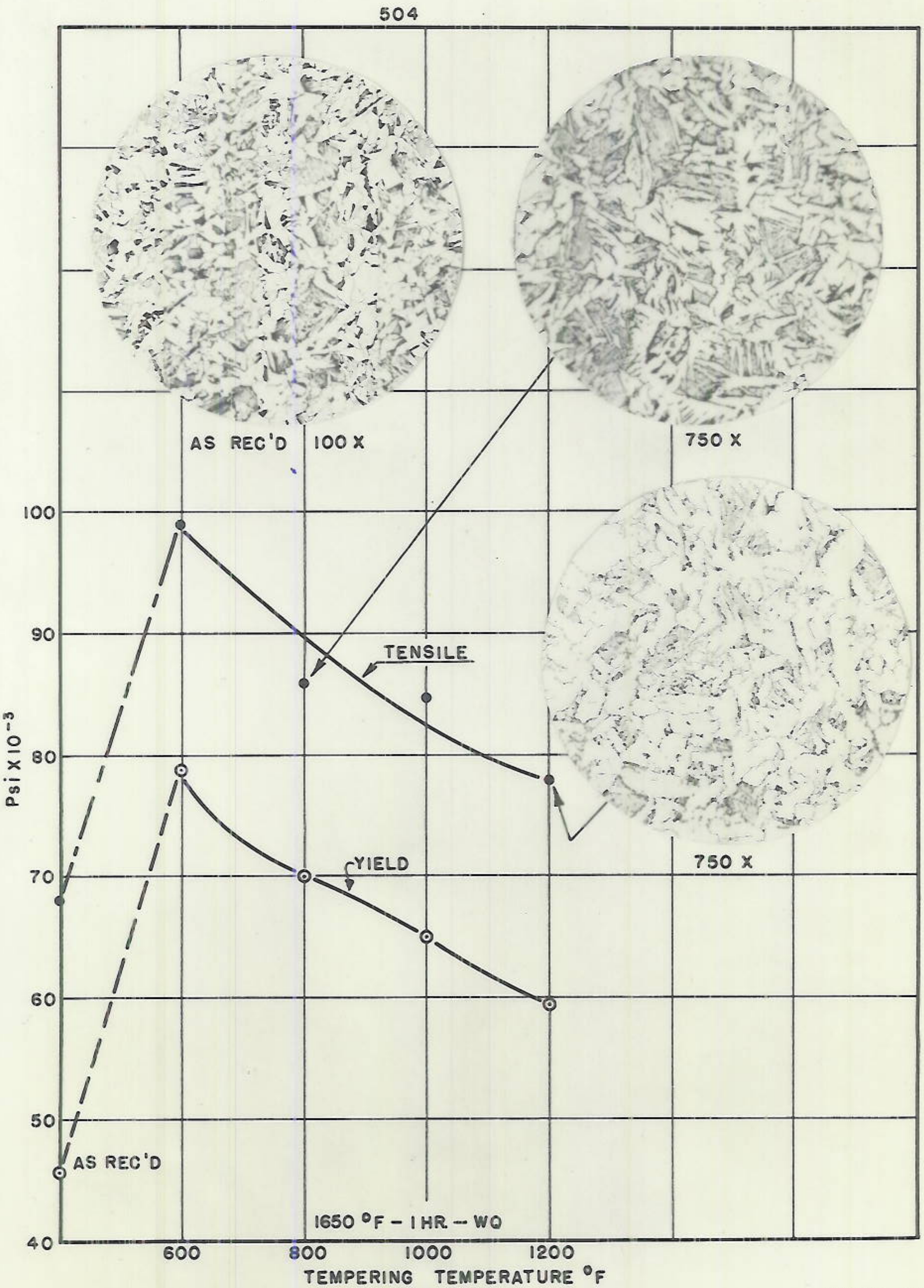
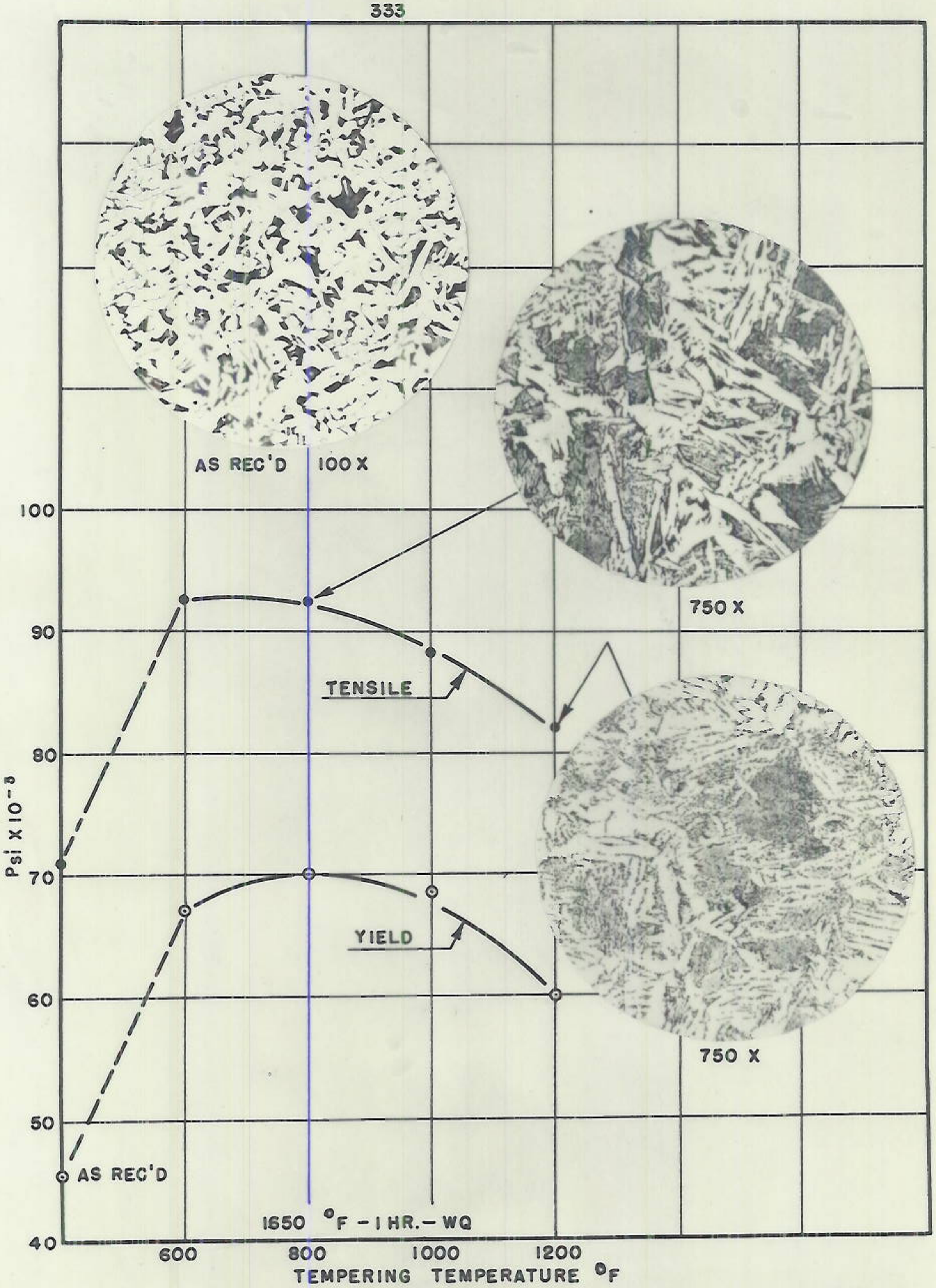

150
140
130
120
110
100
90
80
70
60
PSI X 10⁻³
TENSILE
YIELD
AS REC'D 100 X
750 X
750 X
AS REC'D
1650 °F - 7/8 HR. - WQ
600
800
1000
1200
TEMPERING TEMPERATURE °F
M-3040

PLATE 13



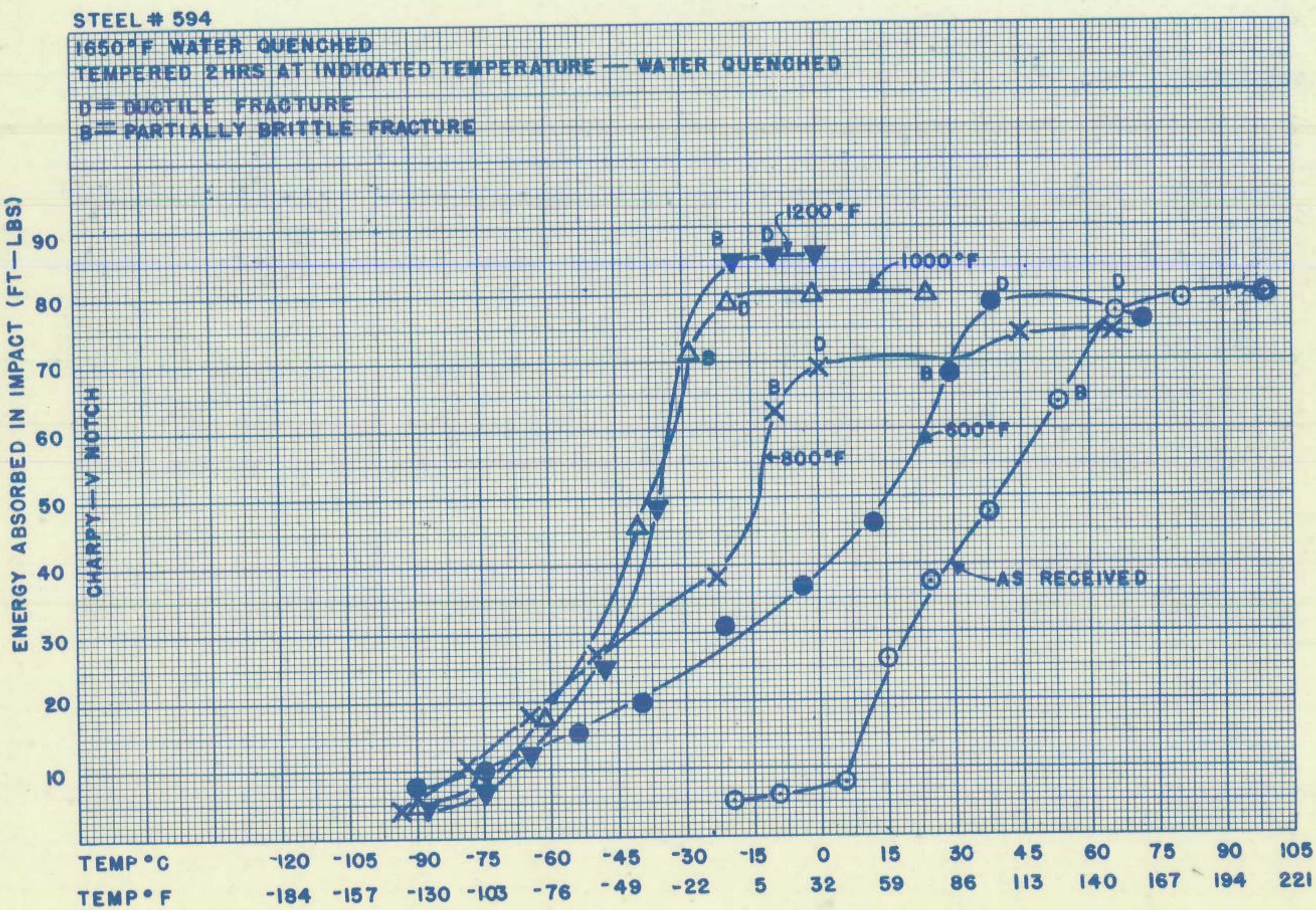
M-3040

PLATE 14



M-3040

PLATE 15



M—3040

PLATE 16

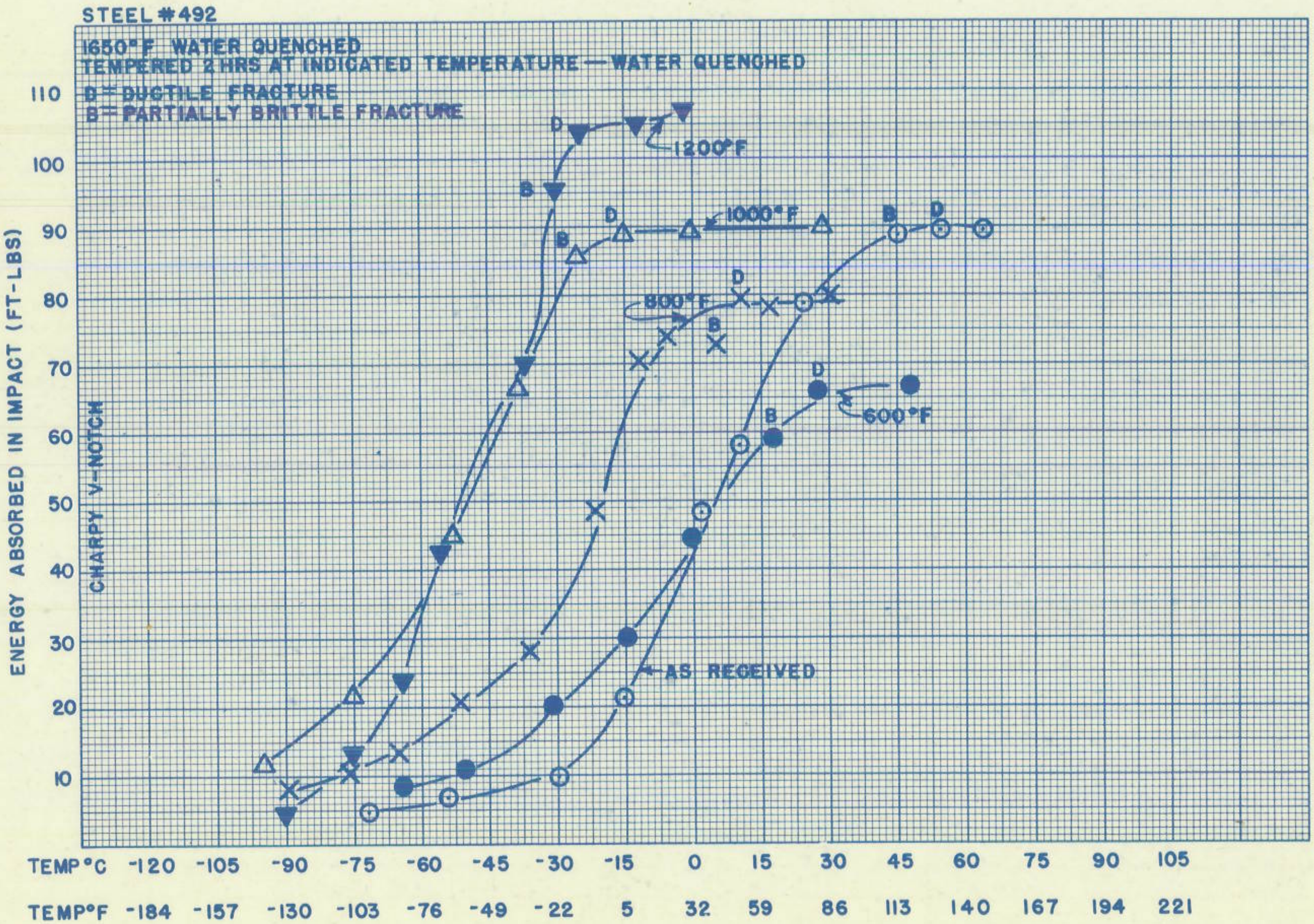


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PLATE 17

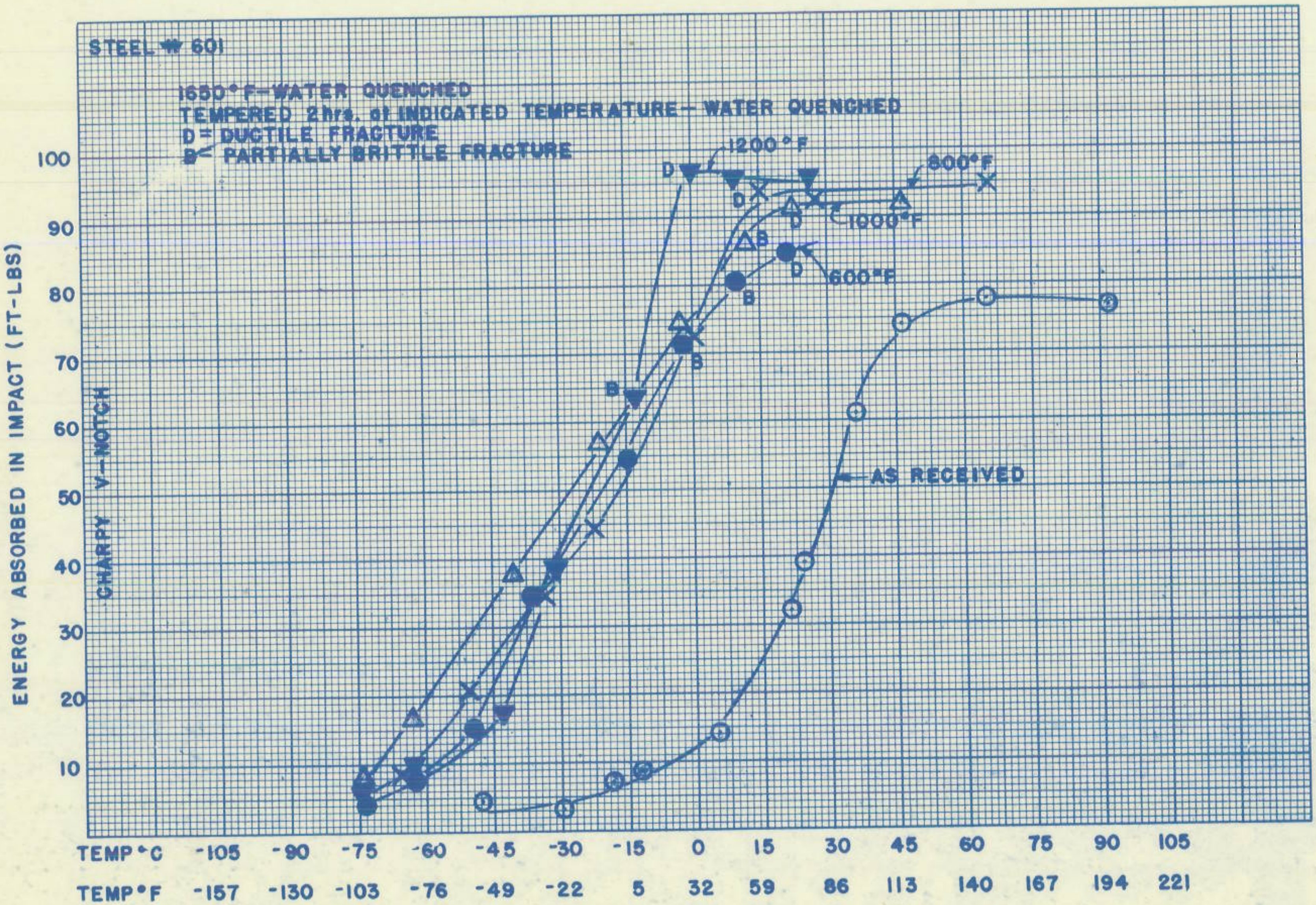

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PLATE 18

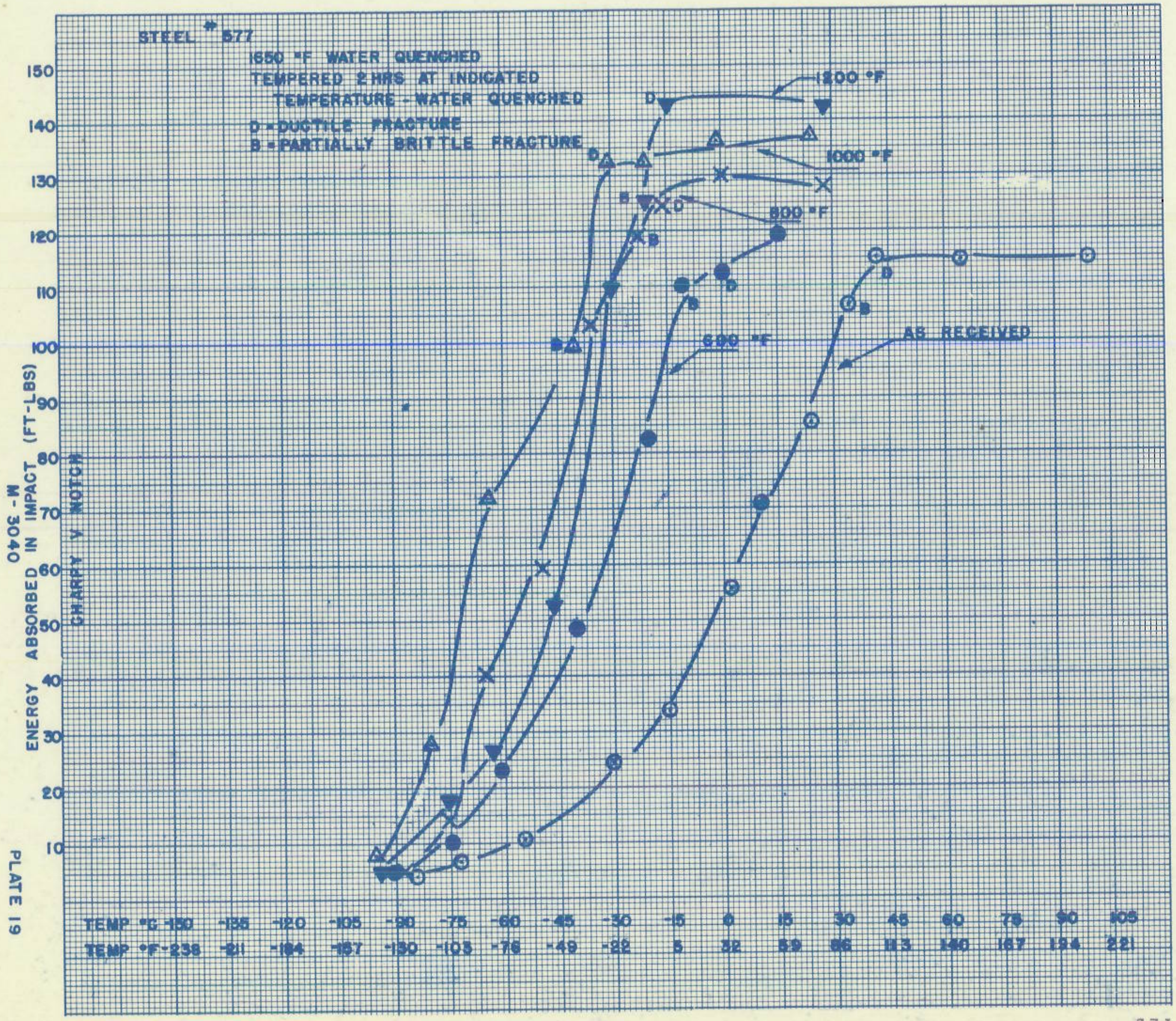

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PLATE 19

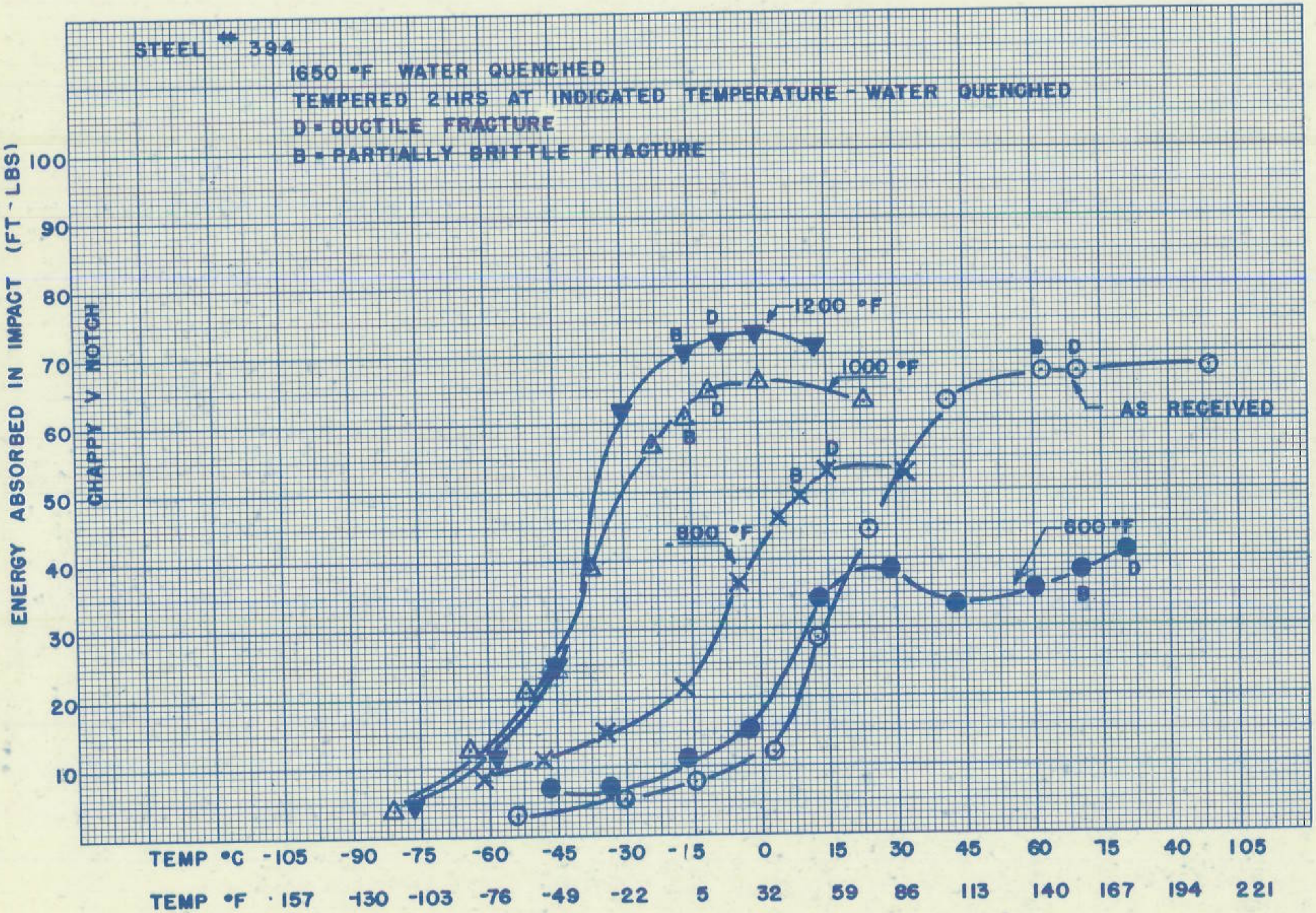

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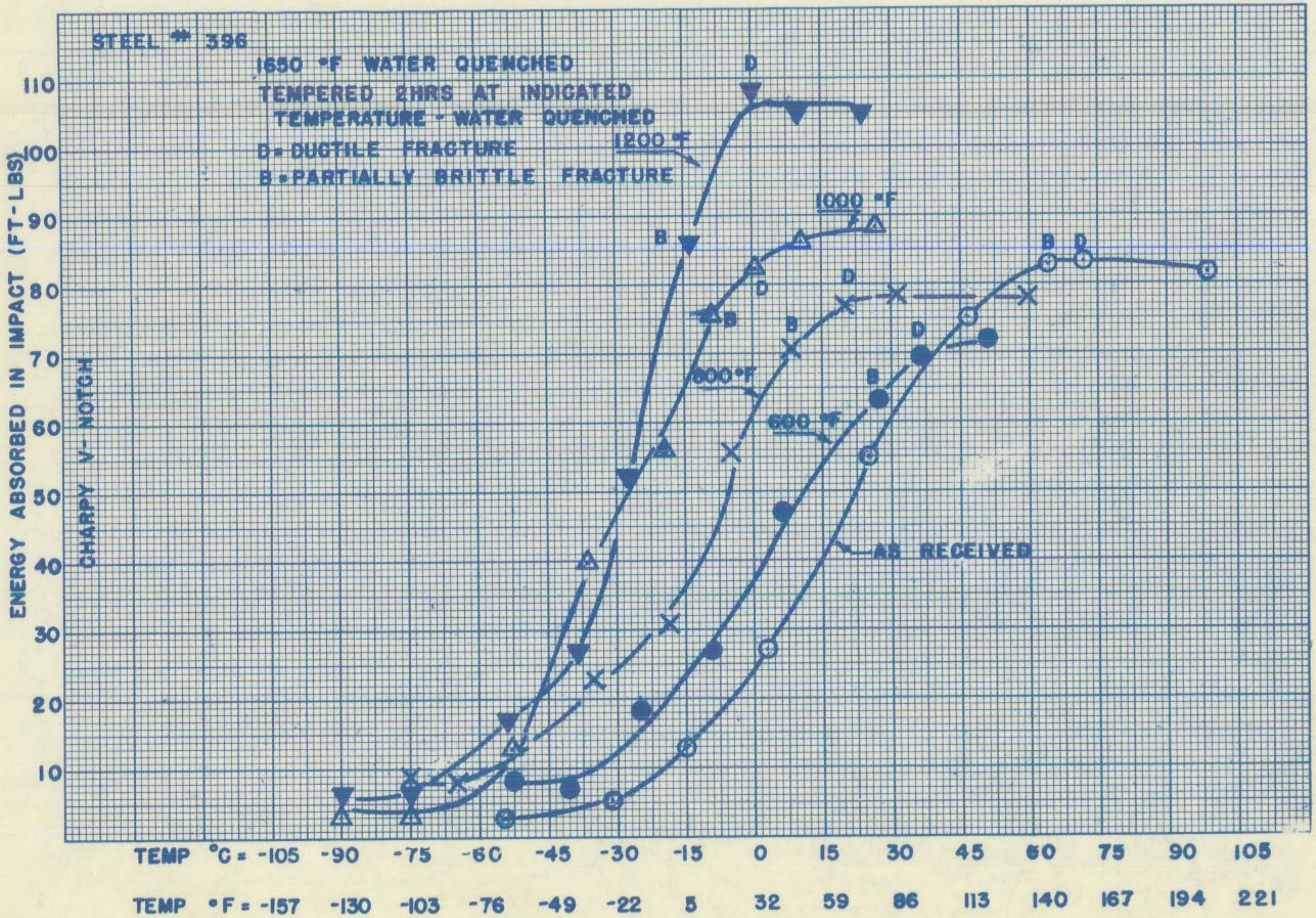
PLATE 20



M - 3040

PLATE 21

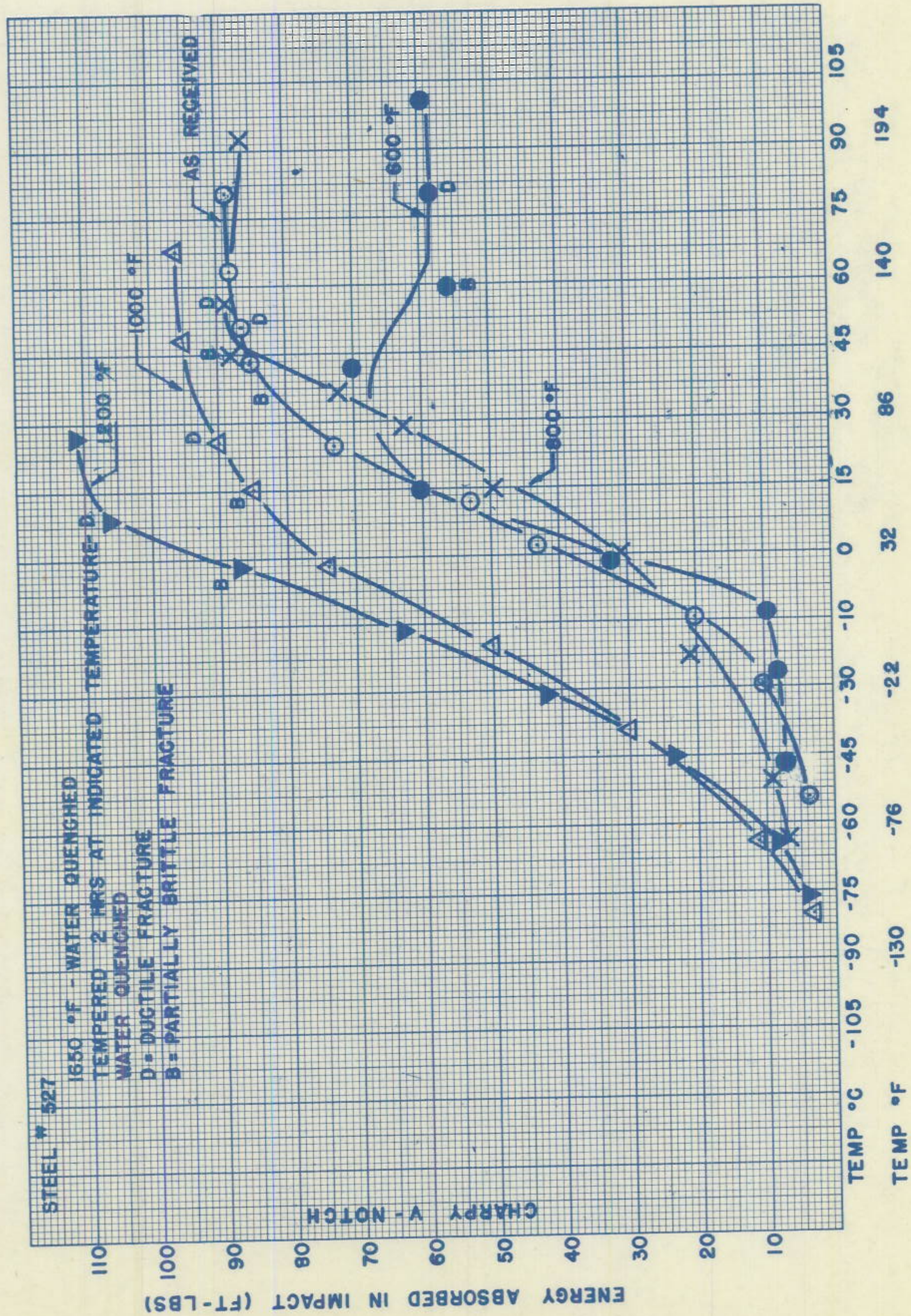


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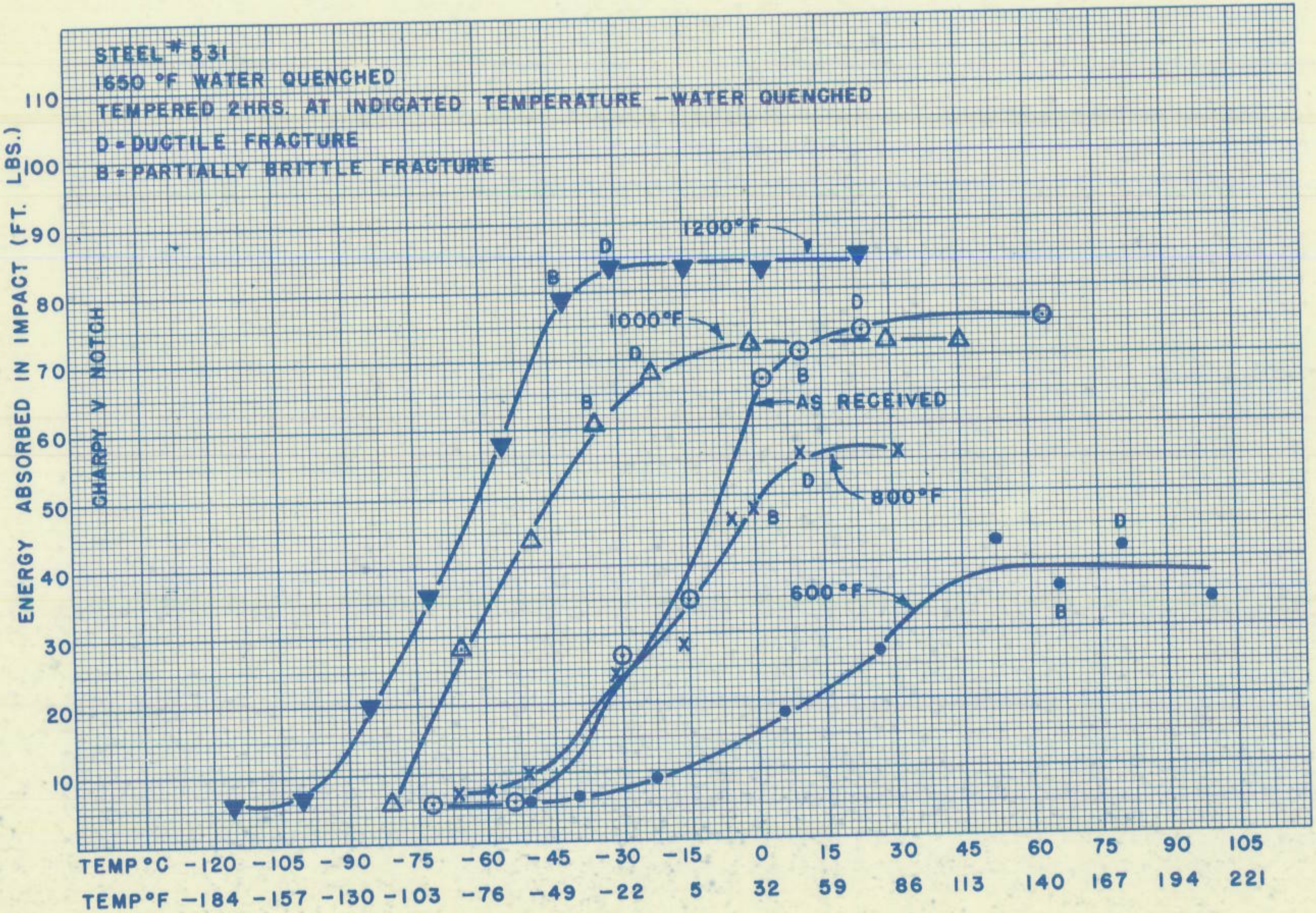
PLATE 22



M - 3040

PLATE 23

UNCLASSIFIED

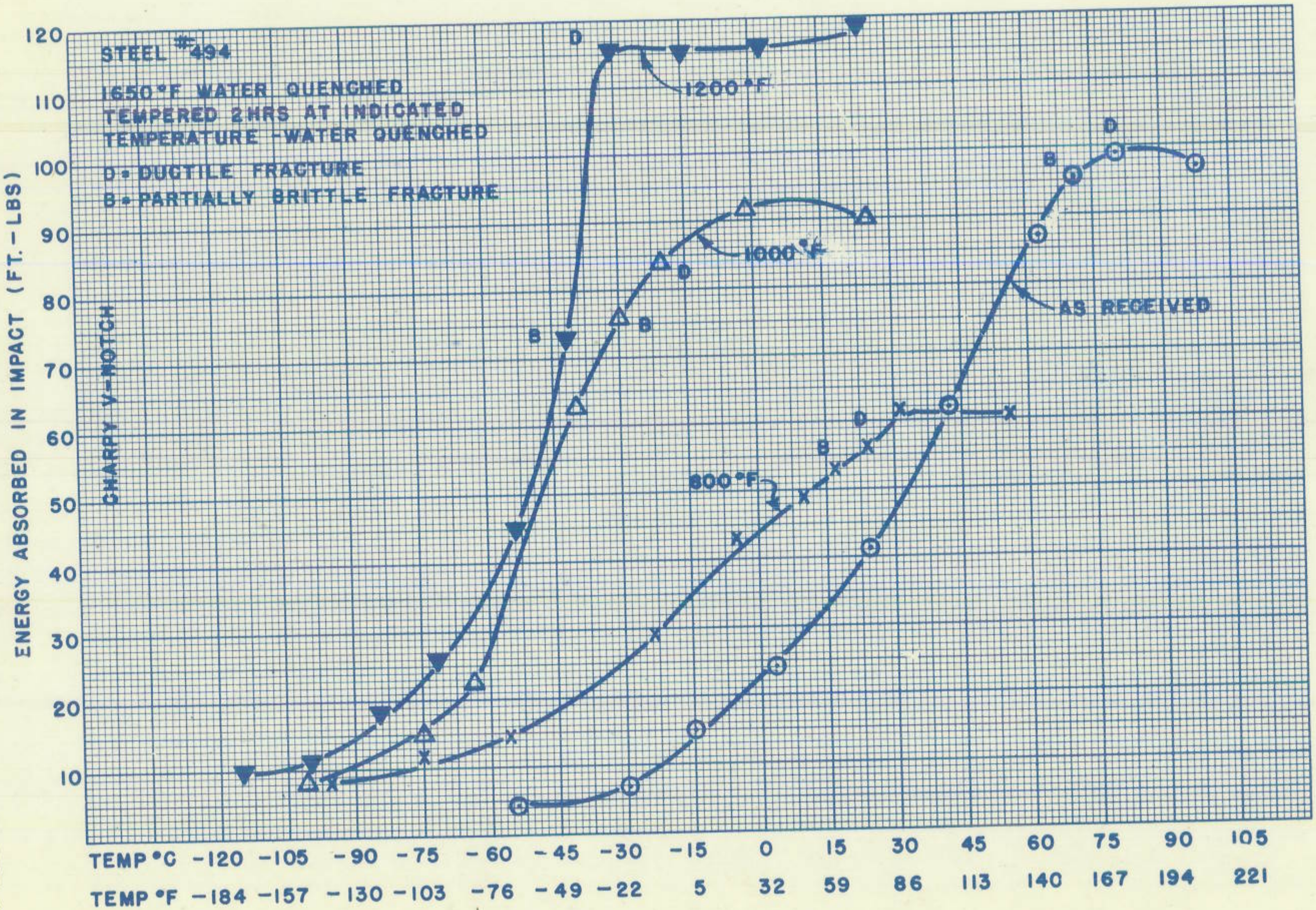


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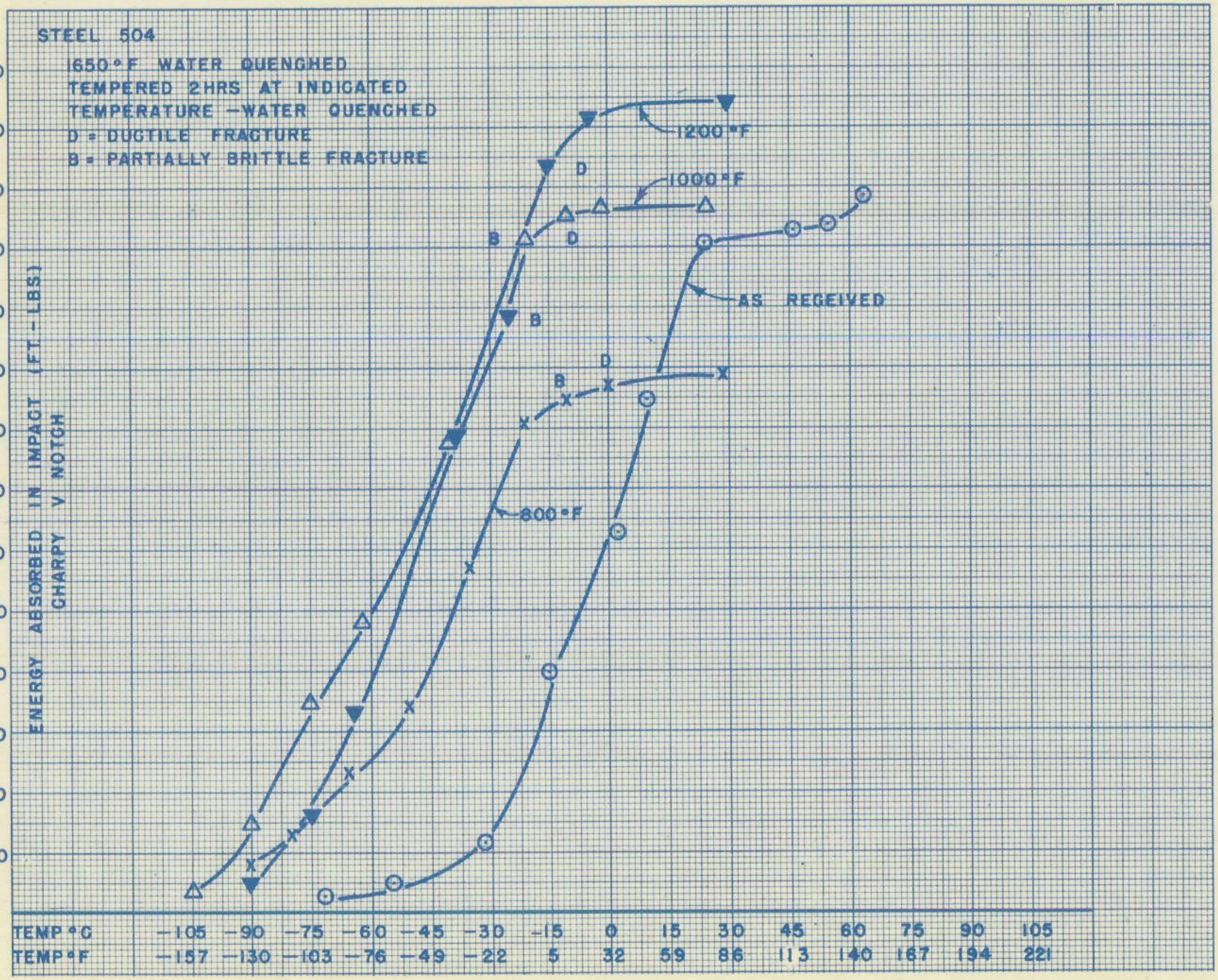
PLATE 24



M - 3040

PLATE 25

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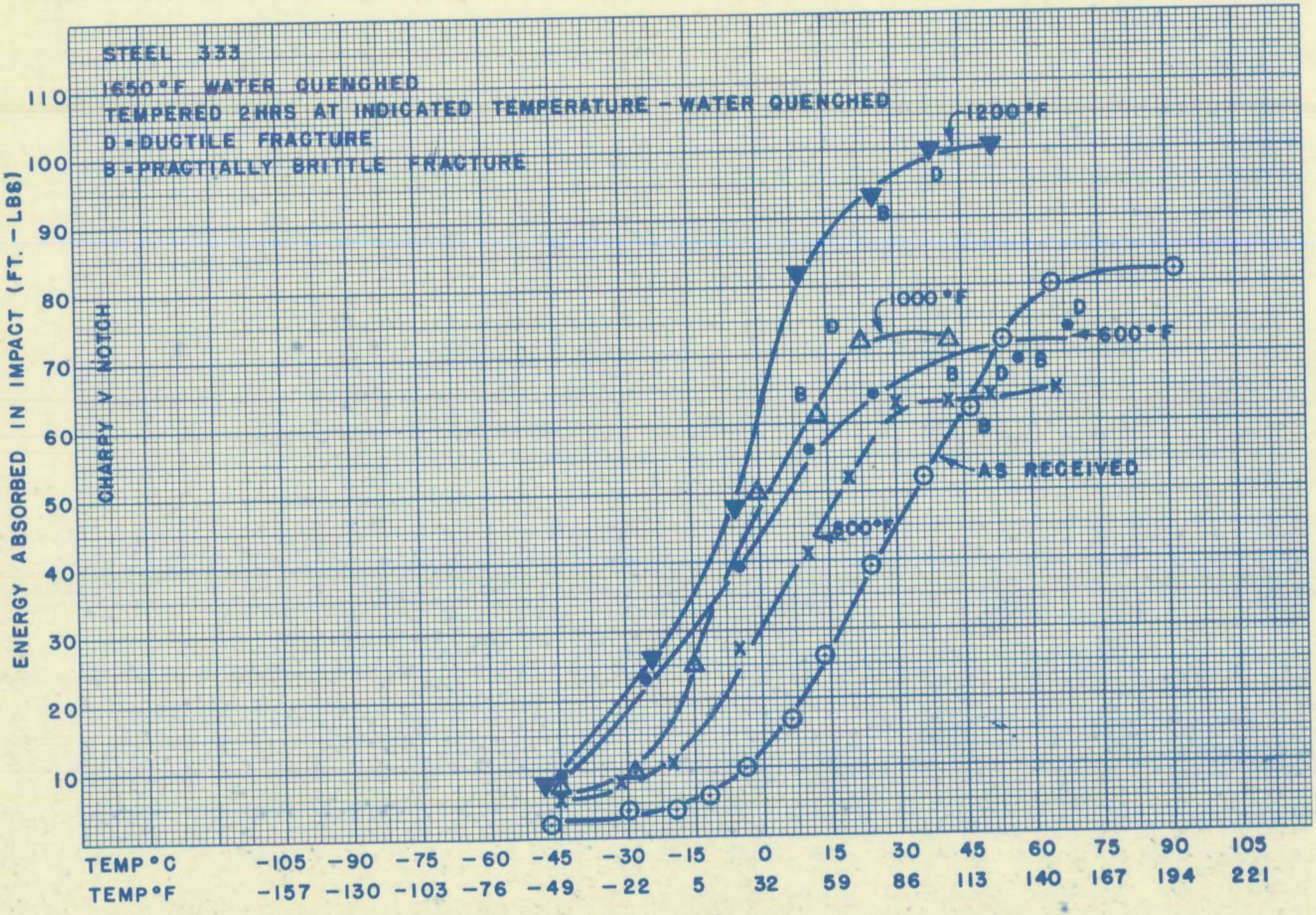

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PLATE 26