June 3, 1944 NRL Report No. M-2301

FR-2301

NAVY DEPARTMENT

NAVAL RESEARCH LABORATORY
Anacostia Station
Washington, D. C.

The Hardenability of Cast Steel

Number of Pages: Text - 12; Plates - 20; Tables - 3; Appendix - 2

Authorization: BuEng letter QP/Castings (6-19-Ds) of 13 July 1928. Base Project 1-R.

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ABSTRACT

Results of this investigation show that cast and forged steels of identical compositions, in the low and medium alloy range, have comparable hardenability when variations in grain size are considered. Increasing the normalizing temperature of the cast steels from 1700°F. (925°C.) to 2000°F. (1090°C.) prior to quenching from 1650°F. (900°C.) has little effect on the hardenability except as it alters the austenitic grain size.

The agreement between calculated and experimentally determined hardenability, as measured by the end-quench bar, is exceptionally good for all of the steels studied except those containing more than small amounts of strong carbide forming elements. In steels containing appreciable amounts of chromium or molybdenum, the carbide forming elements covered in this study, a quenching temperature of 1650°F. (900°C.) is not high enough to ensure complete solution of all of the carbides and, as might be expected, the measured hardenability is considerably lower than that calculated from the chemical composition and austenitic grain size.

A new curve correlating Jominy distance with Grossmann's index of hardenability, D_I, was determined from previously published data on quenched rounds.

Grossmann's hardenability factors were used throughout this study with the exception of the curve for molybdenum. A new molybdenum curve was determined from a reconsideration of Grossmann's data.

Authorization

1. The studies of steel castings are authorized by the Bureau of Engineering letter QP/Castings (6-19-Ds) of 13 July 1928.

Statement of Problem

2. The present investigation is concerned with, first, comparing the hardenability of cast and forged steels for each of several compositions, and second, determining whether the hardenability of cast steel can be calculated from chemical composition and grain size in the same manner and by using the same factors as can be done for wrought steel.

Known Facts Bearing on the Problem

3. By proper heat treatment steel can be made extremely hard and strong, it can be made relatively soft and weak, or it can be made to have intermediate degrees of hardness and strength within the particular limits imposed by composition, primarily the carbon content. High strength is desirable in engineering machine parts and structures, section modulus being duly considered, since mass can be reduced accordingly with resultant savings in material and elimination of dead weight. These points are extremely important when moving parts or mobility of an assembly are involved.

4. Strength is not the only requisite for most applications of steel. Ductility is also necessary so that unexpected overloads or unforeseen notch effects will not cause brittle failure. Unfortunately, the ductility of steel inherently decreases as its strength is raised so that, instead of designing for maximum strength which might be in excess of 200,000 PSI, designers call for only a fraction of that obtainable so that the necessary ductility may be present.

5. Beyond the broad generality that as ductility is increased the tensile strength or hardness is decreased, it is accepted that other factors have a profound influence on this relationship. Nothing more than mention need be made of the fact that coarse grain structure, chain-like inclusions, porosity or excessive hydrogen will cause lower ductility than expected for a given strength. Assuming that these adverse conditions are minimized, there is still another factor which should be fully considered in attempting to develop the maximum ductility at any given strength. This factor is the microstructure, aside from grain size, which is developed by heat treatment. For some time it has been known that forged steels show a much greater ductility at a given strength in the quenched and tempered condition than they do in either the normalized or annealed state (1). Likewise, the best combination of strength and ductility is produced in cast steels by quenching and tempering treatments (2).

6. Table 1 illustrates the improved yield to tensile strength ratio, and the higher ductility at a given strength for plain carbon steels in the quenched and tempered condition. This enhancement of physical properties through quenching and tempering is not restricted to plain carbon steels, but is found in low and medium alloy steels as well. These statements are made with the reservation that the size of section being considered has been hardened throughout.

7. The maximum physical properties derived from quenching and tempering are never realized in a partially hardened section. Plate 1 illustrates the so-called "mass effect" for two SAE steels. In all cases the smaller section sizes yield superior physical properties. This trend can be analysed much more conclusively than by merely designating it as a "mass effect". If a steel is of such a composition that, upon quenching, it will just harden throughout in a one-inch section, any section larger than one inch when similarly quenched will have an unhardened core or center consisting of pearlite and ferrite. Further increases in section size cause a decrease in the percentage of the section which is fully hardened, and thus further decrease the average physical properties. The effect of increasing section size for a carbon-molybdenum steel quenched in oil, water and brine is shown on Plate 2.

8. Quite often special alloying elements have been credited with greatly enhancing the strength of steels in the quenched and tempered condition, when actually they have merely increased the depth of hardening. Boron is an example of such an element. Plate 3 demonstrates the increase in the physical properties of a plain carbon steel through the addition of 0.002 percent boron.

9. It is evident from the above that in order to obtain the maximum benefits of quenching and tempering, it is necessary first to determine the factors which limit the depth to which a steel will harden. Three such factors are particularly apparent from experience:

a. Severity of quench, or the rate at which heat can be removed from the casting by some quenching medium.

b. The inherent response of the material to hardening due to the influence of chemical composition and grain size.

c. The geometry of the piece.

10. The effect of severity of quench has been previously determined (3) and although the index of the severity of quench (H) is actually a heat transfer coefficient it may be expressed in terms of the diameter of rounds which will just harden through under the most severe quenching condition and the diameter of round which willjust harden through under any other specific condition of quenching. A section may be considered hardened throughout when it has a microstructure of fifty percent martensite at the center. This particular microstructure is a satisfactory index and has been selected primarily because of the accuracy with which it can be determined by fracture or etch tests. The most severe possible quench is referred to as an "ideal quench" and is defined as that quench in which the external surface of the piece being cooled is immediately lowered to the temperature of the quenching medium. An "ideal quench" is impossible to achieve in practice, but it does serve as a convenient reference value.

11. The third factor, geometry, can be eliminated as a variable by expressing depth of hardening in terms of that size of round which will just harden through. This is, of course, a function of chemical composition and grain size if the severity of quench is stipulated. Depth of hardening under these limiting conditions may be referred to as that property of steel known as hardenability and may be expressed in terms of Ideal Critical Diameter (D_I). The Ideal Critical Diameter, is then by definition, a round of a size that will just harden through under conditions of an ideal quench. The relation between D_I and the diameter of round which will just harden through with some quench of lesser severity is shown on Plate 4. Since hardenability (D_I) is a function of chemical composition and grain size, many practical quenching problems can be solved if quantitative evaluation of these factors is possible.

12. Fortunately, the need for such a method of calculating hardenability from chemical composition and grain size has been realized in the case of forged steels, and it is of immediate interest to determine whether such a system of calculated hardenability can be applied to cast steel.

13. Since the work done on calculating the hardenability of wrought steel is to be referred to so frequently, it is desirable to review briefly some of the more pertinent investigations in this field. An appreciation of quantitative hardenability originated with such men as Shepherd (4), Burns, Moore and Archer (5), and later Jominy and Boegehold (6), and Grossmann, Asimow and Urban (7). These men were interested in the development of a test for hardenability which could be applied to practical heat treating problems. Of the numberous tests devised, Jominy's method of measuring hardenability holds the greatest promise in the field of low and medium alloy steels because

of its simplicity and relatively wide range of application. The method used by Grossmann yields more fundamental results but requires a more laborious laboratory procedure. Fortunately, it is possible to correlate Grossmann's fundamental results with those of Jominy's simple test, and a workable method for determining fundamental data by means of a simple standardized test is obtained.

14. Jominy's hardenability test consists simply of end-quenching a bar of standard length and diameter from its proper hardening temperature with a controlled stream of water impinging on one end of the specimen, grinding opposite parallel flats along the longitudinal axis, and making hardness determinations at regularly spaced intervals along the ground portions of the bar. A plot of hardness versus distance from the quenched end yields the typical curve shown on Plate 5. To avoid the necessity for reproducing the entire curve when discussing the results of a Jominy test, it is conventional to state, as an index of hardenability, that distance from the quenched end at which the hardness drops to a predetermined value indicative of a microstructure of fifty percent martensite. The reasons for choosing the point of fifty percent martensite have been explained before in connection with its use in rounds. This index of hardenability is referred to as the Jominy distance. It was found possible to correlate Jominy distance with Grossmann's Ideal Critical Diameter (D_I) (12).

15. The first consistent work on calculating hardenability from chemical composition and grain size was described in a paper by Grossmann(8). Wrought steels were used for the development of his principle which consists of establishing a base hardenability for carbon and grain size along and determining independent multiplying factors for each of the additional alloying elements present. This principle has been confirmed by the more recent investigations of Crafts and Lamont (9), of Kramer, Hafner and Toleman (10) and of Comstock (11). Although they substantiated the method, these investigators found certain differences in the numerical values of individual multiplying factors. As explained more fully later, these differences may possibly be attributed to the fact that more recent studies were carried out using the end-quench or Jominy test to measure the hardenability and then converting the end-quench data to Grossmann's D_I, whereas Grossmann's work was carried out entirely on quenched rounds which gave values of D_I directly. This conversion was made by a calculated curve (12) which is believed to be slightly in error.

16. Jackson and Christenson in their paper on the effect of quenching temperature on the Jominy curve (13) point out that if quantitative hardenability is to be determined from the Jominy curve, the effect of quenching temperature must be considered from a purely thermal standpoint. From that paper a curve was derived which may be used to correct the measured Jominy distance at any quenching temperature to the Jominy distance at a quenching temperature of 1600°F. (870°C.), Plate 6.

Theoretical Considerations

17. As previously mentioned, the most probable source of discrepancy between Grossmann's data taken on rounds and more recent data taken from the Jominy test lies in the relationship between Jominy distance and D_I. The curve was based on the equality of half-temperature times at the center of different size rounds and at different distances along the Jominy bar (12). Half-temperature time is defined as the time required to cool from the quenching temperature to a temperature halfway between the quenching temperature and the temperature of the quenching medium.

18. Due to the dissimilarity of the mode of heat transfer during quenching, it is believed that the half-temperature time is not the best correlating parameter between rounds and end quench bars which might have been chosen. The method employed herein to correlate D_I with Jominy distance is based on equality of hardness rather than on the basis of some thermal parameter. The revised correlation curve is shown as the lower curve on Plate 7. (See appendix for method of determining this Jominy distance versus D_I curve).

19. Grossmann's hardenability factors were used throughout this study with the exception of the multiplying factors for molybdenum. The graphic representation of Grossmann's data for the effect of this element on hardenability is shown by the solid lines on Plate 8. It is evident that considerable weight was placed on the point representing zero percent molybdenum in the determination of this curve. If the zero point is ignored entirely, a straight line can be drawn through the remainder of the points (dotted curve on Plate 8) which is believed to indicate more closely the effect of molybdenum on hardenability in the composition range in which it is most commonly used. The agreement between calculated and measured hardenability of the molybdenum steels included in this study appear to justify such a change.

Experimental Procedure

20. Sixteen heats of steel of the compositions shown in Table 2 were used in this investigation. All were made in a 300-lb. coreless induction furnace and poured into green sand molds to produce castings of the size and shape shown by the photographs of Plate 9. The cast plates were fed by two over-sized blind risers and the four-inch cubes were fed by open risers. A standard melting practice was followed which facilitated close composition control. Sheared SAE 1015 steel was used as the melting stock and alloys were added as ferro-alloys or as commercially pure metals.

21. The cast plates were sectioned to obtain four specimen blanks, each being one and one-fourth inches square and six inches long. The four-inch cubes were forged to one and one-half inch diameter bars. Three of the cast coupons from each heat were then normalized at 1700°F. (925°C.), 1850°F. (1010°C.), and 2000°F. (1090°C.), respectively. The forged bars were double normalized at 1850°F. (1010°C.). Normalizing cycles were so adjusted that all pieces were at temperatures for one hour and thirty minutes. After normalizing, the coupons were machined to the standard type Jominy bar (Plate 10).

22. All Jominy bars were heated in close fitting carbon blocks to 1650°F. (900°C.), held for an hour at temperature, and quenched in the jig shown on Plate 11. Opposite parallel flats were then wet ground to a depth of 0.10 inches. This depth was selected because it yielded primarily the same hardness contours as those obtained by grinding to a depth of 0.015 inches, Plate 12, but it eliminated erratic readings due to uncontrolled surface effects and thus ensured the usability of the data. Rockwell "C" hardness surveys were made with a Rockwell hardness tester. The jig shown in Plate 13 was used for rapid and accurate spacing of the hardness indents. The accuracy of the positioning jig is plus or minus 0.004 inches and the hardness determinations are believed to be accurate to plus or minus one Rockwell "C" number.

23. The Jominy bars were electrolytically polished and the grain size of each bar was determined by projecting an image of the etched surface on a screen and making a visual comparison with the standard ASTM grain size chart. In several cases, photomicrographs were taken and actual counts made. Comparison showed the estimated grain size to be accurate within plus or minus one half of an ASTM grain size number.

24. Samples for chemical analysis of each heat were obtained from that portion of the plate remaining after the necessary Jominy bar blanks had been removed.

Data Obtained

25. Jominy curves were plotted for all bars from the hardness data. Using the relationship between carbon content and hardness of fifty percent martensite shown in Plate 14, Jominy distances were read from the Jominy curves, corrected to a quenching temperature of 1600°F. (870°C.), Plate 6, and converted to D_I values by means of the lower curve on Plate 7. D_I values were also calculated by means of Grossmann's method which is illustrated with a sample calculation given in the appendix.

26. All data are tabulated and appear in Table 3.

27. Reproducibility of the data obtained by the testing procedure employed may be seen by comparing the two sets of curves shown on Plates 15 and 16. These are duplicate hardness surveys made on the same steel at different times during the investigation.

Discussion of Results

28. The Jominy curves indicate good correlation between the hardenability of cast and forged steels having identical compositions when differences in grain size are considered. Therefore, it is believed that within the limits of accuracy (amounting to only a few percent) the hardenability factors established for forged steel also apply to cast steel when certain allowances are made for the presence of carbide formers. Careful study of the data shows, as might be expected, that a greater quantity of strong carbide former can be efficiently used to promote hardenability in the lower carbon range than can be used in the higher carbon range.

29. Plate 17 illustrates the relation between calculated D_I and measured D_I. The correlation is extremely good in all cases except those where excessive quantities of stable carbide forming elements are present, and good correlation can not be expected in these cases since as previously explained, the quenching temperature 1650°F. (900°C.) was not sufficiently high to cause solution of all the carbides.

30. With the exception of these heats containing excessive amounts of elements forming stable carbides, the only steel covered in this investigation for which calculated hardenability does not agree reasonably well with experimentally determined hardneability is a steel (Heat N) which contains boron. The calculated hardenability of Heat S, another steel containing boron, agrees quite well with its experimentally determined hardenability. This apparent anomaly may be explained by the fact that Heat N was poured at a much higher temperature

than was Heat S. Boron is thought to be readily oxidized at steel making temperatures (14) and thus it is possible that the effect of boron on hardenability may be nullified when steel for castings is poured at the high temperatures necessary to attain good fluidity. This observation of the loss of the effect of boron on hardenability is confirmed by open hearth shops where it has been noticed that there is a decrease in the hardenability from the first to the last ingot of steel heats containing boron (15). This "fading effect" has been attributed to the oxidation of the boron while the steel is in the ladle. Further, since boron is known to cause some coarsening of the austenitic grain (this is substantiated by the coarse grain size in Heat S), the moderate aluminum and fine grain size of Heat N are further indications that the boron in this heat was oxidized.

Conclusions

31. For all practical purposes, cast steels may be said to have the same hardenability as forged steels of the same composition and grain size.

32. Within the range of compositions used in this study, normalizing treatments as high as 2000°F. (1090°C.) prior to quenching from 1650°F. (900°C.) did not materially affect the hardenability of cast steel except as they altered the as-quenched grain size.

33. Methods and factors applicable to the calculation of hardenability for wrought steels also apply to cast steels.

34. From these very limited observations on boron steels, it appears that boron can greatly increase the hardenability of cast steel. However, loss of effectiveness of the boron should be expected if high pouring temperatures are necessary.

35. When relatively high hardenability is desired in cast steel at the level of 0.35 to 0.45 percent carbon, strong carbide formers such as chromium and molybdenum should be held to limited quantities for reasons of economy; otherwise their potential benefit to hardenability is not fully effective. At lower carbon levels, such as 0.15 to 0.25 percent, increased amounts of such strong carbide formers can be used without sacrificing their full effect on hardenability.

Recommendations

36. Although it is recognized that quenching and tempering can not be applied effectively to some steel castings because of mass or

complicated design, the properties of many steel castings now heat treated by annealing or normalizing can be improved by quenching and tempering. It is recommended, therefore, that quenching and tempering be given thorough consideration for the heat treatment of steel castings having permissable section size and design.

37. It is further recommended that calculation of hardenability be utilized to its fullest extent in determining proper compositions for specific castings which are to be quenched and tempered. In this manner adequate hardenability may be predicted without unde waste of residual or added alloys.

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TABLE 1

Physical Properties Developed by Indicated Heat Treatments

	Quenched and Tempered	Normalized	Annealed
Tensile Strength, PSI	80,000	80,000	80,000
Yield Strength, PSI	65,000	48,000	43,000
Reduction of Area	65%	50%	45%
Tensile Strength, PSI	100,000	100,000	100,000
Yield Strength, PSI	74,000	55,000	45,000
Reduction of Area	56%	37%	30%
Tensile Strength, PSI	120,000	120,000	
Yield Strength, PSI	95,000	64,000	
Reduction of Area	50%	26%	

TABLE 2

Heat Compositions and Alloy Multiplying Factors

Heat		C	Mn	Si	P	S	Ni	Cr	Mo	Cu	Al	Boron
A	Composition	.37	1.00	.57	.019	.031	.11	.12	.05	.25	.04	
	Multiplying Factors		4.3	1.53	1.04	.981	1.04	1.28	1.12	1.07	1.04	
B	Composition	.42	.90	.62	.010	.025	.18	.03	.22	.27	.06	
	Multiplying Factors		3.95	1.58	1.02	.985	1.06	1.07	1.52	1.08	1.05	
C	Composition	.33	.82	.59	.038	.020	.16	.05	.20	.25	.02	
	Multiplying Factors		3.7	1.55	1.08	.987	1.06	1.11	1.48	1.07	1.02	
D	Composition	.38	.57	.62	.008	.028	.60	.47	.03	.25	.07	
	Multiplying Factors		2.9	1.58	1.01	.982	1.21	2.08	1.07	1.07	1.07	
E	Composition	.34	.82	.62	.011	.028	.54	.46	.02	.25	.07	
	Multiplying Factors		3.70	1.58	1.023	.982	1.19	2.05	1.05	1.07	1.07	
G	Composition	.22	.53	.45	.010	.016	.55	.48	.40	.27	.15	
	Multiplying Factors		2.75	1.415	1.02	.990	1.19	2.10	1.96	1.07	1.14	
H	Composition	.19	.53	.47	.010	.017	.23	.75	.24	.28	.07	
	Multiplying Factors		2.75	1.44	1.02	.989	1.08	2.72	1.57	1.08	1.07	
I	Composition	.24	.85	.45	.010	.022	.21	.75	.23	.28	.07	
	Multiplying Factors		3.80	1.415	1.02	.987	1.07	2.72	1.55	1.08	1.07	
J	Composition	.38	.56	.52	.010	.022	.21	.28	.25	.29	.05	
	Multiplying Factors		2.85	1.485	1.02	.987	1.07	1.65	1.60	1.08	1.05	
K	Composition	.40	.93	.47	.012	.023	.17	.065	.41	.28	.07	
	Multiplying Factors		4.05	1.44	1.025	.986	1.06	1.14	1.98	1.07	1.07	
L	Composition	.22	.54	.41	.004	.019	.15	.40	.39	.27	.03	
	Multiplying Factors		2.77	1.38	1.01	.988	1.05	1.92	1.94	1.07	1.03	
M	Composition	.32	.61	.47	.007	.022	.21	.07	.23	.29	.01	
	Multiplying Factors		3.00	1.44	1.01	.987	1.07	1.16	1.55	1.08	-	
O	Composition	.26	.41	.31	.019	.031	.14	.23	.23	.25	.08	
	Multiplying Factors		2.35	1.29	1.04	.98	1.05	1.53	1.55	1.07	1.075	
P	Composition	.31	1.55	.51	.022	.031	.12	.12	.06	.26	.07	
	Multiplying Factors		6.1	1.48	1.05	.98	1.04	1.28	1.15	1.07	1.07	
N	Composition	.41	.55	.56	.010	.028	.64	.41	.02	.27	.05	.002 (*)
	Multiplying Factors		2.80	1.53	1.02	.983	1.23	1.94	1.05	1.07	1.05	1.41
S	Composition	.45	.73	.58	.009	.028	.23	.01	.02	.29	.07	.002 (*)
	Multiplying Factors		3.40	1.54	1.01	.983	1.08	1.02	1.05	1.08.	1.07	1.41

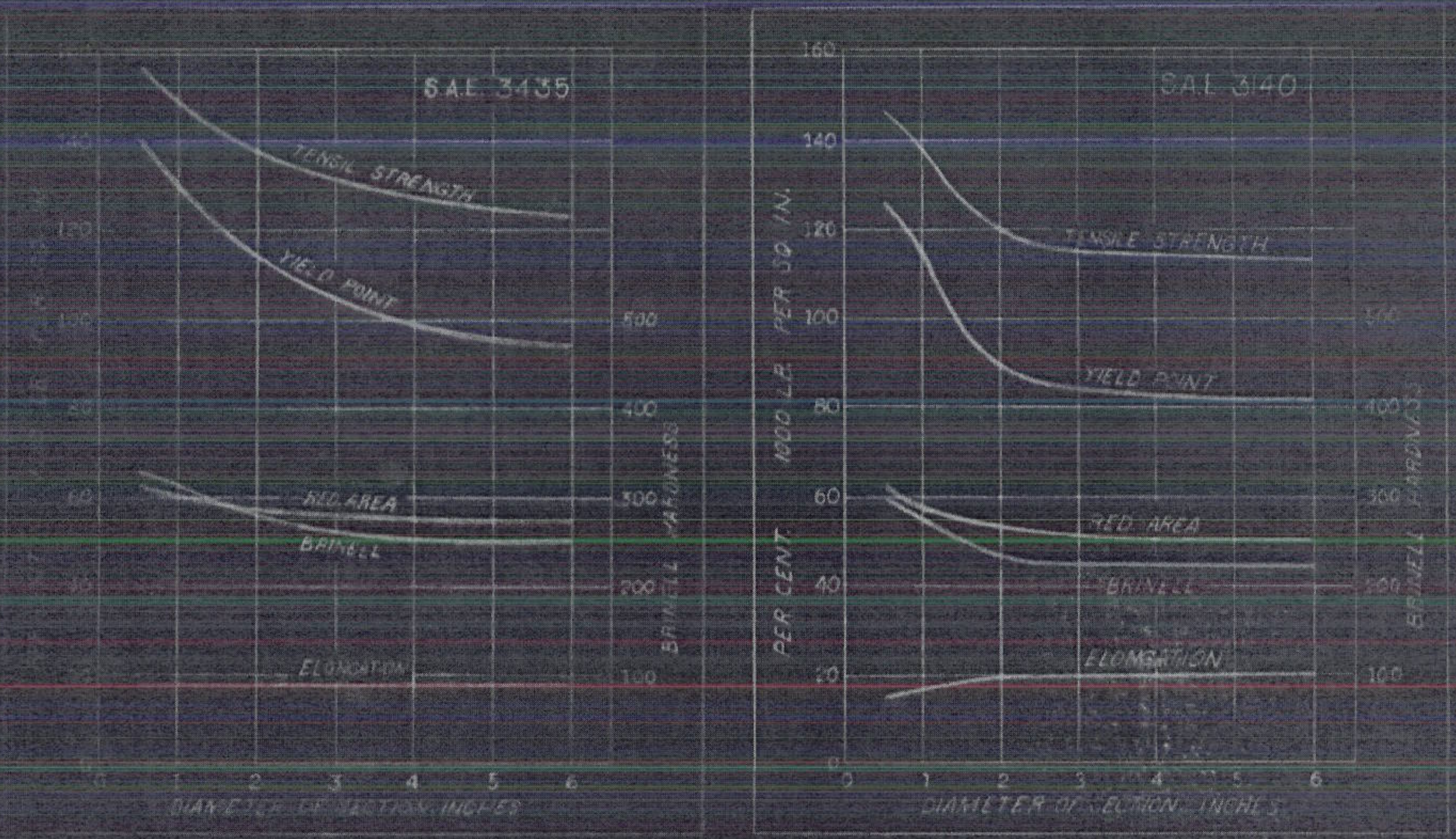
(*) - Percent added

TABLE 3

Hardenability Data

Heat	Prior Treatment	Grain Size	D_I C & Gr.S.	J.D.Meas. / 15	J.D.Meas. @ 1600/16	D_I Meas.	D_I Calc.
A	As Cast	8	.185	4.7	4.85	2.15	2.10
	1700 Soak	8	.185	4.7	4.85	2.15	2.10
	1850 Soak	8	.185	4.7	4.85	2.15	2.10
	2000 Soak	7	.201	5.3	5.46	2.30	2.28
	Forged	8	.185	4.7	4.85	2.15	2.10
B	As Cast	6½	.225	7.1	7.33	2.70	2.73
	1700 Soak	8	.197	6.1	6.30	2.48	2.40
	1850 Soak	7½	.206	6.3	6.50	2.52	2.50
	2000 Soak	6½	.225	7.1	7.33	2.70	2.73
	Forged	6½	.225	7.1	7.33	2.70	2.73
C	As Cast	6½	.200	5.9	6.10	2.44	2.38
	1700 Soak	6	.210	6.1	6.30	2.48	2.50
	1850 Soak	5	.228	7.2	7.43	2.72	2.72
	2000 Soak	4½	.240	7.6	7.84	2.80	2.85
	Forged	5	.228	7.4	7.64	2.75	2.72
D	As Cast	9	.173	5.2	5.36	2.28	2.44
	1700 Soak	9	.173	4.8	4.95	2.18	2.44
	1850 Soak	9	.173	5.0	5.15	2.23	2.44
	2000 Soak	8½	.180	5.5	5.67	2.34	2.54
	Forged	9	.173	6.1	6.30	2.48	2.44
E	As Cast	8	.177	9.0	9.30	3.10	3.12
	1700 Soak	9	.162	7.2	7.43	2.72	2.84
	1850 Soak	9	.162	8.0	8.25	2.88	2.84
	2000 Soak	8½	.170	8.3	8.56	3.00	3.00
	Forged	10	.149	6.5	6.70	2.56	2.63
G	As Cast	12	.101	5.6	5.87	2.40	2.38
	1700 Soak	12½	.097	5.3	5.46	2.31	2.28
	1850 Soak	12	.101	5.6	5.87	2.40	2.38
	2000 Soak	12	.101	5.6	5.87	2.40	2.38
	Forged	12½	.097	5.3	5.46	2.31	2.28
H	As Cast	9½	.117	5.2	5.36	2.28	2.50
	1700 Soak	9½	.117	5.2	5.36	2.28	2.50
	1850 Soak	9	.122	5.2	5.36	2.28	2.60
	2000 Soak	9	.122	5.2	5.36	2.28	2.60
I	As Cast	9½	.130	8.3	8.56	2.95	3.64
	1700 Soak	9½	.130	7.4	7.64	2.76	3.64
	1850 Soak	9	.137	8.8	9.06	3.05	3.84
	2000 Soak	9	.137	8.8	9.06	3.05	3.84
	Forged	9	.137	8.8	9.06	3.05	3.84
J	As Cast	8	.188	6.2	6.40	2.50	2.56
	1700 Soak	8	.188	5.8	5.97	2.40	2.56
	1850 Soak	7	.205	6.8	7.01	2.65	2.83
	2000 Soak	6	.224	6.3	6.50	2.52	3.06
	Forged	8½	.180	5.4	5.57	2.32	2.47
K	As Cast	7½	.201	9.8	10.10	3.25	3.25
	1700 Soak	7½	.201	9.8	10.10	3.25	3.25
	1850 Soak	7½	.201	10.0	10.30	3.29	3.25
	2000 Soak	6½	.220	11.6	11.98	3.58	3.56
	Forged	8	.194	9.2	9.50	3.14	3.14
L	As Cast	8	.143	4.7	4.85	2.15	2.15
	1700 Soak	8	.143	4.9	5.05	2.20	2.15
	1850 Soak	8	.143	4.9	5.05	2.20	2.15
	2000 Soak	7½	.150	5.2	5.36	2.28	2.27
	Forged	7½	.150	5.1	5.25	2.25	2.27
M	As Cast	3½	.211	3.8	3.92	1.92	1.90
	1700 Soak	4	.202	3.6	3.72	1.87	1.83
	1850 Soak	3½	.211	3.8	3.92	1.92	1.90
	2000 Soak	3½	.211	3.8	3.92	1.92	1.90
	Forged	3	.222	4.4	4.53	2.07	2.02
O	As Cast	6½	.177	2.7	2.78	1.60	1.57
	1700 Soak	8	.155	2.1	2.17	1.40	1.38
	1850 Soak	7½	.162	2.3	2.37	1.48	1.44
	2000 Soak	7	.170	2.5	2.58	1.55	1.51
	Forged	7	.170	2.5	2.58	1.55	1.51
P	As Cast	10	.142	5.4	5.57	2.32	2.32
	1700 Soak	8½	.162	7.0	7.22	2.64	2.64
	1850 Soak	8½	.162	6.0	6.20	2.46	2.64
	2000 Soak	8	.169	6.0	6.20	2.46	2.75
	Forged	10	.142	5.5	5.67	2.35	2.32
(*) E	As Cast	7	.212	8.7	8.97	3.02	3.62
	1700 Soak	7	.212	10.0	10.30	3.29	3.62
	1850 Soak	6	.231	12.4	12.75	3.71	3.94
	2000 Soak	5	.252	13.0	13.40	3.80	4.30
	Forged	8	.195	7.6	7.85	2.80	3.33
(x) S	As Cast	4½	.275	6.9	7.10	2.65	2.68
	1700 Soak	4½	.275	7.1	7.30	2.70	2.68
	1850 Soak	4½	.275	7.0	7.20	2.67	2.68
	2000 Soak	4	.290	7.5	7.74	2.78	2.82
	Forged	4½	.275	7.1	7.30	2.70	2.68

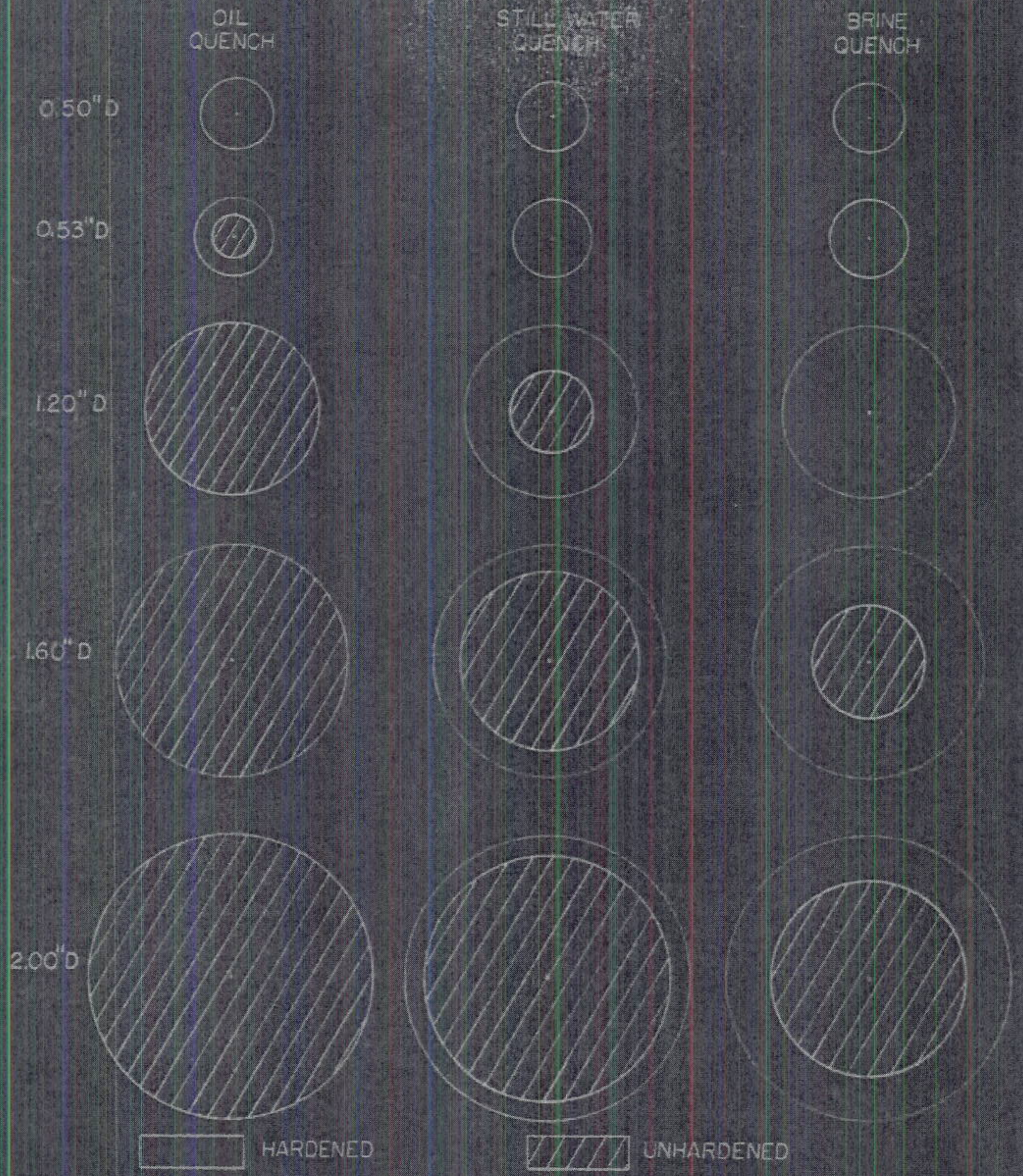
(*) - Poured Hot
(x) - Poured Cold (Skull)



MASS EFFECT FOR TWO STEELS

OIL QUENCHED AND TEMPERED AT 1000°F.

THE EFFECT OF SIZE & QUENCHING MEDIA ON THE DEPTH OF HARDENING OF A CARBON-MOLYBDENUM STEEL.



COMPOSITION: 0.22C 0.61Mn 0.47Si 0.21Ni 0.23Mo

GRAIN SIZE: 4+

PLATE 2

Physical Properties of SAE 1035 And SAE 1035+Boron Steels. Oil Quenched At 1500 Deg., Drawn At 1000 Deg. Sections are 1 In. (From Iron Age, Feb. 4, 1943)

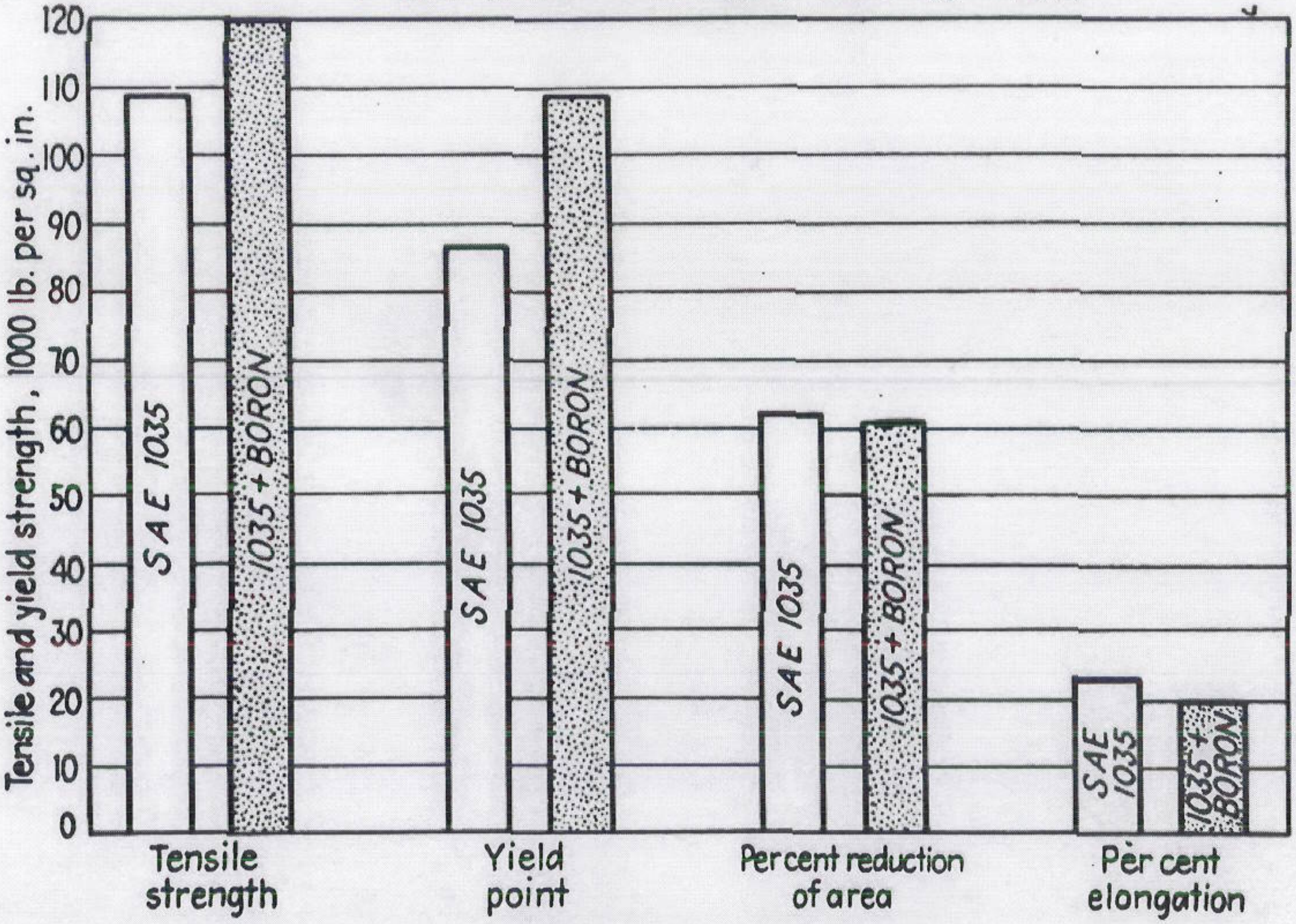
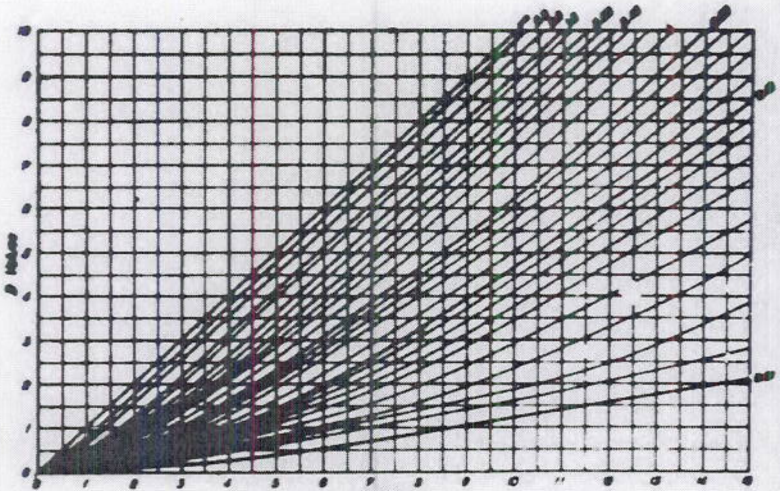
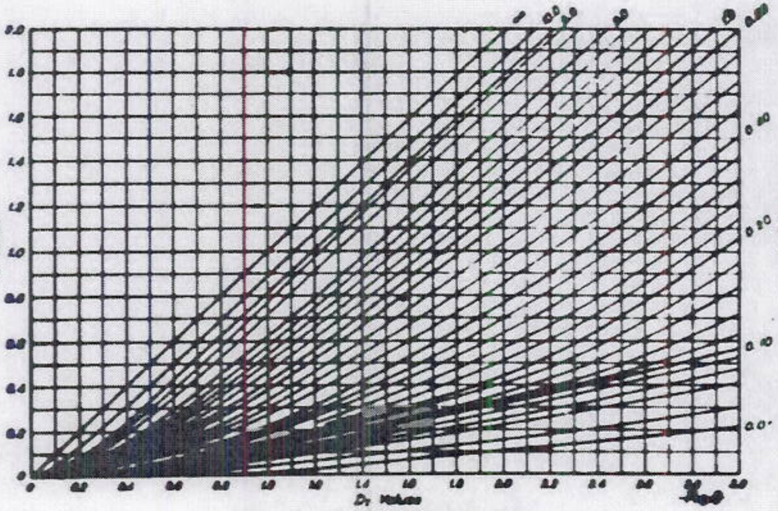


PLATE 3



Relationships Among Ideal Critical Size D_I, Actual Critical Size D and Severity of Quench H.



Same as above but Different Scale.

PLATE 4

COMPOSITION

C	Mn	Si	P	S	Ni	Cr	Mo	Cu	Al
.42	1.04	.54	.015	.032	.14	.11	.04	.25	.07

TYPICAL END QUENCH CURVE

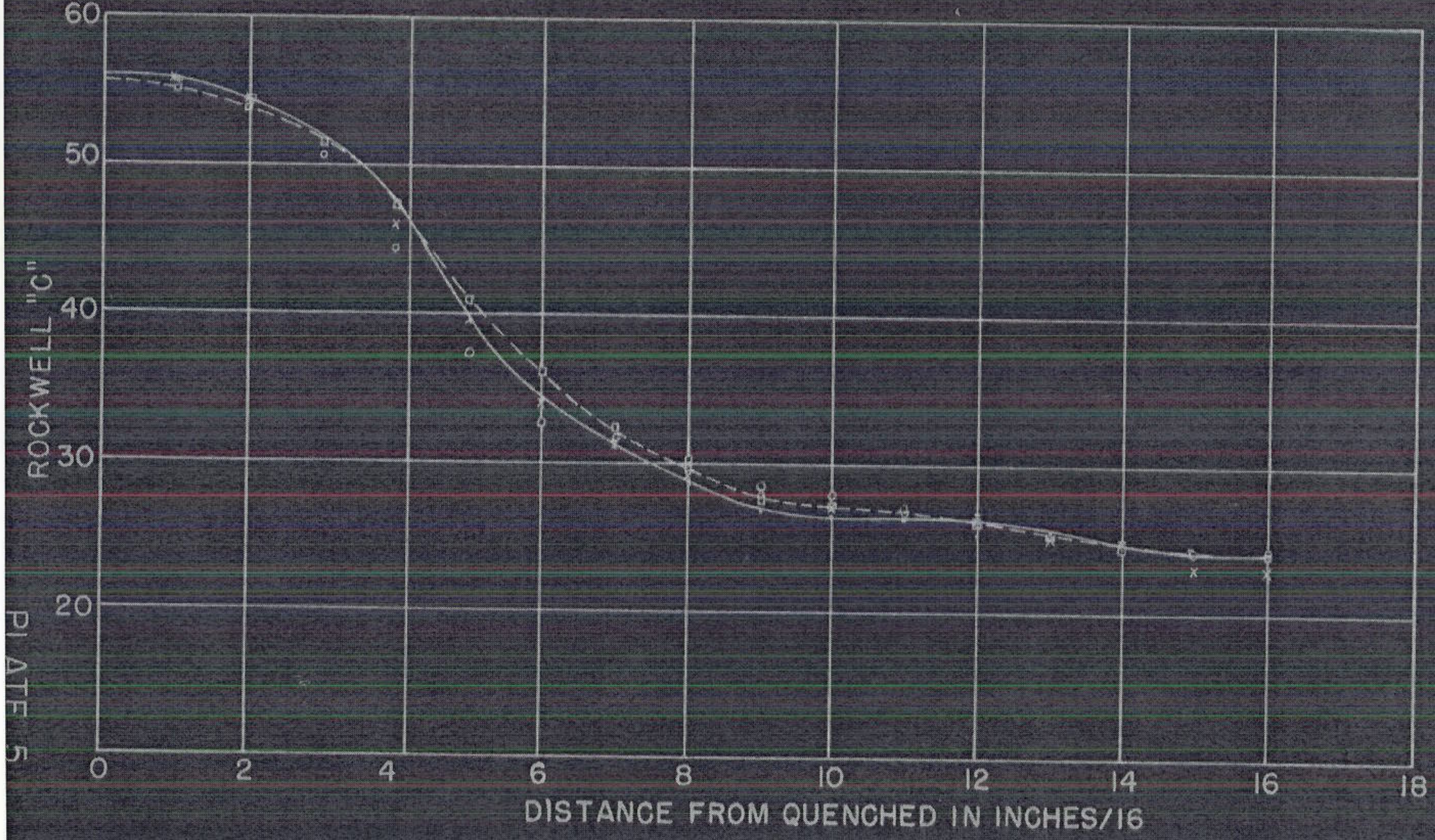


PLATE 5

CORRECTION OF DISTANCE ALONG END-QUENCH HARDENABILITY BAR FOR QUENCHING TEMPERATURE

$$\frac{\text{END-QUENCH DISTANCE (MEASURED)}}{\text{FACTOR}} = \text{END-QUENCH DISTANCE AT 1600°F.}$$

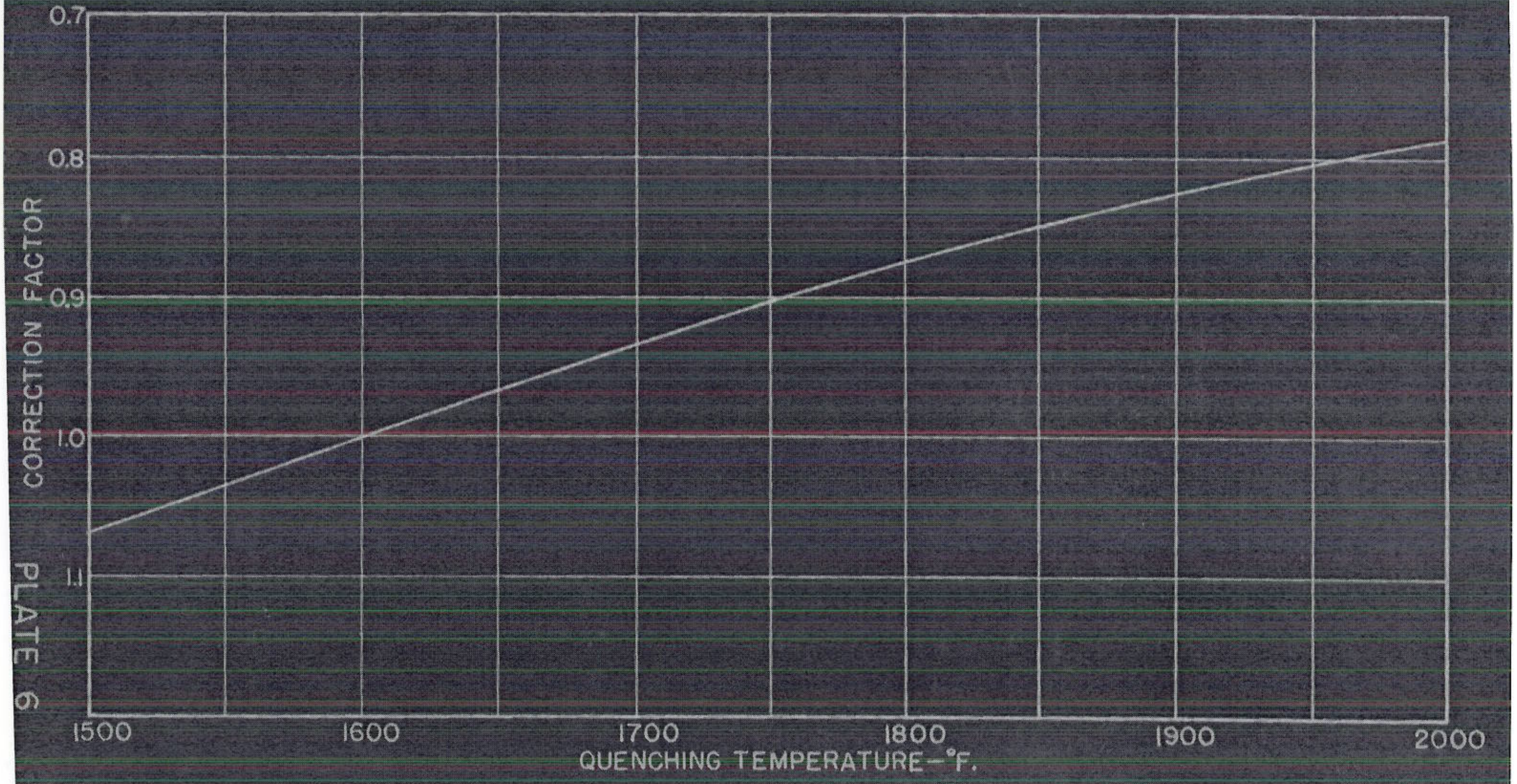


PLATE 6

JOMINY DISTANCE VS. IDEAL CRITICAL DIAMETER

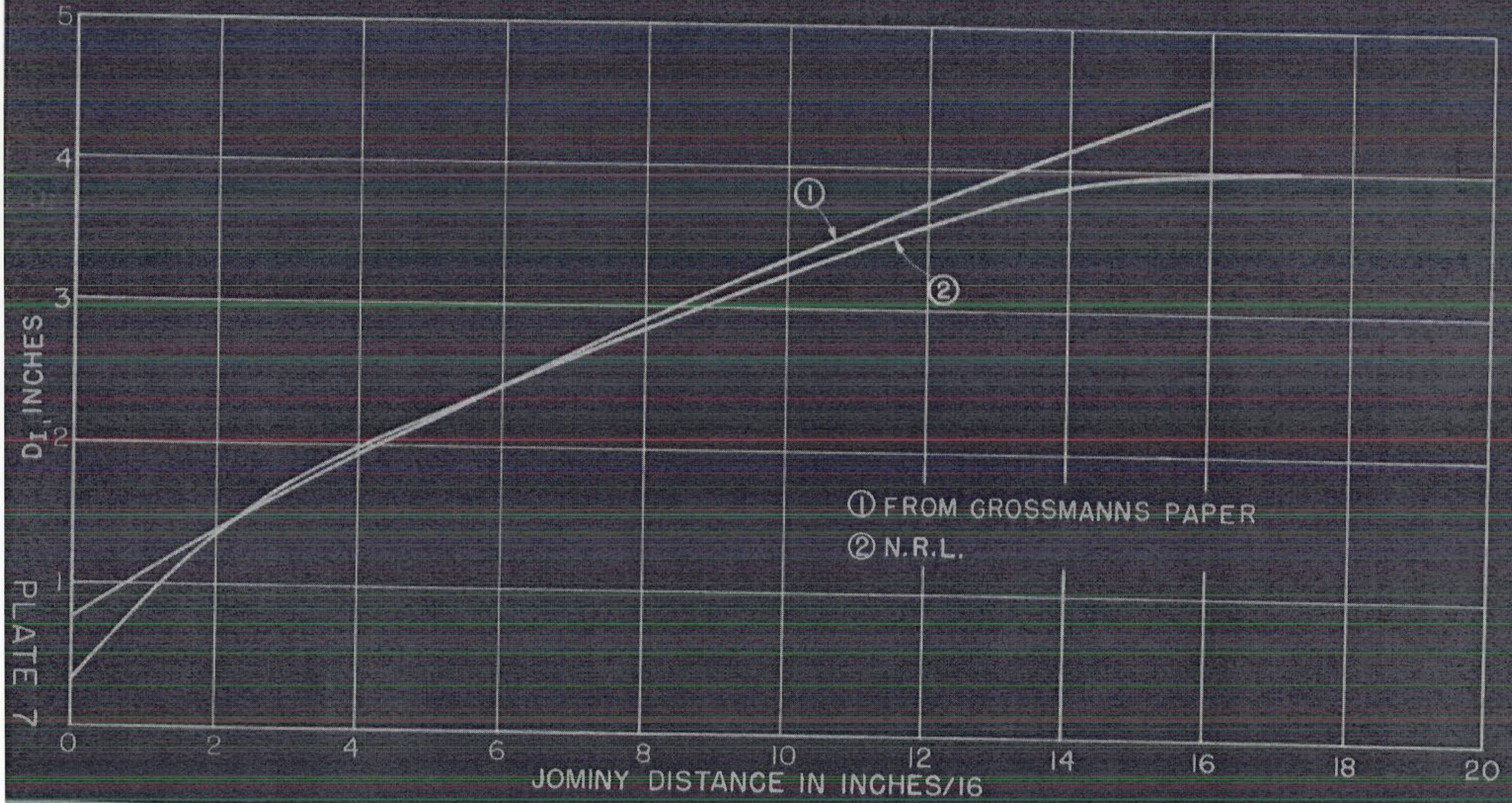


PLATE 7

DETERMINATION OF THE REVISED HARDENABILITY FACTOR CURVE FOR MOLYBDENUM

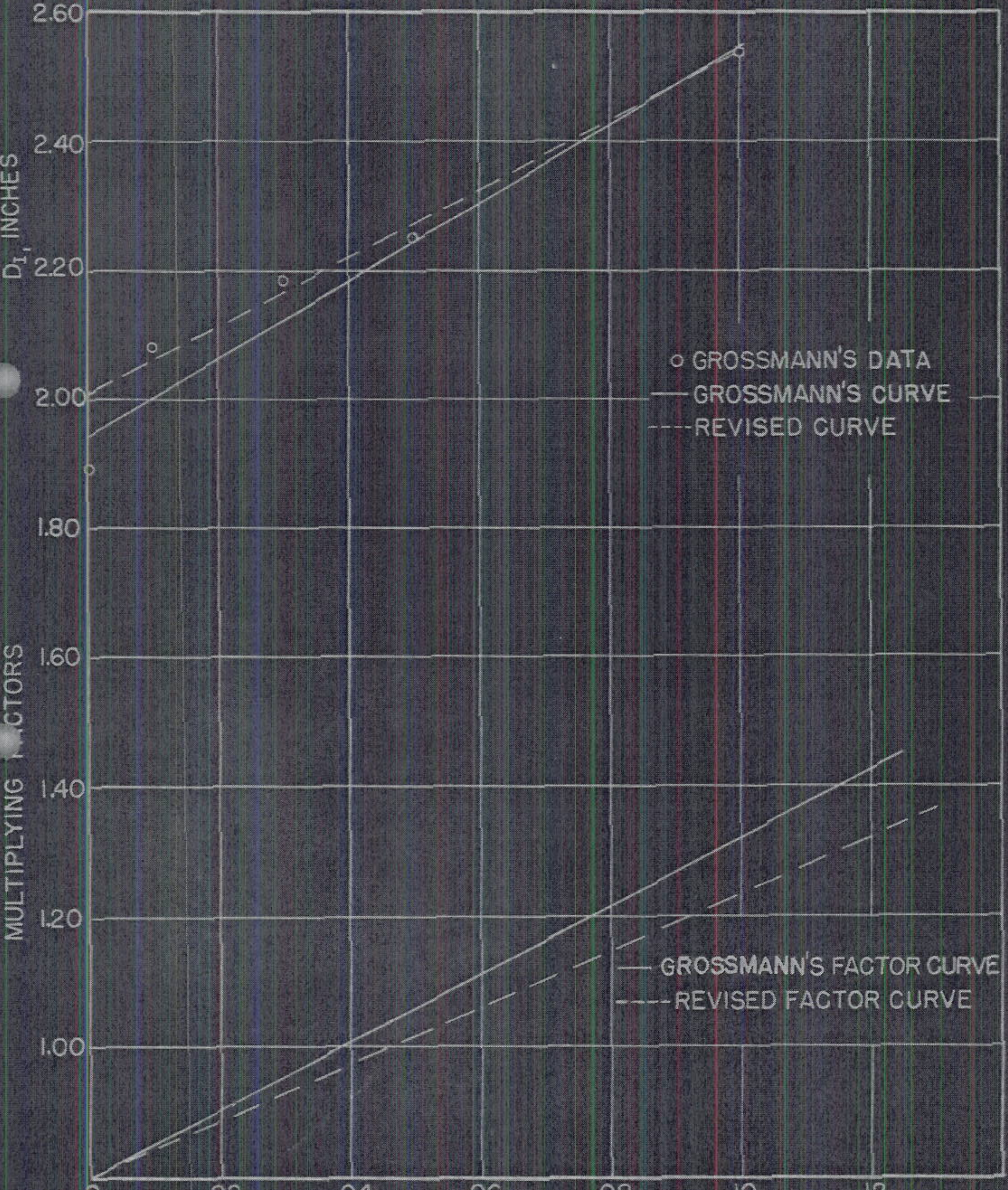
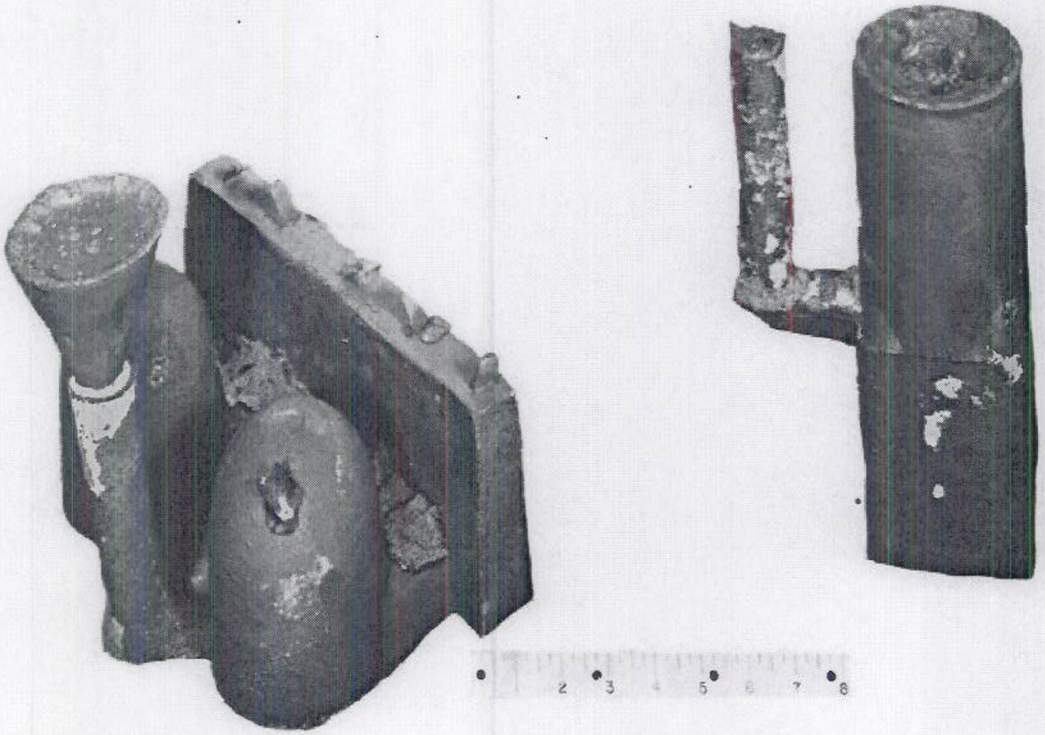


PLATE 8



TEST CASTINGS AS REMOVED FROM MOLDS

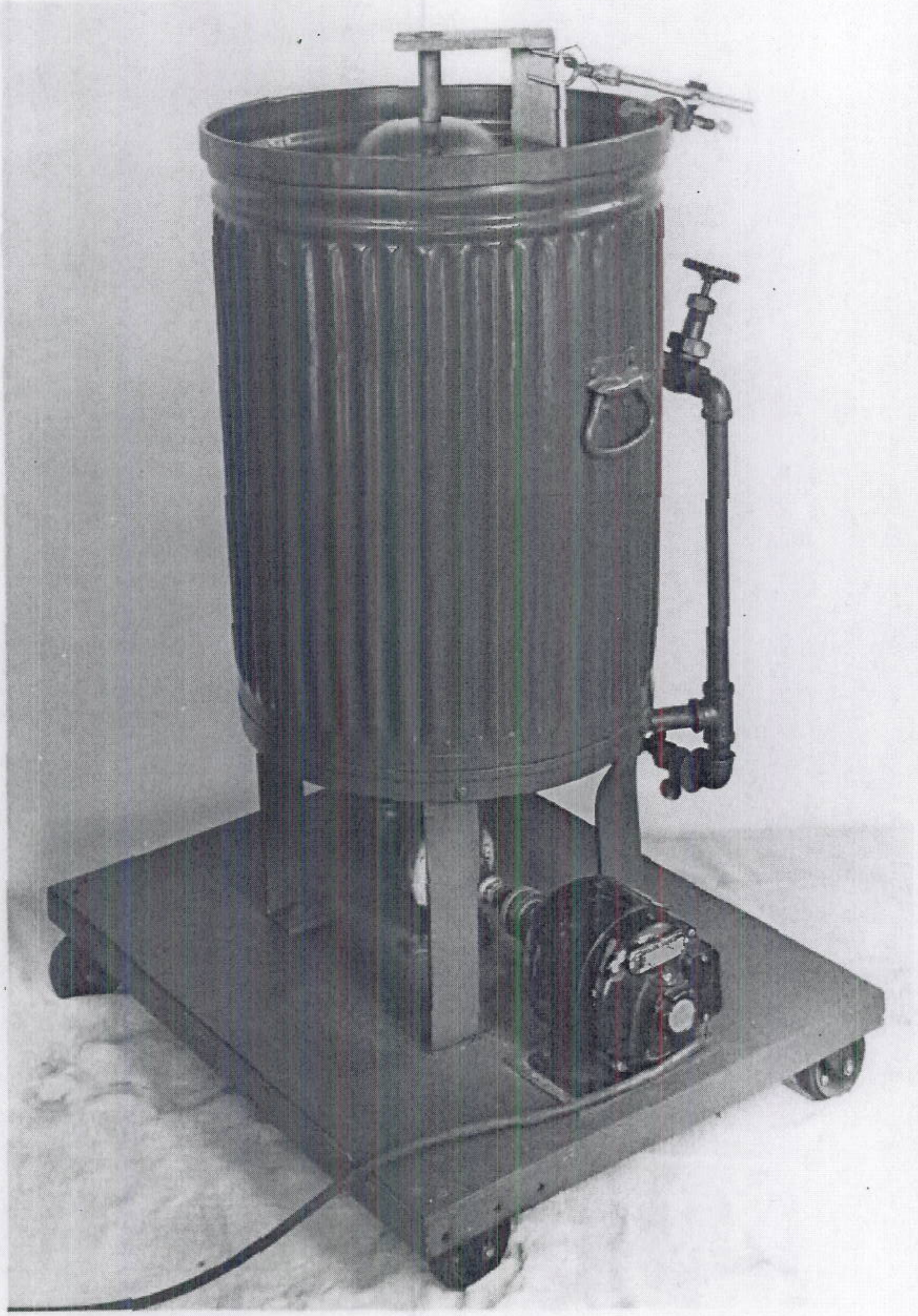
PLATE 9

STANDARD JOMINY BAR

AS PREPARED
FOR QUENCHING

AS PREPARED FOR
HARDNESS SURVEY

PLATE 10



QUENCHING EQUIPMENT WITH BAR IN POSITION

THE EFFECT OF DEPTH OF GRIND ON THE JOMINY CURVE

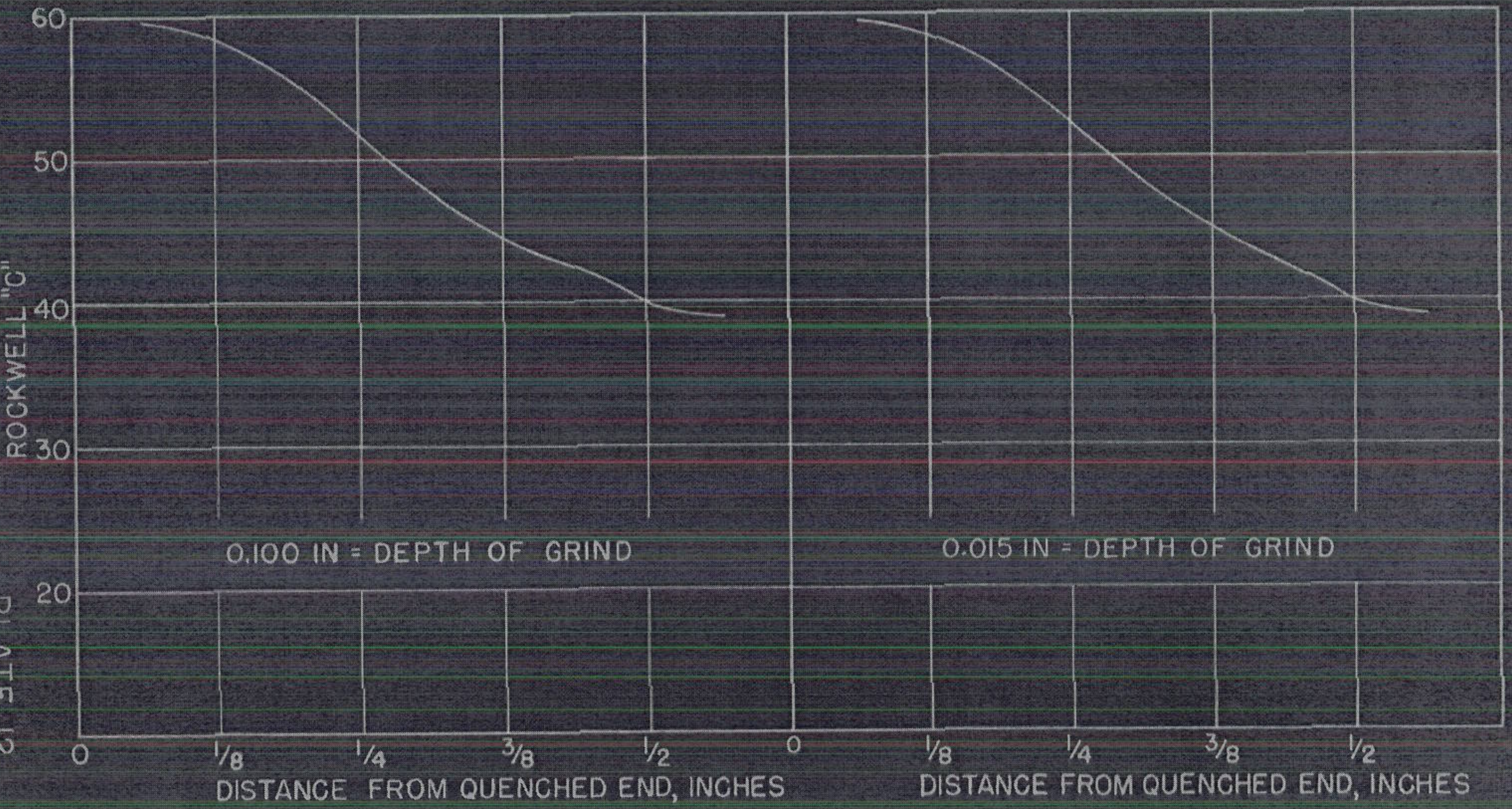
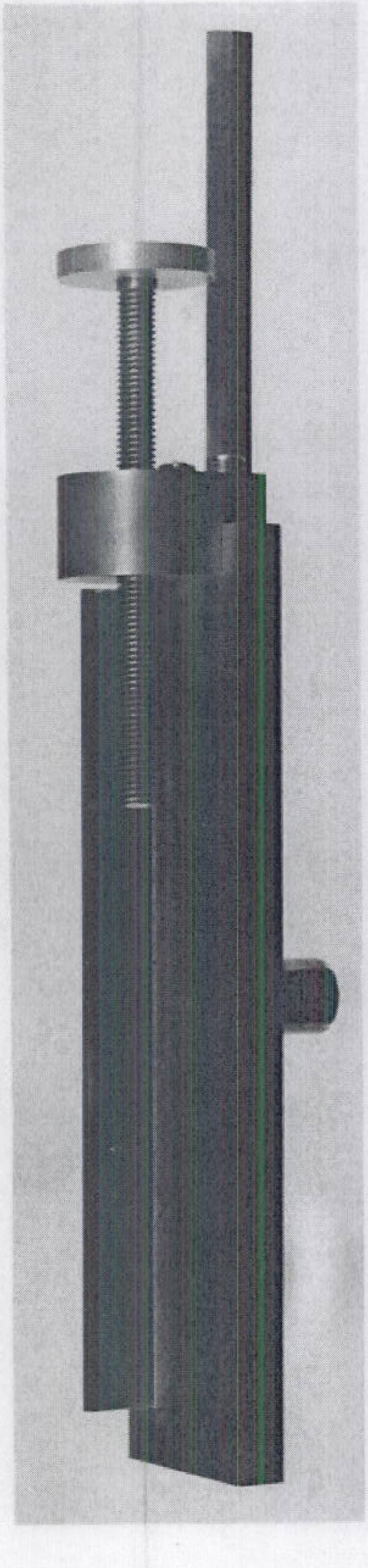


PLATE 12



SPACING JIG FOR USE WITH HARDNESS TESTER

PLATE 13

50 PERCENT MARTENSITE HARDNESS
VS.
CARBON CONTENT

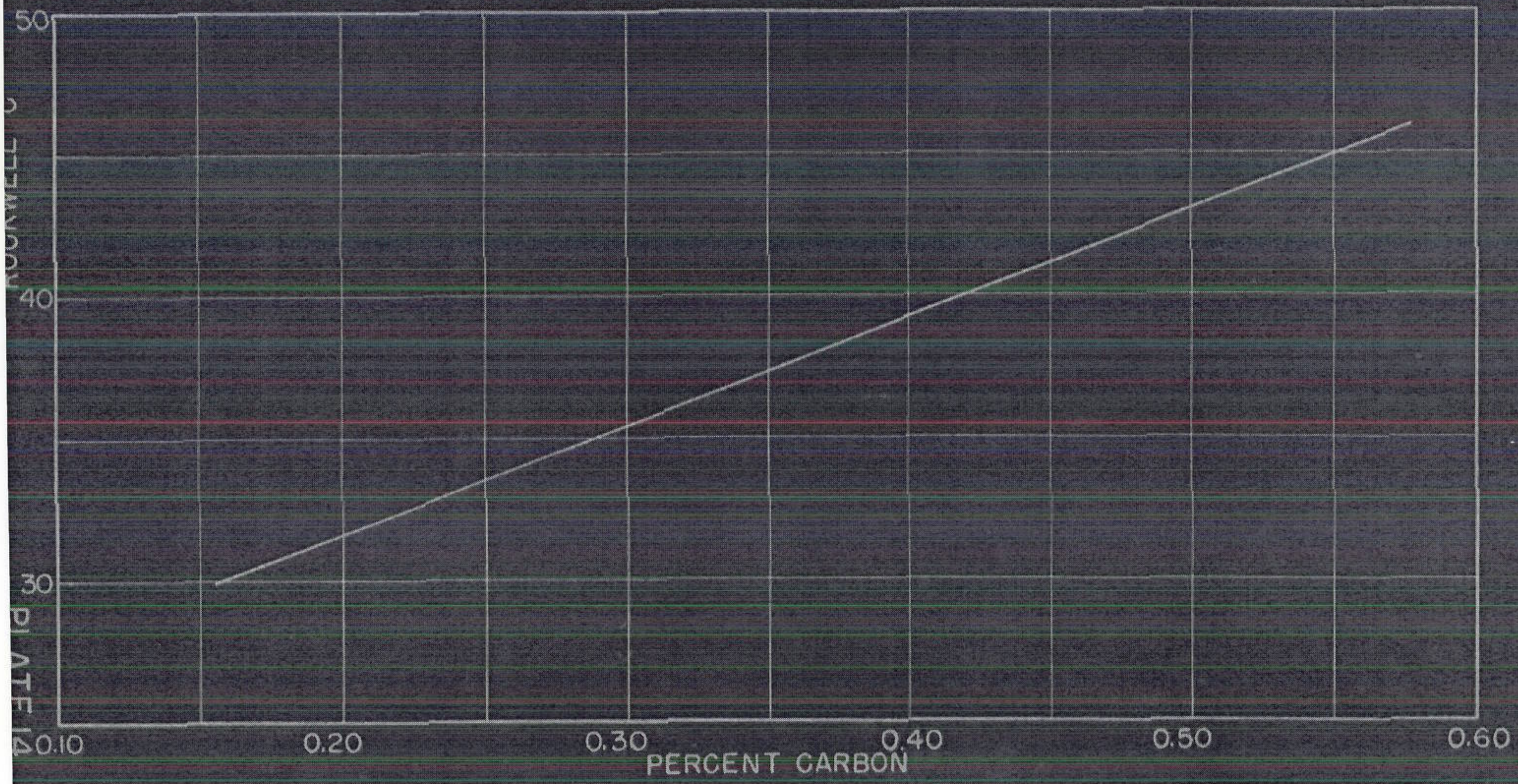
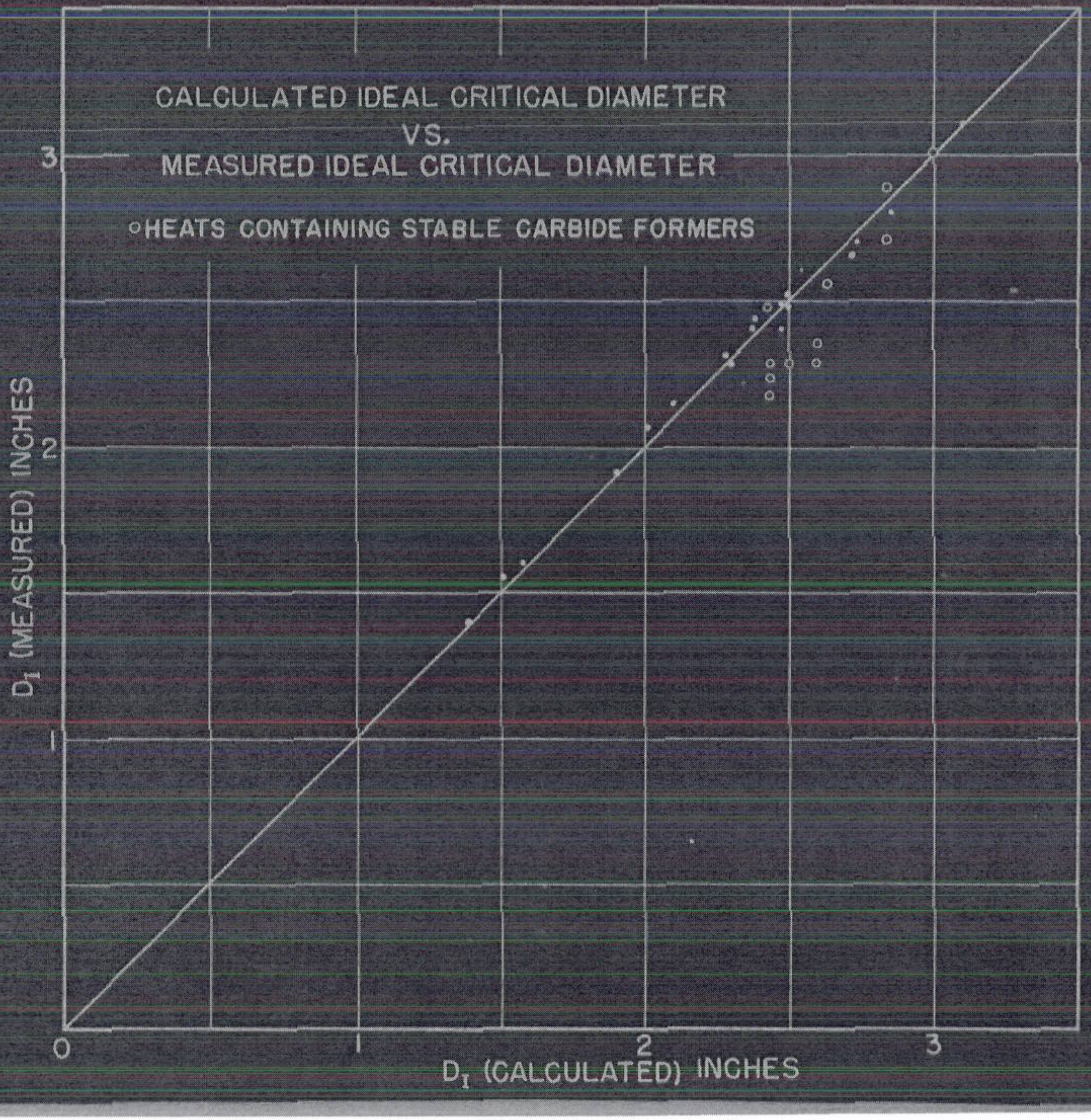


PLATE 14

PLATE 17



CALCULATED IDEAL CRITICAL DIAMETER
VS.
MEASURED IDEAL CRITICAL DIAMETER

CARBON CONTENT AND GRAIN SIZE
VS.
IDEAL CRITICAL DIAMETER

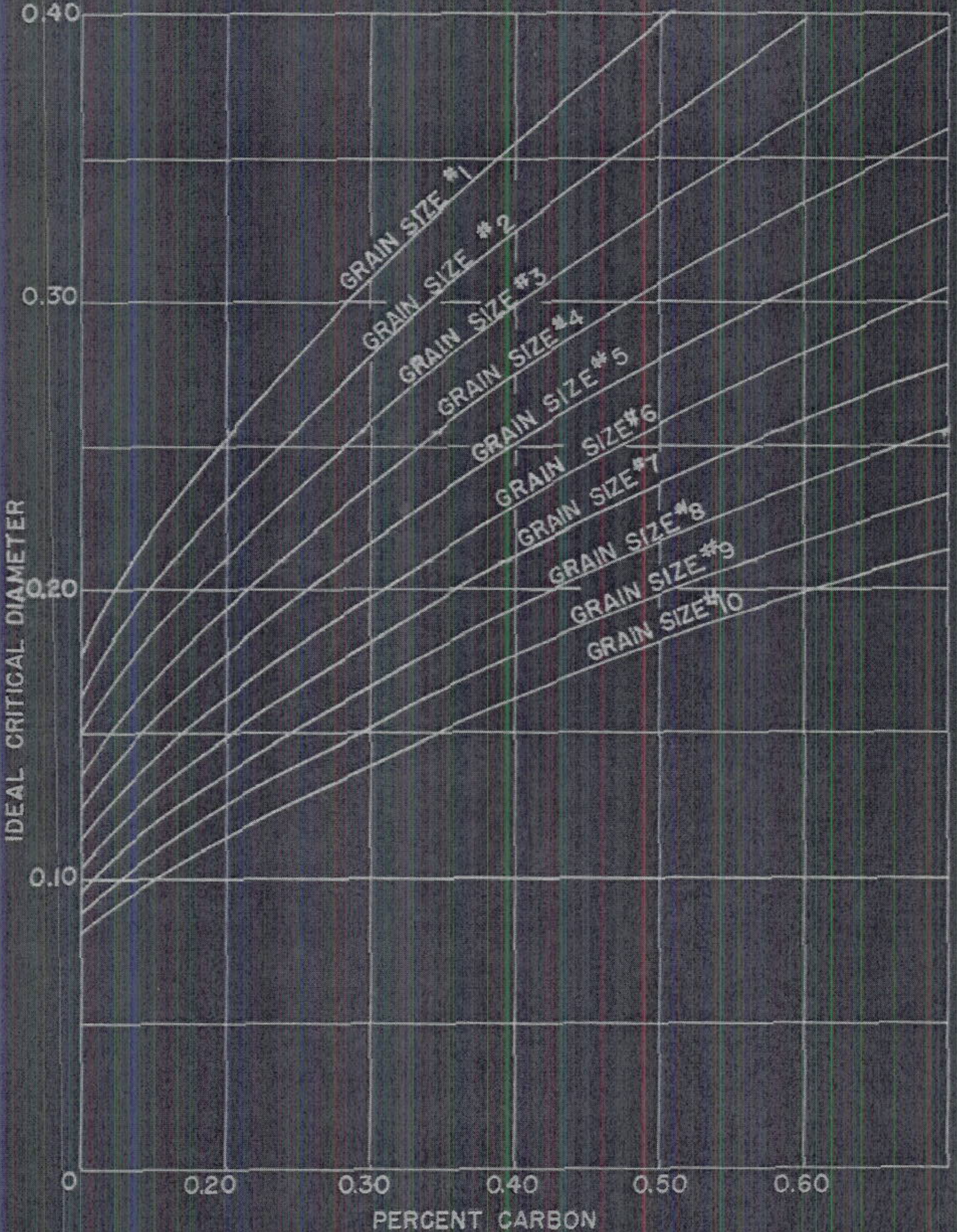


PLATE 18

HARDENABILITY MULTIPLYING FACTORS VS. PERCENT ALLOY

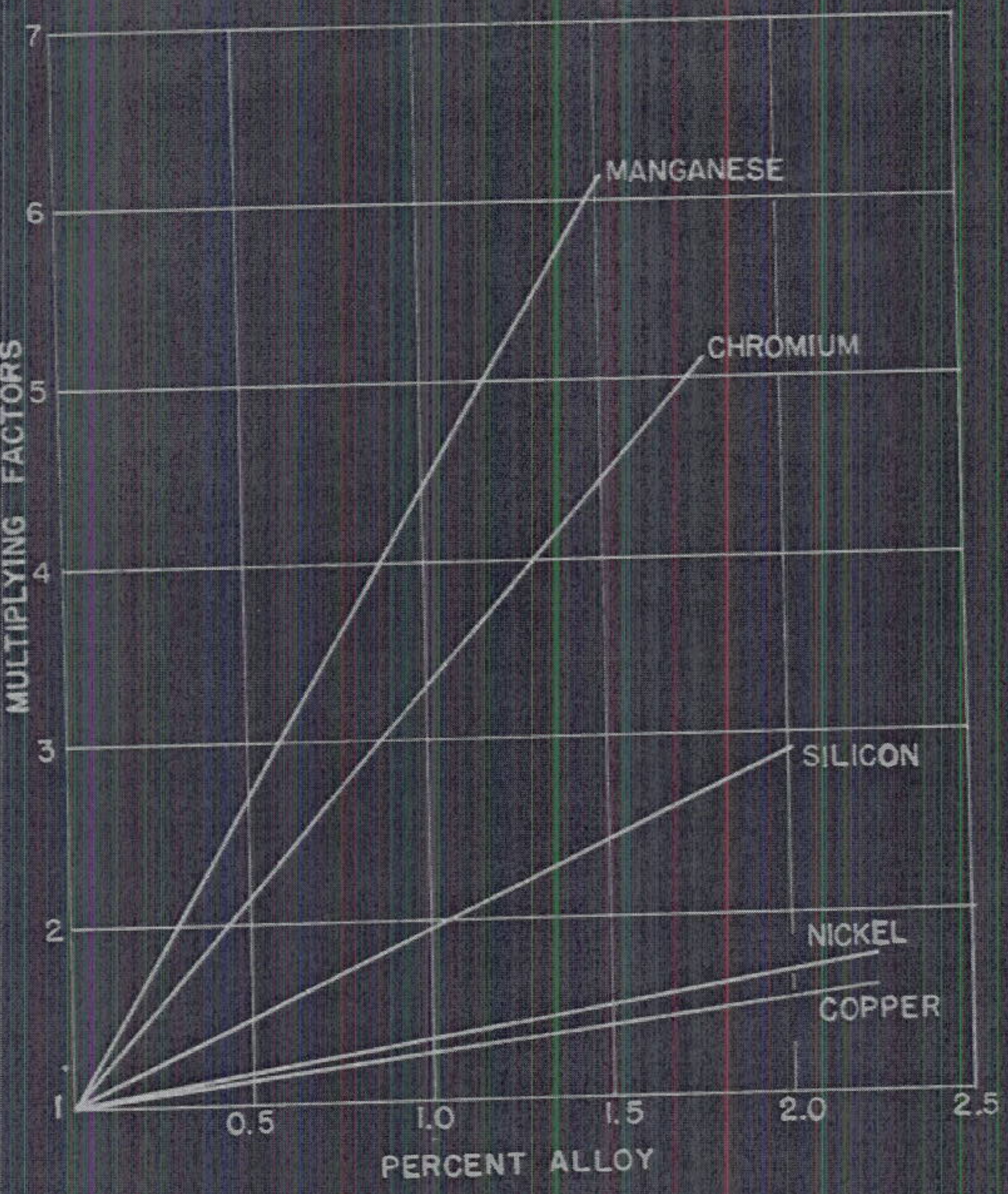


PLATE 19

HARDENABILITY MULTIPLYING FACTORS
VS.
PERCENT ALLOY

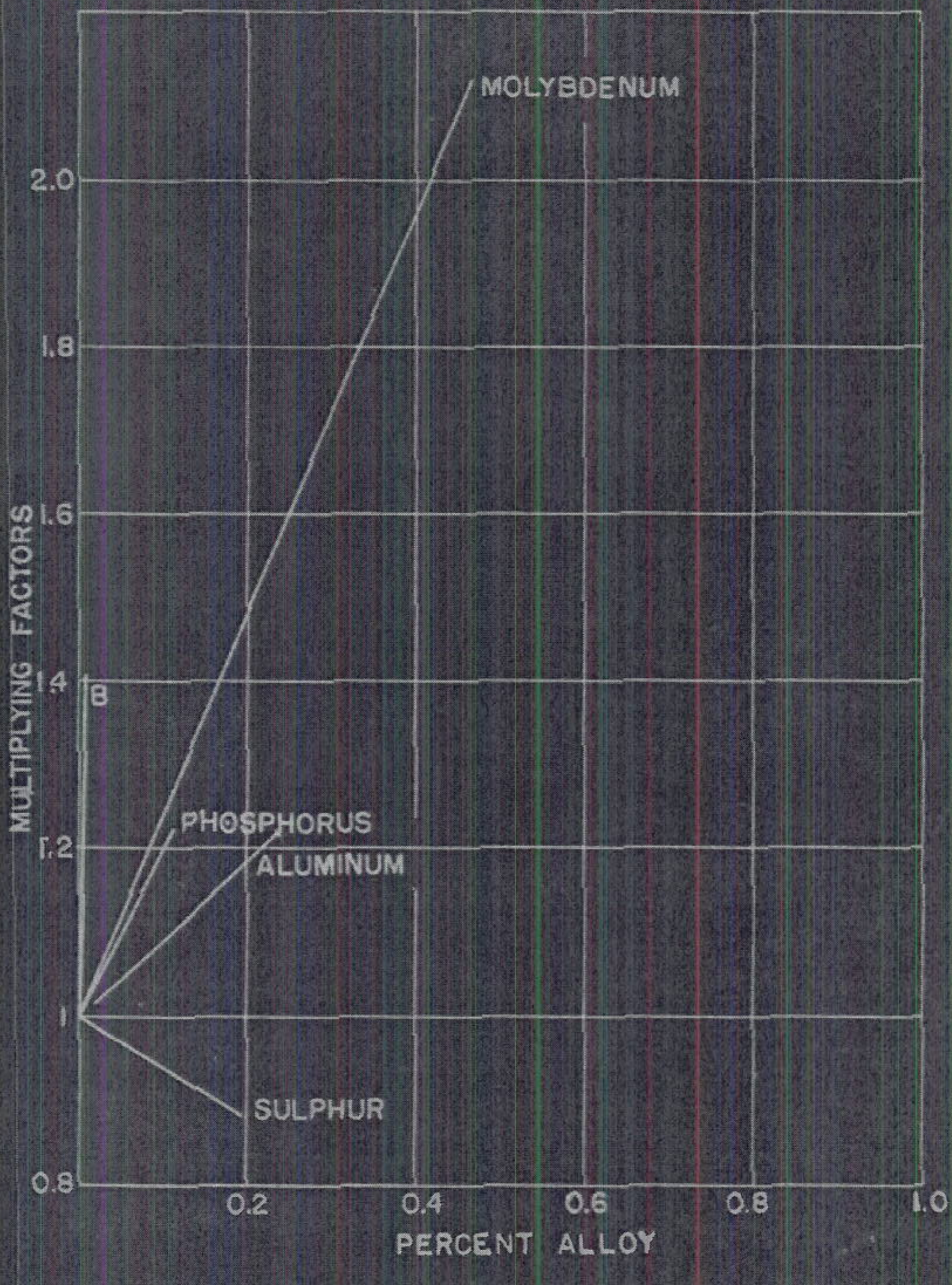


PLATE 20

APPENDIX

Development of Jominy Distance vs. D_I Curve

The method used in this paper to convert Jominy distances to Ideal Critical Diameter depends upon the generally accepted principle that, for almost all steels, the cooling rate during transformation at the center of a quenched round is the same as the cooling rate during transformation at a position of equal hardness on a Jominy bar of the same steel. For the same size of round, the cooling rate at the center must be the same when the severity of quench and quenching temperature remain the same, regardless of the composition of the steel unless thermal conductivity is materially altered by the change of composition.

A chart* published by the Republic Steel Corporation (12) shows the relationship between diameters of rounds quenched in still water and distances along the Jominy bar at which the hardness values are equal to the center hardness values of the respective rounds. Since the diameter of any round which will harden to a structure of fifty percent martensite at its center in a still water quench (severity of quench equals unity) can be converted to Ideal Critical Diameter by means of the curve shown on Plate 4, it is only necessary to assume several steel compositions which will give fifty percent martensite at different distances along the Jominy bars and convert the corresponding diameters of rounds of the corresponding steels with equal center hardness values from a still water quench to D_I values in order to locate the desired curve. For example, if the Jominy curve of a particular steel yields a hardness indicative of a microstructure of fifty percent martensite at 0.25 inches from the quenched end of the bar, a round bar of 1.2 inches diameter quenched in still water will have the same center hardness and structure, and the D_I corresponding to that Jominy distance is 1.96 inches. In like manner, the corresponding D_I values for other Jominy distances were found and the Jominy distance vs. D_I curve of Plate 7 was drawn.

(*) - It is to be emphasized that this chart is admittedly approximate and, therefore, the accuracy of the lower curve on Plate 7 is not as great as is desirable. However, agreement between calculated D_I and D_I converted from experimental Jominy test results has been improved in numerous instances by its use and it is believed to be more reliable than the similar curve developed from calculated half-temperature times.

APPENDIX

Sample Calculation of D_I by Grossmann's Method

D_I for carbon and grain size is read from Plate 18, and the individual multiplying factors for the corresponding amount of each alloy present are read from the curves on Plates 19 and 20. The product of D_I for carbon and grain size and the alloy factors is equal to D_I for the steel in question.

Elements	Percent of Composition	Multiplying Factor
C	0.37	0.201*
Mn	1.00	4.3
Si	0.57	1.53
P	0.019	1.04
S	0.031	0.981
Ni	0.11	1.04
Cr	0.12	1.28
Mo	0.05	1.12
Cu	0.25	1.07
Al	0.04	1.04

Product of Factors 2.28
D_I - 2.28 inches

(*) - D_I for grain size of ASTM No. 7