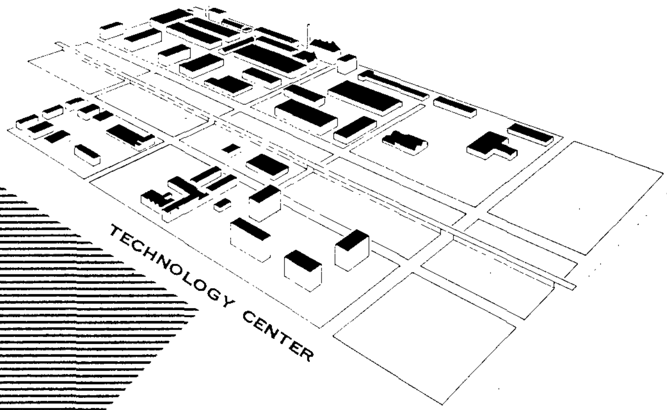
ARF 2214-4
(Summary Report)

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY



DEVELOPMENT OF AN AIR-HARDENABLE CAST STEEL FOR THICK SECTIONS

Detroit Arsenal
Center Line, Michigan

Contract No. DA-11-022-ORD-3686

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ARMOUR RESEARCH FOUNDATION
of
ILLINOIS INSTITUTE OF TECHNOLOGY
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for

Commanding Officer
Detroit Arsenal
Center Line, Michigan

Attn: Mr. E. Mackiewicz
ORDMC-REM1

June 6, 1962

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ABSTRACT

The objective of this program has been to develop a steel alloy composition suitable for cross sections of up to 5 inch thickness which can develop adequate toughness down to $-40^{o}F$ after air hardening and tempering. As a result of systematic variations in alloy content, it has been shown that there are upper limits for each of the major elements in common use. Moreover, a critical carbon content for optimum toughness exists. From all of this, two preferred chemistries have been chosen which in a 5-inch section are capable of providing 18-20 ft-lb impact strength at $-40^{o}F$ and a tempered hardness after air hardening of 22-24 Rc.

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DEVELOPMENT OF AN AIR-HARDENABLE CAST STEEL FOR THICK SECTIONS

I. INTRODUCTION

The function of armor is to resist the shock of explosives and the penetration of projectiles. It fails to do this by permitting punch-through or by fracturing in various ways. In the case of steel, the attributes of strength and toughness make for resistance to failure. These are intensive measures. The extensive factor is the thickness of the armor. In mobile vehicles, therefore, the thickness of armor plate may vary from 1-8 inches depending on the anticipated need.

Both strength and toughness of steel are enhanced by heat treatment. From the viewpoint of strength alone, it is important to increase hardness only, for there is a linear relationship between ultimate tensile strength and hardness. Toughness, however, is a much more subtle property depending on hardness, microstructure, and manner of test.

When a hardness requirement is laid down, the implication usually is that the hardness should be uniform throughout the section. This imposes a requirement of the steel to have adequate hardenability--the ability to harden uniformly throughout the section. Hardenability is an intrinsic property of the steel and its composition, but the achievement of uniform hardness depends also on the thickness and rate of quench involved. The purpose of alloying is primarily to increase the intrinsic hardenability of the steel to permit uniform hardening through a thicker section or to reduce the necessary intensity of quench or both.

The toughness of a steel depends indirectly on intrinsic hardenability, for it is well recognized that the existence of the microconstituents pearlite and

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proeutectoid ferrite are deleterious to toughness. A structure of quenched and tempered martensite provides the most propitious condition for high toughness. The equivalence of tempered bainite is controversial. Certainly at higher carbon levels (> 0.3% C) bainite is inferior to tempered martensite.

The qualification of an armor steel, cast or wrought, is in terms of uniformity of hardness throughout the section and uniformity of toughness as measured by the V-notch Charpy impact test with specimens at -40°F.

A number of steel compositions have been or are now in use to provide cast armor sections of 2-5 inch thickness. These generally contain 0.25-0.33% C with the tendency more recently toward the lower carbon levels. Alloy chemistries range: 0.7-1.5% Mn, 0.5-2.5% Cr, 0.25-1.5% Ni, 0.3-0.7% Mo; with total alloy ranging from 2.5-4%. A typical chemistry involves: 0.28% C, 1.5% Mn, 1.5% Ni, 0.55% Mo, 0.05% V. The development of optimum properties involves austenitizing, oil or water spray quench, and tempering to hardness levels between 200 and 300 BHN.

These hardness levels are quite low compared to the maximum attainable with carbon contents of 0.25-0.33%. Even with only 0.15% C, a maximum hardness of 400 BHN can be achieved. The additional carbon serves only as a cheap source of hardenability and a convenience to the foundrymen from a lower melting temperature viewpoint. Work in recent years, however, points out that there is a price to pay. Higher carbon levels narrow the structural conditions for high toughness, increase the likelihood of flaking and quench cracking, and increase the dangers of cracking in welding.

This program has set out to search for new compositions of cast steel which can deliver, in the heat-treated state, improved combinations of hardness and subzero toughness uniformly through cast sections of up to 5 inches thickness. Furthermore, it was to be a major qualification of these new steels that they be capable of providing these mechanical properties by air hardening (and subsequent tempering). Air hardening is a very useful attribute because it by-passes the costs associated with oil or water quenching arrangements and it minimizes residual stresses from non-uniform cooling.

Bearing in mind the cost limitations imposed on steel used for armor, the choice of alloying elements is limited to C, Mn, Ni, Cr, Mo, and Si with, at most, very minor additions of V or B. Furthermore, the total alloy content was not permitted to exceed 6 per cent by weight.

More than 38 experimental steel compositions were studied--the compositions representing various systematic trends in chemistry. In nearly every instance, the following information was obtained:

1. Hardness distribution after air quenching.
2. Tempering characteristics.
3. V-notch Charpy impact toughness at -40°F and at R. T. for hardness levels of approximately 25 and 30 Rc.
4. Distribution of toughness through a 5-inch section.

The bulk of this information was derived from the testing of small heats. One steel composition of superior performance was tested in the form of large cast slabs of 5-inch, 4-inch, and 3-inch thick sections cast in sand molds.

II. EXPERIMENTAL PROCEDURES

The analysis of the behavior of various cast steel compositions in an appropriate state of heat treatment involved the following sequence of operations:

Production of cast specimens.

Homogenizing and softening anneal.

Preliminary cutting and machining where necessary.

Austenitizing uniformly at 1700°F.

Air quenching in actual or simulated 5-inch section.

Exploration of the tempering process as a function of temperature.

Measurement of the as-quenched hardness variation through the section.

Tempering to appropriate hardness in actual or simulated 5-inch section.

Machining to impact or tensile test specimens.

Mechanical testing at R. T. or -40°F.

Metallographic analysis.

For reader comfort, this section will summarize the procedures used, and detailed descriptions will be relegated to the Appendix.

Because of the need to closely control composition and structure in a large number of experimental steels, and because of cost and productivity considerations, the major portion of this exploration was conducted in terms of 50 lb melts producing 25 lb ingots cast into steel molds. Armco iron was used as melting stock.

In order to control such variables as cast grain size and shape, soundness, segregation, and inclusion amount and distribution, the melting was conducted in the closed shell of a vacuum induction melting facility. The vacuum capability itself was not used. The unit was simply sealed and the minor oxygen content of the chamber equilibrated with the melt. Under these conditions, planned chemistries could be maintained closely without the use of a slag cover. The melt was sequentially deoxidized with 0.5% Si and 0.1% Al. Two tapered ingots of approximately 25 lb weight with adequate hot tops were produced in steel molds providing the following approximate dimensions: top section 2 1/2 in. x 3 in.; bottom section 2 1/2 in. x 2 in.; length 8 in. The hot top was additionally heated with exothermic additions to improve the soundness of the ingot.

The ingots were given a homogenizing anneal at 1800°F for 8 hours and furnace cooled at 150°F per hour to soften and permit cutting. An alternative softening treatment involved air cooling, reheating to 1300°F for 15 hours, and air cooling. The ingots were cut longitudinally into three pieces as shown in Figure 1. Any unsoundness was contained in the flat plate center section, and this portion was used for hardness testing only in regions of good soundness. The two taper sections after heat treatment were used to produce V-notch Charpy impact specimens. The cast structures did not show any pronounced columnar grain structure.

The taper test sections were machined to fit as wedge inserts into a large block of steel containing a centrally located rectangular hole. The block itself had the dimensions 5 in. thick x 10 1/2 in. x 12 1/4 in. and was of a steel of comparable composition to the test specimens. By wedge fitting the tapered test blocks (three pieces) into the square hole, air-hardening in a 5-inch section could be simulated. The specimen-block assembly was austenitized at 1700°F in an electrically heated furnace with an argon blanket. A photograph of this arrangement is shown as Figure 2.

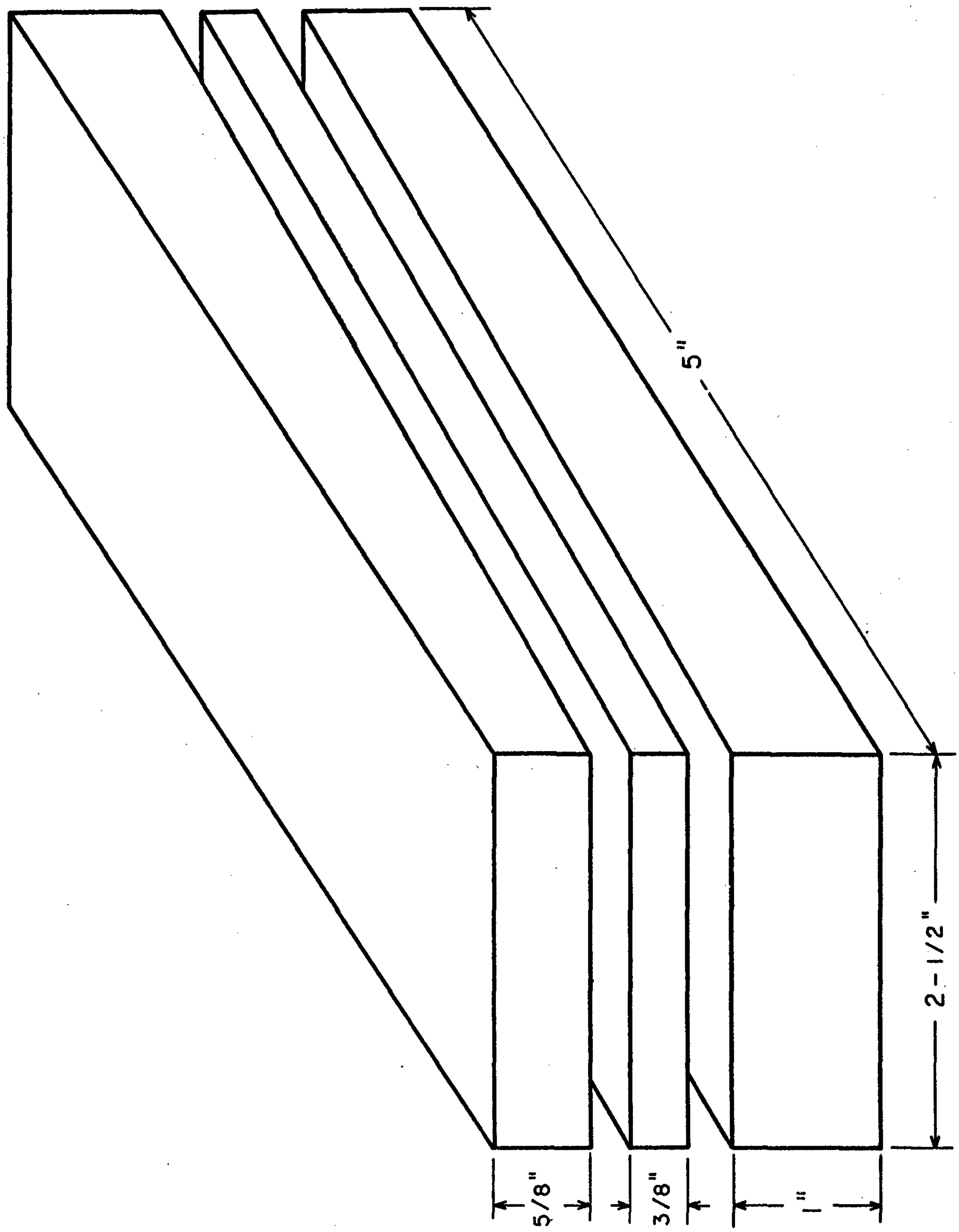

FIG.1 DIMENSIONS AND ASSEMBLY OF TEST SPECIMENS.

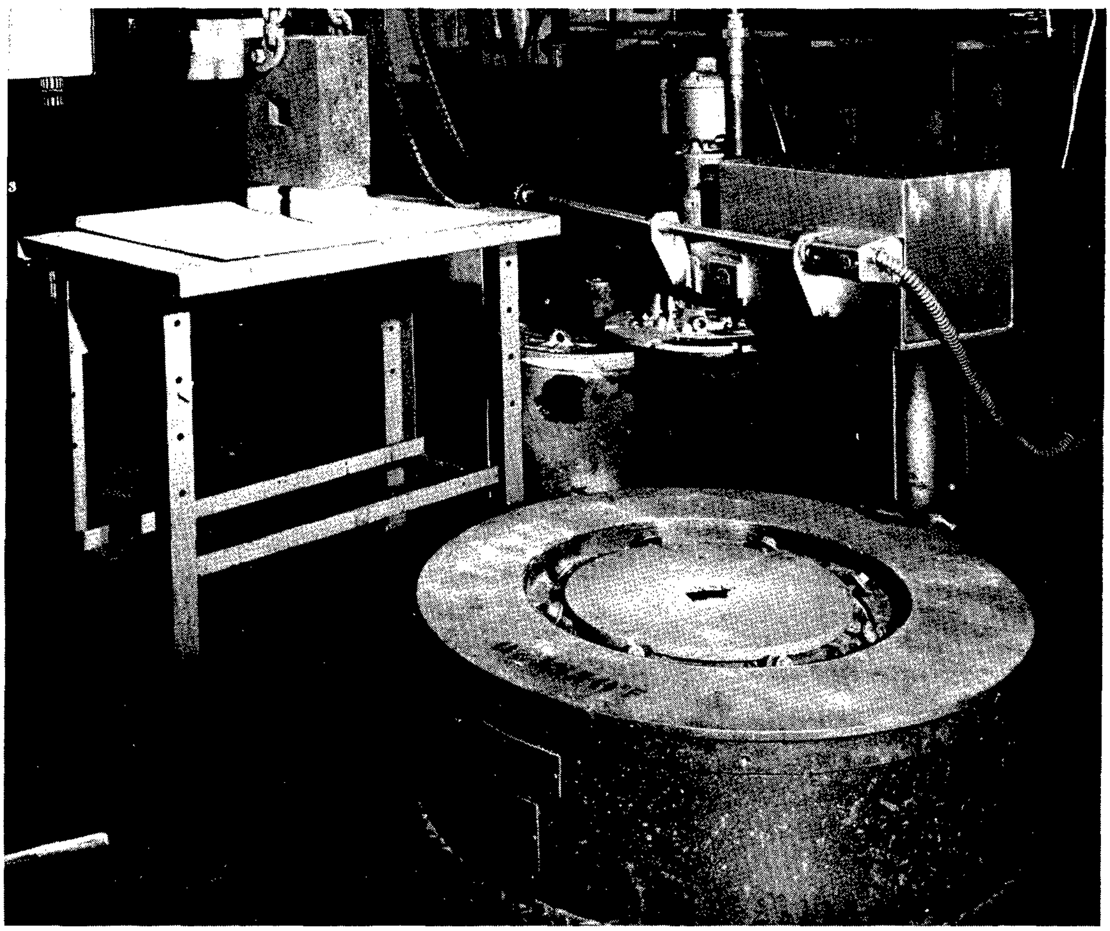

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FIG. 2 - VIEW OF THE EXPERIMENTAL INSERT BLOCK FOR HARDENING AND THE FURNACE ARRANGEMENT.

The hardening phase consisted of removing the block-specimen assembly from the 1700°F furnace and quenching in a moving air stream provided by a large industrial ventilating fan. By calibration, this air-cooling system provided a quench severity, H, of 0.08. The details of this determination are given in the Appendix.

The flat ingot center slice was used to make hardness traverses and to establish the necessary tempering cycle to achieve certain desired tempered hardnesses. For tempering, the tapered specimens were re-inserted into the dummy block. Tempering temperatures were of the order of 1100°-1200°F. The block-specimen assembly was quenched in oil or water from the tempering furnace.

The appropriately hardened and tempered specimens were cut into V-notch Charpy impact bars representing points at about 1/2-inch spacing from surface to center in the quenching direction. Impact specimens were tested in detail at -40°F and in somewhat less detail at room temperature.

As a final phase of the program, the most promising alloy was reproduced as 600-lb heats by induction melting in air under a slag cover. The heats were used to pour slabs in green sand of 5, 4, and 3-inch thickness, respectively, and lateral dimensions: 18 x 18 inches. The slab was cast in a vertical position with a hot top on one of the 18-inch thickness faces. A center slice cut out later from the heat-treated condition was radiographed to assess soundness.

III. SELECTION OF ALLOY COMPOSITIONS

The independent variables in the composition of a steel are:

Carbon level

Alloy species

Amount of each alloy

Multiplicity of alloying elements

The most important decision preliminary to a steel development program of this nature is the choice of carbon level. While carbon is one of the most effective, and certainly the cheapest, hardenability agents that can be added to a steel, there are practical limitations to its use. With increasing carbon level comes increasing propensity for quench cracking, weld cracking, and hydrogen flaking. In the other direction there is a minimum carbon level to reach any desired hardness. The position on toughness is not clear. Experience points to the low toughness of carbon contents in excess of 0.40%, and intuition indicates a lower limit where carbide distribution cannot counteract the deleterious influence of certain alloying elements.

Cost and effectiveness in hardenability limit the selection of alloying elements in steel to Mn, Ni, Cr, Mo, and Si in major amounts and to V and B in minor amounts. Yet even with this limited list of alloying candidates, the permutations of possible compositions are very many. Two considerations are generally reckoned to impose guides and limitations. The first of these is multiplicity. Experience with low-alloy steels dictates that hardenability is accentuated by a wide multiplicity of alloying elements. Therefore, most of the alloys to be studied should have all five of the major alloying species present. The second consideration is total alloy content. In this case the nature of the end product dictates that a total alloy content of less than 6% is probably mandatory, and of this total the major fraction should preferably be of the lower cost alloying species.

The scheme of exploration of the mechanical properties of air-hardened steel was to choose a base composition with a high multiplicity of alloying elements in minor amount and an intrinsic ability to air harden uniformly through a 5-inch section to a hardness in excess of 30 Rc. To these base compositions were added progressive increments of one alloy species. In this way relationships between each alloy species and hardening or toughening capability were built upon a composition of minimum adequacy. The outcome was to be the establishment of preferable alloy species in major amounts and the limits, if any, to be imposed. In terms of the main objective of this program, the produce of this systematic investigation would be the assessment of the possibility and conditions for attaining high uniform toughness coupled with high hardness in air-hardened cast steel of up to 5-inch section thickness.

One group of compositions was designed by progressive elemination of minor alloying species to test the importance of multiplicity of alloy species in the chemistry of steel. This multiplicity concept is taken for granted today, and it is appropriate in a research program frequently to challenge assumptions.

The question of optimum carbon level was solved in the beginning by testing a series of heats with a common alloy content and carbon varying between 0.10 and 0.30%. The base alloy content was arbitrarily selected to ensure good air-hardening characteristics and contained the following nominal amounts:

Mn	Ni	Cr	Mo	Si
1.5%	1.0%	0.5%	1.0%	0.5%

The expectation of good air-hardening capabilities with this alloy base was borne out, for hardness traverses through the 5-inch sections in all cases showed no significant variations from surface to center. Of course, the actual hardness levels achieved varied with the carbon content as shown in Figure 3. These hardnesses are not the maxima attainable with their respective carbon levels, indicating that the air-quenched structures are not fully martensitic. However, they are in each case adequate to achieve the tempered hardness levels generally sought for cast armor plate applications.

Impact toughness measurements made at -40°F disclosed no large variations between surface and center and a generally linear trend downward in that direction. The envelope of results for the range of carbon contents is shown in Figure 4, where it may be seen that a definite optimum carbon content for high toughness exists at about 0.18%. The permissible variation in carbon about this optimum cannot be designated with these data, but it would appear to be of the order of 0.16-0.20%. This optimum carbon level is significantly lower than generally in use for cast armor at the present time, and represents an important consideration.

As a result of the preliminary study, all subsequent alloys were confined to a carbon level of 0.18%. In Table I the program of steel compositions studied has been organized to show the series typifying the behavior of each individual alloying element. The compositions of certain heats are repeated because they were used to establish trends in more than one series.

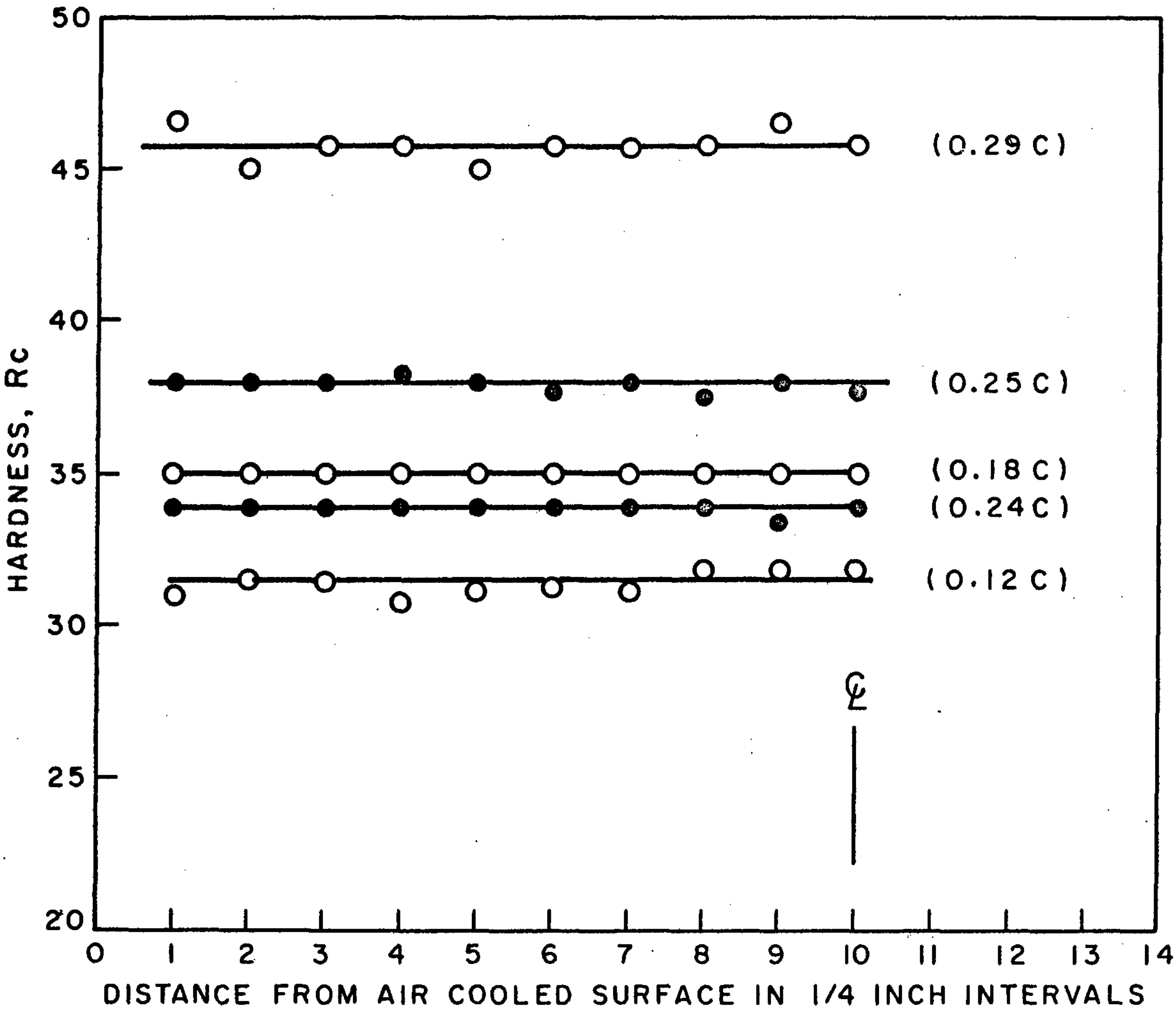


FIG. 3 HARDNESS TRAVERSES ON STEELS OF FIVE CARBON LEVELS HAVING THE SAME NOMINAL ALLOY CONTENT, 1.5% Mn, 1% Ni, 0.5% Cr, 1% Mo, 0.5% Si.

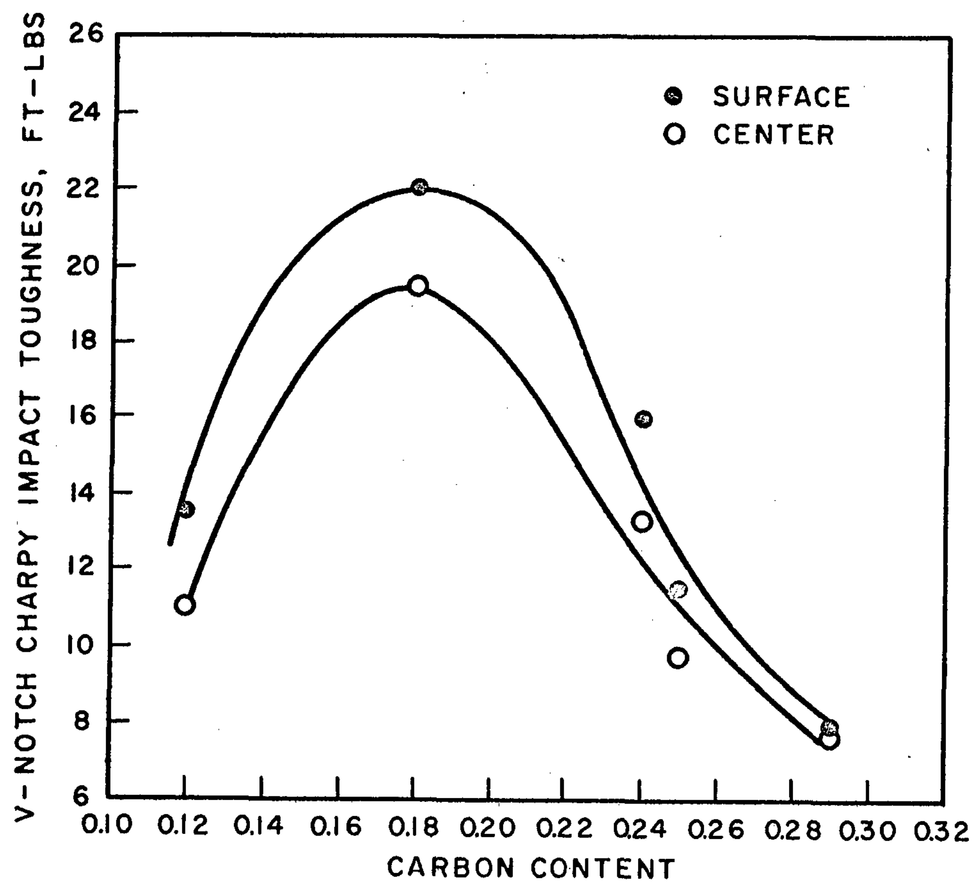


FIG. 4 INFLUENCE OF CARBON CONTENT ON THE -40°F TOUGHNESS OF A STEEL CONTAINING NOMINALLY 1.5 Mn, 1 Ni, 0.5 Cr, 1 Mo, 0.5 Si.

TABLE I

COMPOSITIONS OF EXPERIMENTAL STEELS

Series	Heat No.	Per cent Addition	Composition, w/o					
			Mn	Ni	Cr	Mo	Si	C
Carbon	--	--*	1.5	1.0	0.5	1.0	0.5	--
	6	0.12	1.60	1.31	0.65	1.18	0.58	--
	7	0.18	1.65	1.15	0.53	1.18	0.50	--
	8	0.24	1.20	1.13	0.52	1.16	0.24	--
	9	0.25	1.68	1.14	0.58	1.19	0.53	--
	10	0.29	1.86	1.14	0.96	1.22	0.61	--
Manganese	--	--*	--	0.5	1.0	0.5	0.5	
	13	0.55	--	0.58	1.10	0.44	0.45	0.17
	12	0.95	--	0.59	0.85	0.45	0.52	0.21
	17	1.89	--	0.56	1.04	0.58	0.54	0.17
	18	2.40	--	0.53	1.06	0.61	0.52	0.18
	30	3.60	--	0.58	1.06	0.63	0.49	0.18
Nickel	--	--*	0.5	--	1.0	0.5	0.5	
	13	0.58	0.55	--	1.10	0.44	0.45	0.17
	16	1.12	0.57	--	1.07	0.44	0.54	0.17
	19	1.59	0.67	--	0.97	0.60	0.47	0.18
	20	2.09	0.42	--	1.04	0.60	0.53	0.18
	33	2.51	1.07	--	1.05	0.60	0.47	0.19
	37	2.97	1.14	--	0.40	0.55	0.44	0.16
Chromium	--	--*	1.0	0.5	--	0.5	0.5	
	11	0.52	0.96	0.63	--	0.42	0.37	0.18
	12	0.85	0.95	0.59	--	0.45	0.52	0.21
	21	1.52	0.68	0.60	--	0.61	0.54	0.18
	22	1.84	0.51	0.61	--	0.59	0.38	0.20
	28	2.56	1.05	0.55	--	0.58	0.41	0.17
Molybdenum	--	--*	0.5	0.5	1.0	--	0.5	
	13	0.44	0.55	0.58	1.10	--	0.45	0.17
	15	0.87	0.51	0.64	1.12	--	0.39	0.15
	23	1.76	0.70	0.50	0.98	--	0.55	0.20
	24	2.22	0.38	0.69	0.81	--	0.25	0.20
Silicon	--	--*	0.5	0.5	1.0	0.5	--	
	13	0.45	0.55	0.58	1.10	0.44	00	0.17
	14	0.63	0.52	0.61	1.09	0.44	--	0.22
	25	0.90	2.03	0.50	1.07	0.55	--	0.17
	27	1.59	1.48	0.58	1.14	0.53	--	0.16
	26	1.64	2.03	0.62	1.12	0.56	--	0.18

TABLE I (CONT'D)

Series	Heat No.	Per cent Addition	Composition, w/o					
			Mn	Ni	Cr	Mo	Si	C
Others	--	--*	1.5	0.5	1.0	0.5	0.5	0.18
	31	0.63V	1.60	0.65	1.16	0.62	0.37	0.17
	32	0.001B	0.43	0.65	1.16	0.59	0.38	0.18
	38	0.0025B	1.71	0.68	0.98	0.62	0.42	0.17
Miscellaneous	35		2.40	2.27	--	--	0.41	0.18
	34		2.86	0.62	1.59	--	0.46	0.16
	36		4.65	0.65	--	--	0.51	0.18

* Nominal composition is given of base steel to which additions were made; analyzed compositions are given otherwise.

Only in the case of the Mo series was the base composition inadequate in its hardenability. This prevented the assessment of the capability of minor amounts of Mo, but fortunately this can be appreciated from some of the other composition variations.

IV. AIR-QUENCHED HARDNESSES OF EXPERIMENTAL STEELS

It must first be remarked that air quenching of all of the experimental alloy steels produced a uniform hardness throughout the 5-inch section. There were no hardness gradients and no differences in hardness between surface and center. The hardness plots of Figure 3 are typical. The actual hardnesses, however, varied considerably between 12 and 45 Rc. The latter hardness represents approximately the maximum attainable with an 0.18% C steel--i.e., with a fully martensitic structure. A complete summary of as-air-quenched hardnesses is given in Table II.

By plotting each of the series of one element increased incrementally, the relative hardening capability of the various alloying elements can be appreciated. Note here that hardening capability is not the same as hardenability, the latter pertaining to position differences in hardness. The as-quenched hardnesses of several series are shown in Figure 5. Of the common alloy additions, Mn is clearly the most effective. Mo is also very effective but only in amounts up to about 1.5%. Si has no effect. Of the minor additions, V was detrimental. Boron showed effectiveness only at the 0.0025% addition and would appear to be required in the amount of about 0.004% to equal Mn. This is rather more than is commonly used. The larger amounts of any of the alloying elements either gain very little in hardening ability or, as in the case of Ni and Mo, actually lead to a loss in hardening. Some of the problems with Mo may simply be that at the higher concentrations, the austenitizing temperature of 1700°F is inadequate to ensure total carbide solution into the austenite.

An interpretation of these results might be as follows: At the lower levels of alloy addition, the trend of increased hardening is due to progressive elimination of the last vestiges of pearlite and upper bainite. Having eliminated these, the contest is between lower bainite and martensite, the latter being somewhat harder. With a high M_s temperature, the temperature range of formation of lower bainite is narrow. The kinetics of initiation of

TABLE II

AIR-QUENCHED HARDNESSES OF EXPERIMENTAL STEELS

Series	Heat No.	Per cent Addition	Hardness (Rc) at Distance from Surface 1/2 in.	Hardness (Rc) at Distance from Surface 2 1/2 in.
Carbon	6	0.12	32	33
	7	0.18	35	35
	8	0.24	34	34
	9	0.25	38	37
	10	0.29	45	45
Manganese	13	0.55	12	12
	12	0.95	28	29
	17	1.89	38	38
	18	2.40	42	41
	30	3.60	43	40
Nickel	13	0.59	12	12
	16	1.12	27	28
	19	1.59	29	29
	20	2.09	35	35
	33	2.51	35	33
	37	2.97	30	30
Chromium	11	0.52	15	15
	12	0.85	28	29
	21	1.52	33	32
	22	1.84	37	35
	28	2.56	34	34
Molybdenum	13	0.44	12	12
	15	0.87	18	19
	23	1.76	33	32
	24	2.22	31	30
Silicon	13	0.45	12	12
	14	0.63	25	23
	25	0.90	35	34
	27	1.59	33	30
	26	1.64	37	34
Others	--*	--*	32	32
	31	0.63V	29	25
	32	0.001B	31	31
	38	0.0025B	38	38

* Interpolated for same alloy content.

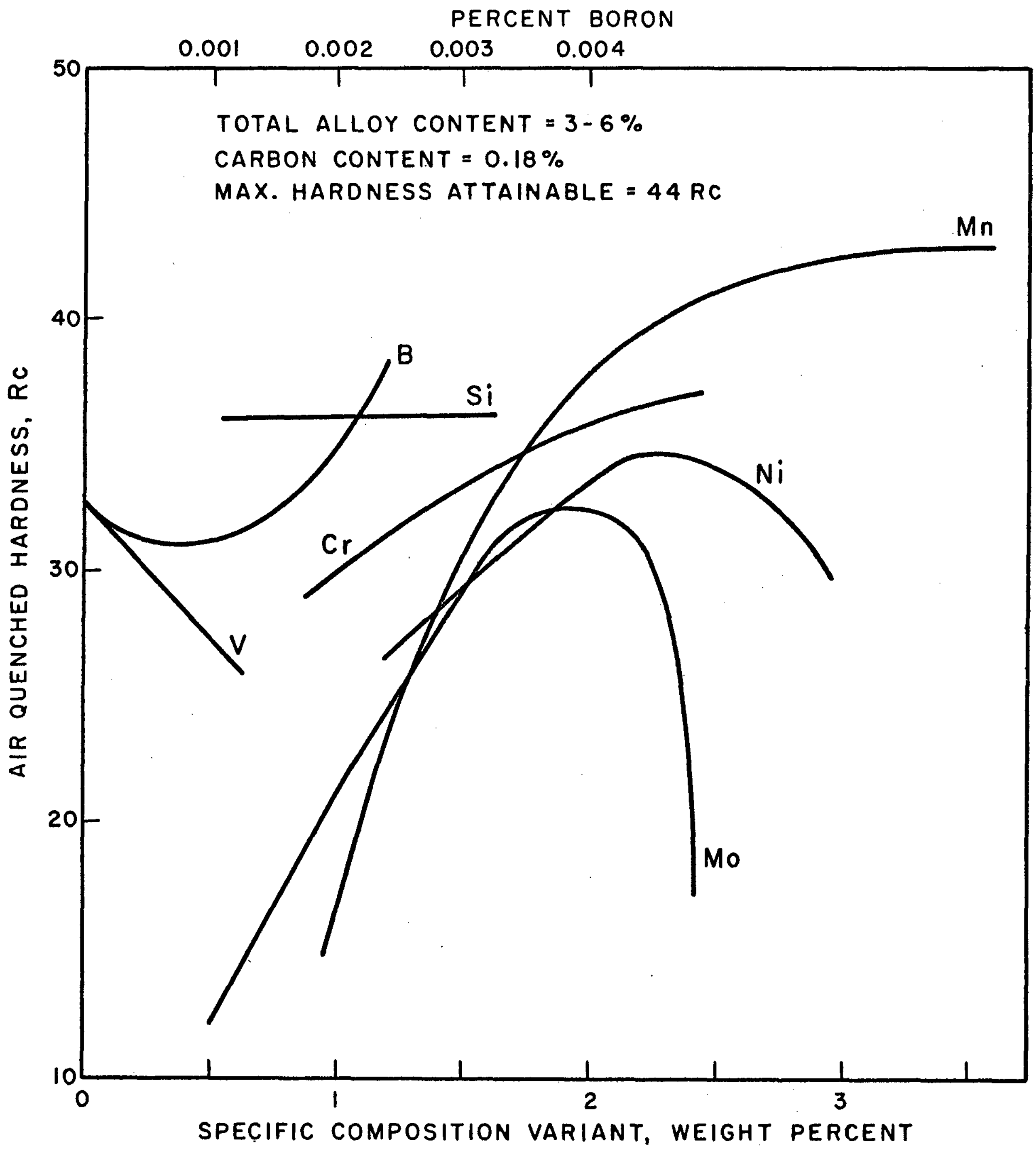


FIG. 5 INFLUENCE OF SPECIFIC ALLOYING ELEMENTS ON THE AS AIR QUENCHED HARDNESS FOR THE CONDITION OF 0.18% C AND 3-6% TOTAL ALLOY CONTENT.

lower bainite are not particularly affected by alloy content, but the M_s is progressively depressed. Thus at the higher range of alloy content, the temperature range of lower bainite formation is broadened with consequent loss in as-quenched hardness.

Comparison of heats Nos. 18, 34, 35, and 36 provides an interesting test of the significance of multiplicity of alloying elements in air hardening. For convenience, their compositions are reproduced as follows:

Heat No.	Mn	Ni	Cr	Mo	Si	C	As-Quenched Hardness
34	2.40	0.62	1.59	--	0.5	0.18	33 Rc
35	2.86	2.27	--	--	0.5	0.16	36.5 Rc
36	4.65	0.65	--	--	0.5	0.18	45 Rc
18	2.40	0.53	1.06	0.61	0.52	0.18	41.5 Rc

It would appear that eliminating Cr and Mo and transposing their amounts to Mn and Ni did not reduce the capacity for hardening. In fact, the nearly binary alloy with only minor amounts of Ni and Si gave superior hardening ability.

V. IMPACT TOUGHNESS OF EXPERIMENTAL STEELS

The search for high toughness involved three sets of independent variables:

(1) Toughness as a function of position; surface to center of a 5-inch section.

(2) Toughness as a function of temperature; -40°F and room temperature.

(3) Toughness as a function of tempered hardness; approximately 30 and 25 Rc.

The most detailed work concerned the toughness as a function of position, measured at -40°F for a tempered hardness of about 30 Rc. The tempered hardness is difficult to control and the data more properly refer to the hardness ranges 27-31 Rc and 22-26 Rc. This is to say that the hardness in any one test block was invariably uniform, but the ability to choose the correct tempering temperature was not good enough to get an accuracy better than about ± 2 Rc.

Because of the choice of hardness levels, those experimental steels which air-hardened to less than the intended tempered hardness could not be used. This eliminated heats Nos. 11, 13, and 15.

The attempt will be made at this point to present the substance of the results in graphical form. First it may be stated that toughness from surface to center generally varied in a simple linear fashion with not large differences between the extremes. Some examples are shown in Figures 6 and 7. Because of these simple trends, the effects of systematic changes in chemistry can be adequately represented by a band whose limits are the curves of surface and center data, respectively. Data are presented in this manner in Figures 8 to 14, inclusive.

Apart from these graphical trends, it is useful to examine the results of restricting the number of alloying elements without materially changing the total alloy content. Data from Heats 18, 34, 35, and 36 permit the comparison summarized in Table III. In this series a four-component alloy composition giving comparatively good toughness was reduced to a three-component composition by elimination of Mo, to a two-component composition by the elimination of chromium, and finally an almost single component composition by eliminating all but a minor amount of Ni. Unfortunately, in this latter case the analyzed Mn content ran about 0.5% higher than intended. It is apparent that the more complex composition gave the better behavior. It is particularly noteworthy that the 4.65 Mn-0.65 Ni composition which air-quenched to full hardness (45 Rc) gave the poorest toughness. This may be a reflection of temper brittleness which occurs because this alloy requires a lower tempering temperature (1070°F) to produce the desired final hardness (29 Rc). Low impact strengths are occasionally encountered with some alloy steels that are tempered in the range of 850°-1100°F.

Consideration of the trends and magnitudes of the toughness data presented suggests the following observations:

(a) Although the center of a 5-inch section tends to have less toughness than the quenched surface, the differences are not large.

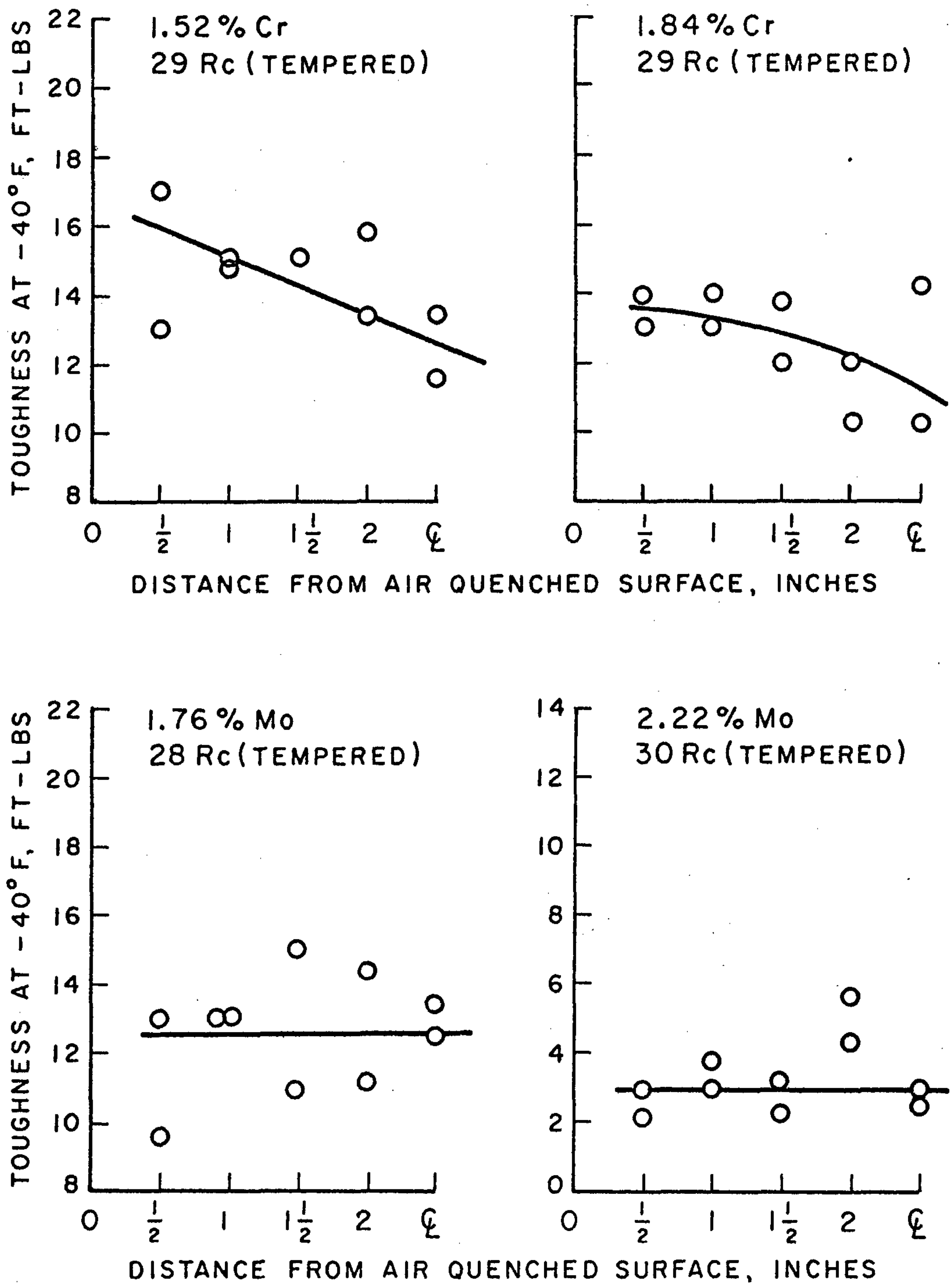


FIG. 6 CORRELATION BETWEEN V-NOTCH CHARPY IMPACT TOUGHNESS AT -40°F AND INCREMENTS OF Cr and Mo.

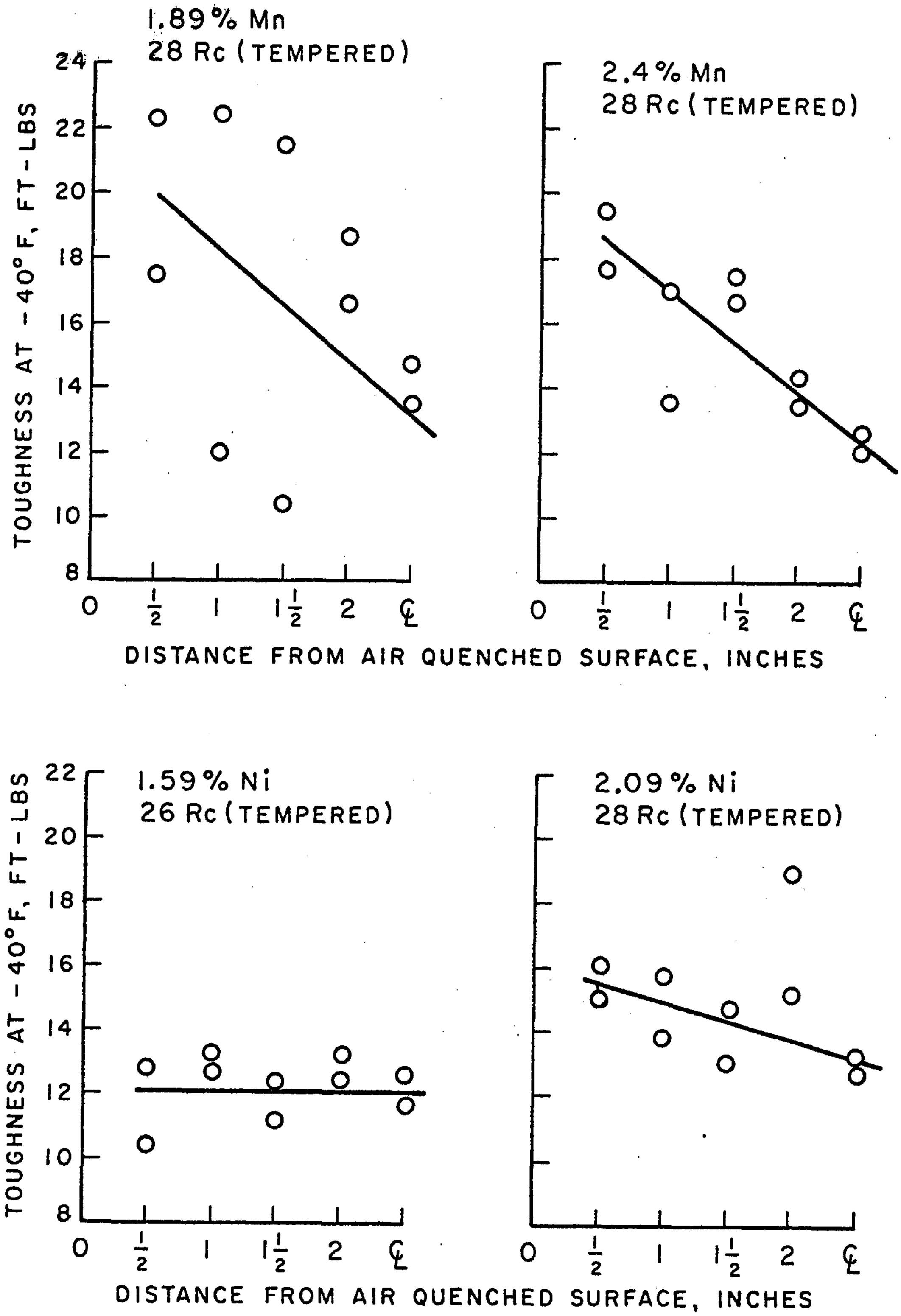


FIG. 7 CORRELATION BETWEEN V-NOTCH CHARPY IMPACT TOUGHNESS AT -40°F AND INCREMENTS OF Mn and Ni.

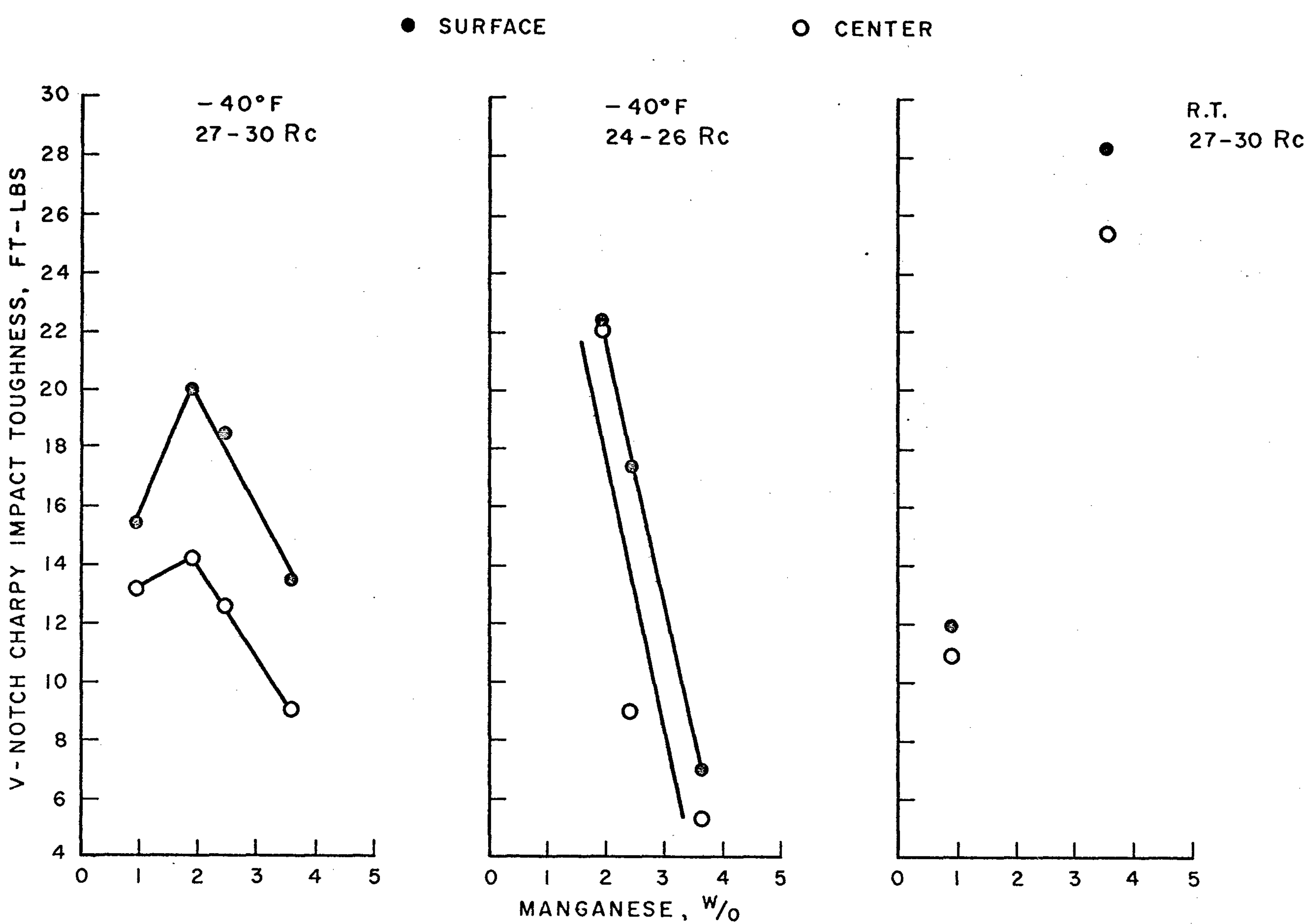


FIG. 8 INFLUENCE OF MANGANESE ON THE V-NOTCH CHARPY IMPACT TOUGHNESS IN A BASE COMPOSITION (NOMINAL) OF 0.5% Ni, 1.0% Cr, 0.5% Mo, 0.5% Si, 0.18% C. STEEL AIR-QUENCHED AND TEMPERED TO INDICATED HARDNESS AND TESTED AT INDICATED TEMPERATURE. FIVE-INCH SECTION THICKNESS.

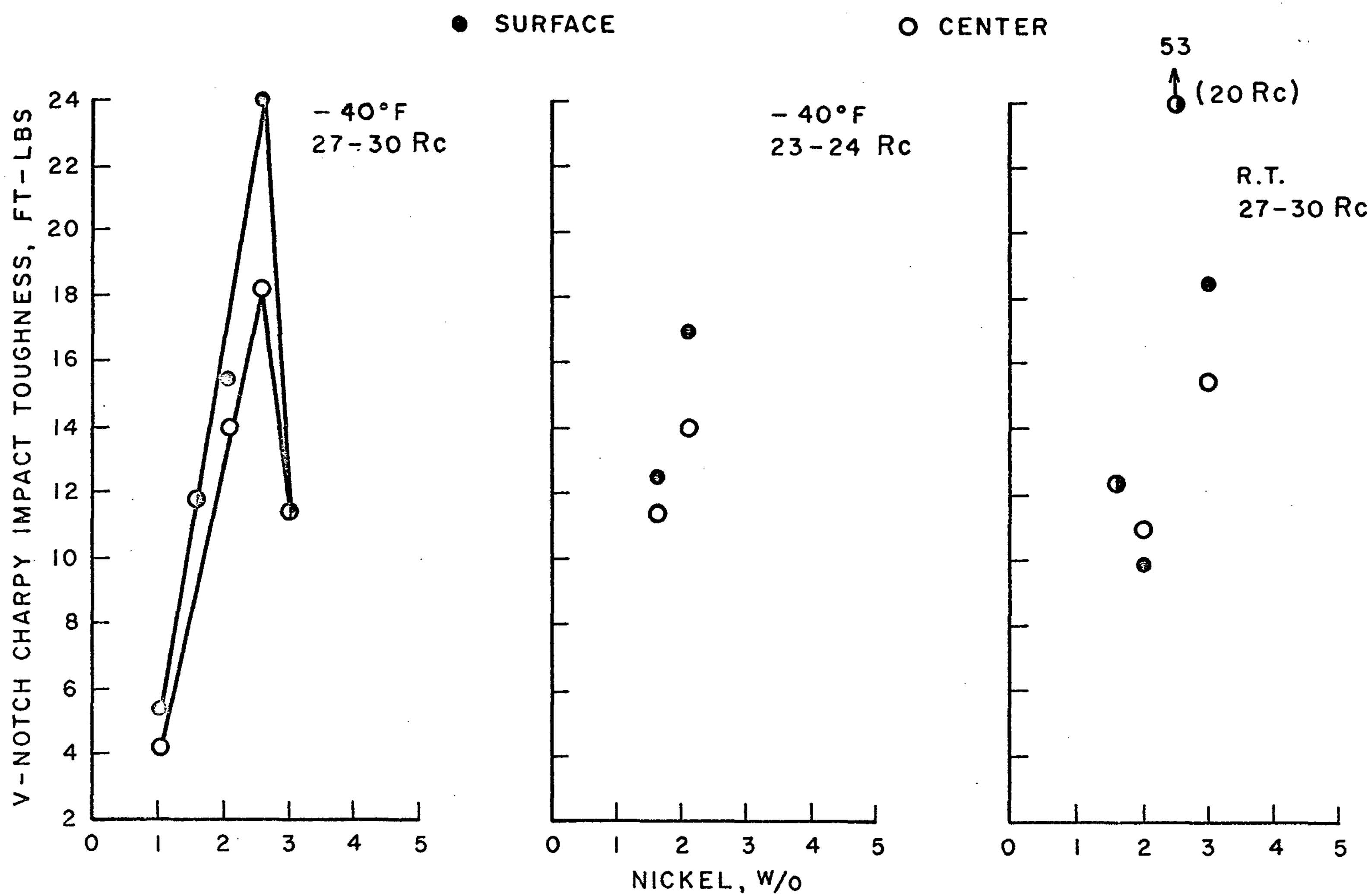


FIG. 9 INFLUENCE OF NICKEL ON THE V-NOTCH CHARPY IMPACT TOUGHNESS IN A BASE COMPOSITION (NOMINAL) OF 0.5% Mn, 1% Cr, 0.5% Mo, 0.5% Si, 0.18% C. STEEL AIR-QUENCHED AND TEMPERED TO INDICATED HARDNESS, TESTED AT INDICATED TEMPERATURE. FIVE-INCH SECTION THICKNESS.

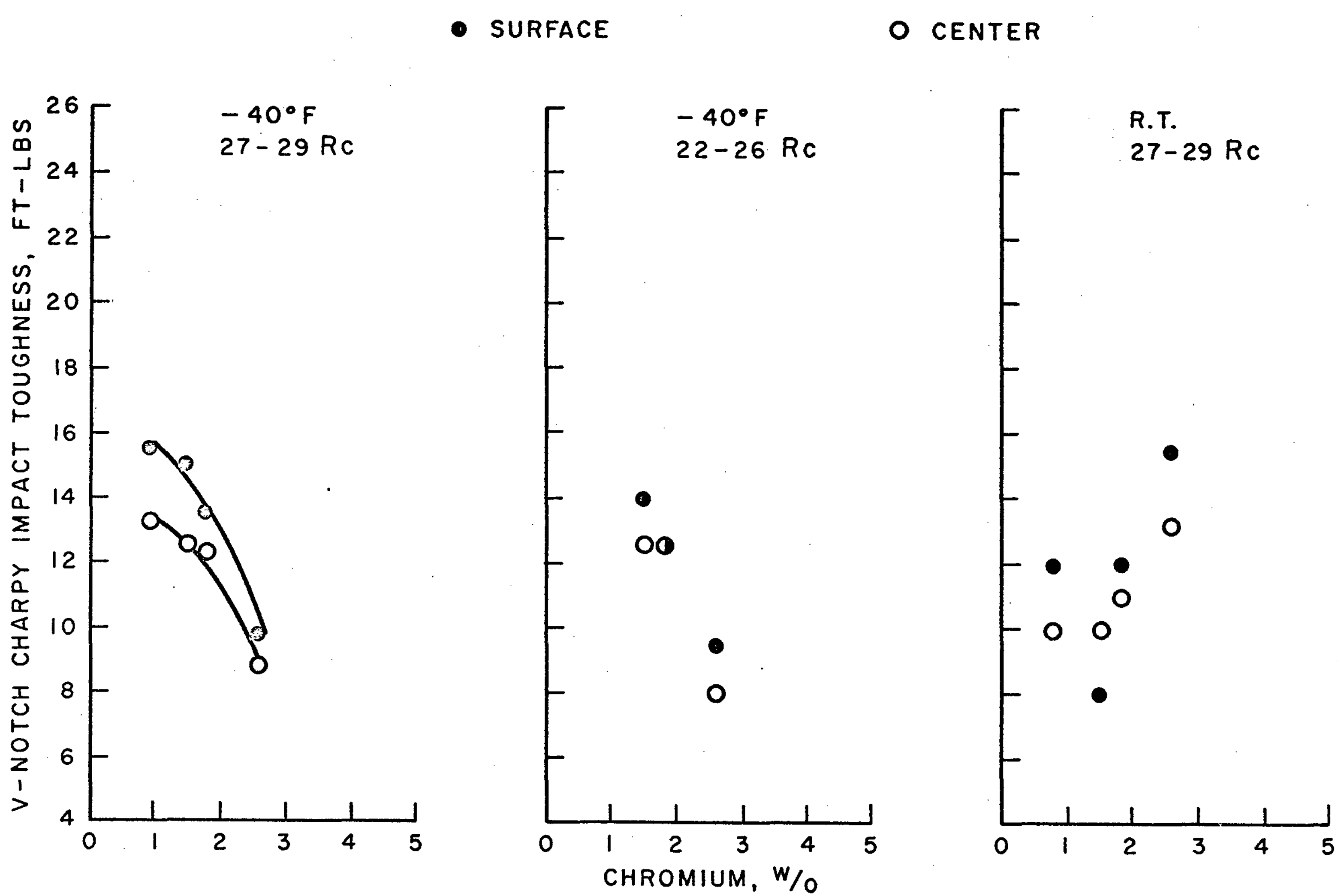


FIG. 10 INFLUENCE OF CHROMIUM ON THE V-NOTCH CHARPY IMPACT TOUGHNESS IN A BASE COMPOSITION (NOMINAL) OF 1% Mn, 0.5% Ni, 0.5% Mo, 0.5% Si, 0.18% C. STEEL AIR-QUENCHED AND TEMPERED TO INDICATED HARDNESS. TESTED AT INDICATED TEMPERATURE. FIVE-INCH SECTION THICKNESS.

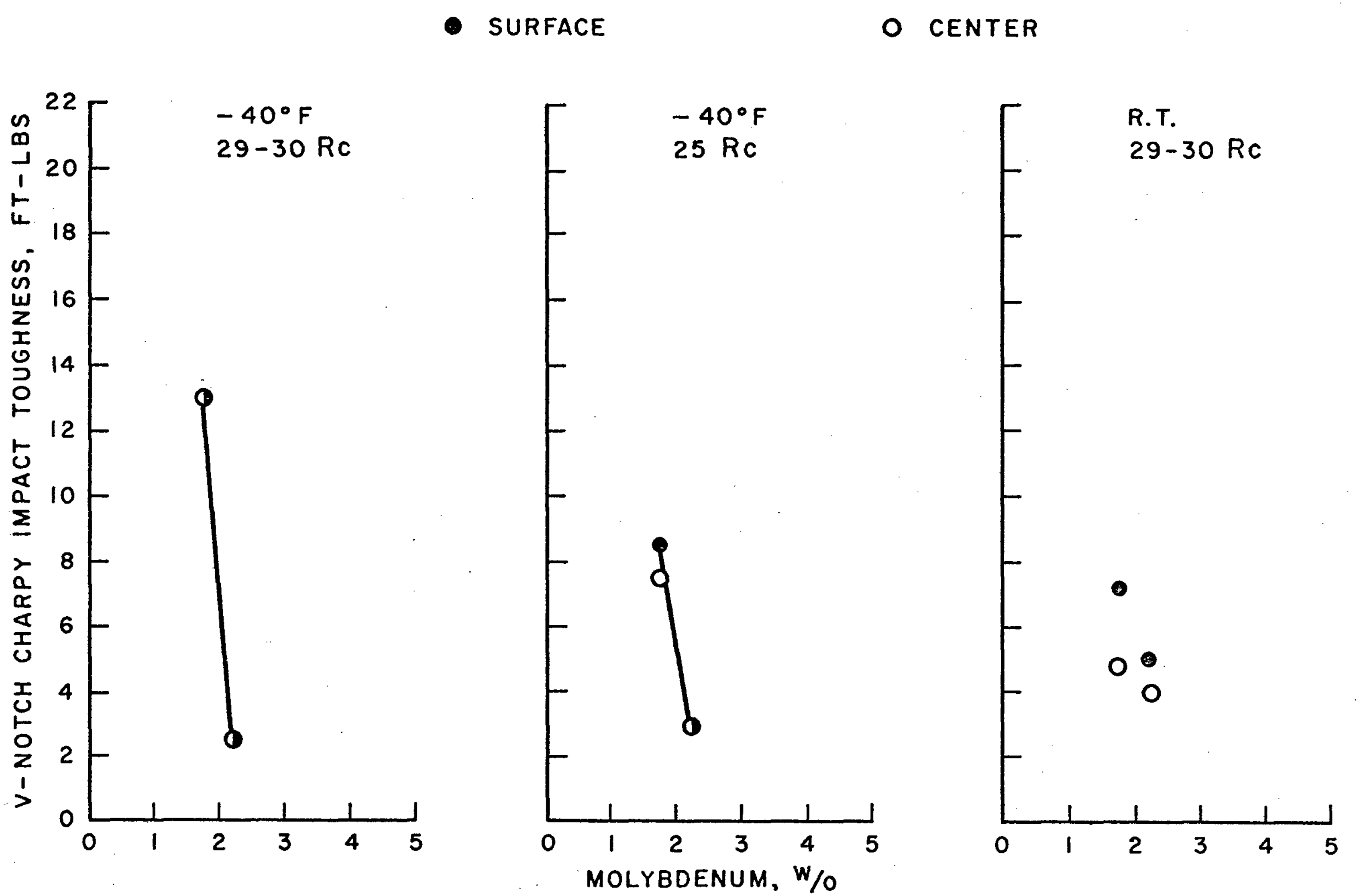


FIG. 11 INFLUENCE OF MOLYBDANUM ON THE V-NOTCH CHARPY IMPACT TOUGHNESS ON A BASE COMPOSITION (NOMINAL) OF 0.5% Mn, 0.5% Ni, 1% Cr, 0.5% Si, 0.18% C. STEEL AIR-QUENCHED AND TEMPERED TO INDICATED HARDNESS. TESTED AT INDICATED TEMPERATURE. FIVE-INCH SECTION THICKNESS.

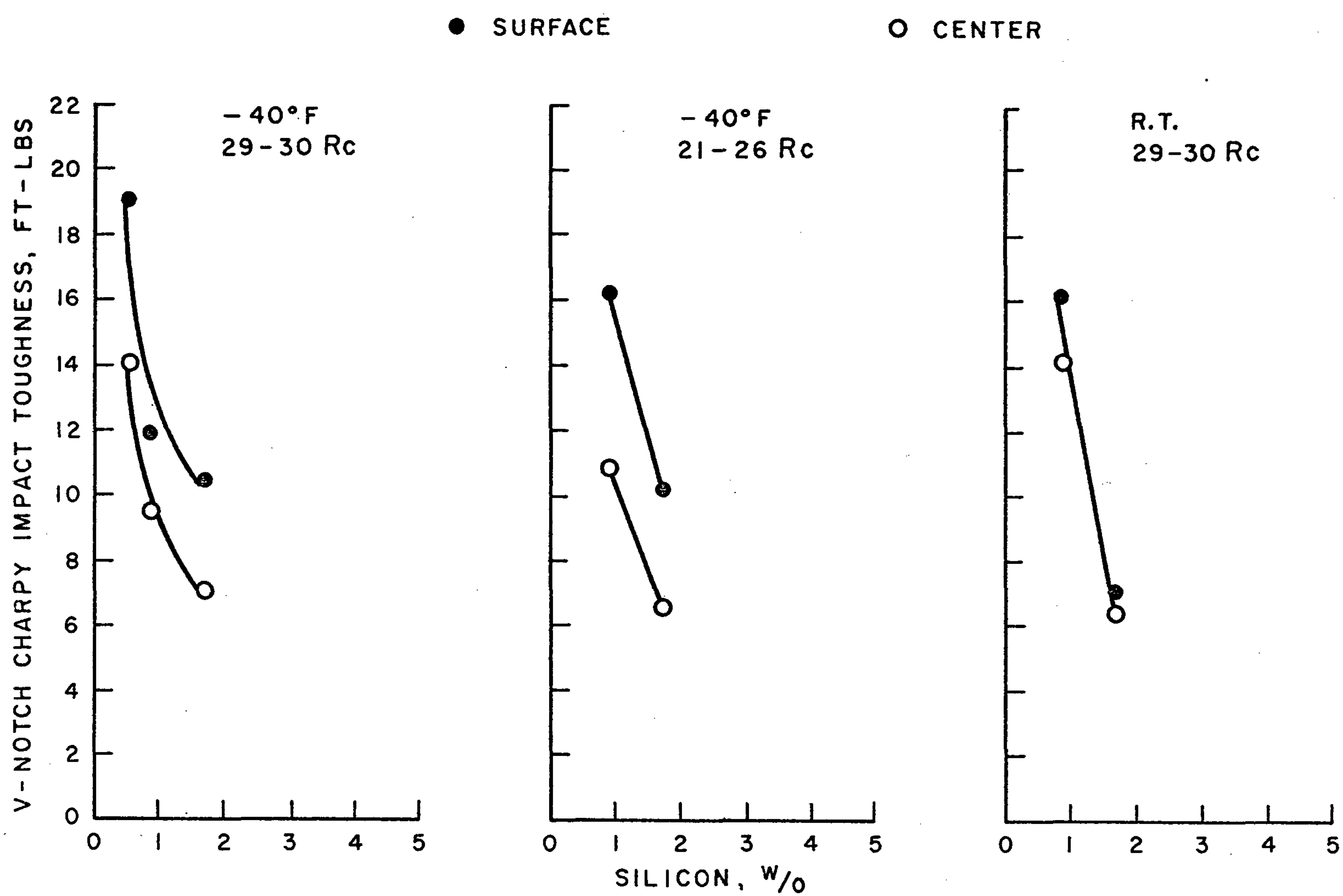


FIG. 12 INFLUENCE OF SILICON ON THE V-NOTCH CHARPY TOUGHNESS IN A BASE COMPOSITION (NOMINAL) OF 0.5% Mn, 0.5% Ni, 1% Cr, 0.5% Mo, 0.18% C. STEEL AIR-QUENCHED AND TEMPERED TO INDICATED HARDNESS. TESTED AT INDICATED TEMPERATURE. FIVE-INCH SECTION THICKNESS.

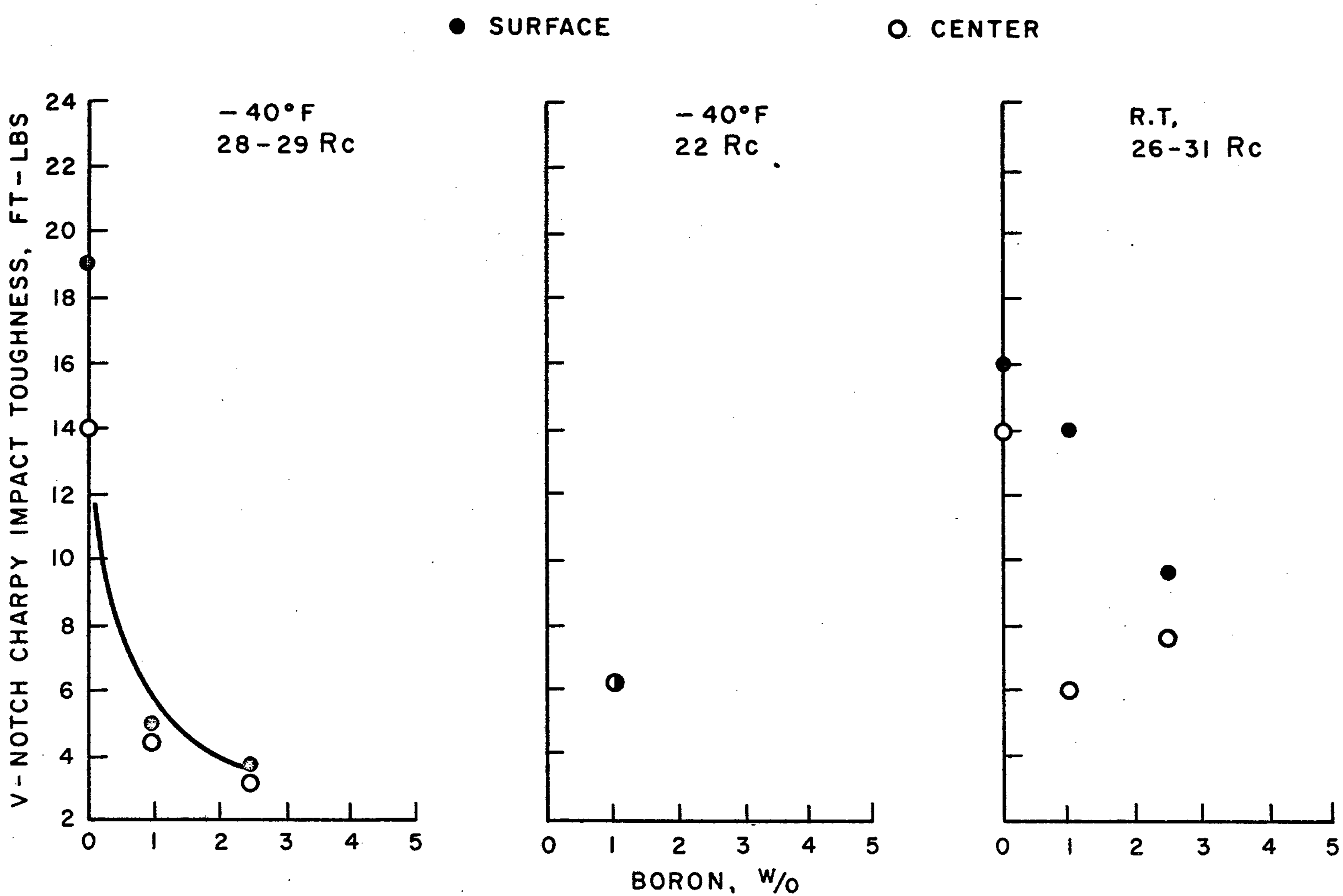


FIG. 13 INFLUENCE OF BORON ON THE V-NOTCH CHARPY IMPACT TOUGHNESS IN A BASE COMPOSITION (NOMINAL) OF 1.5% Mn, 0.5% Ni, 1% Cr, 0.5% Mo, 0.5% Si, 0.18% C. STEEL AIR-QUENCHED AND TEMPERED TO INDICATED HARDNESS. TESTED AT INDICATED TEMPERATURE. FIVE-INCH SECTION THICKNESS.

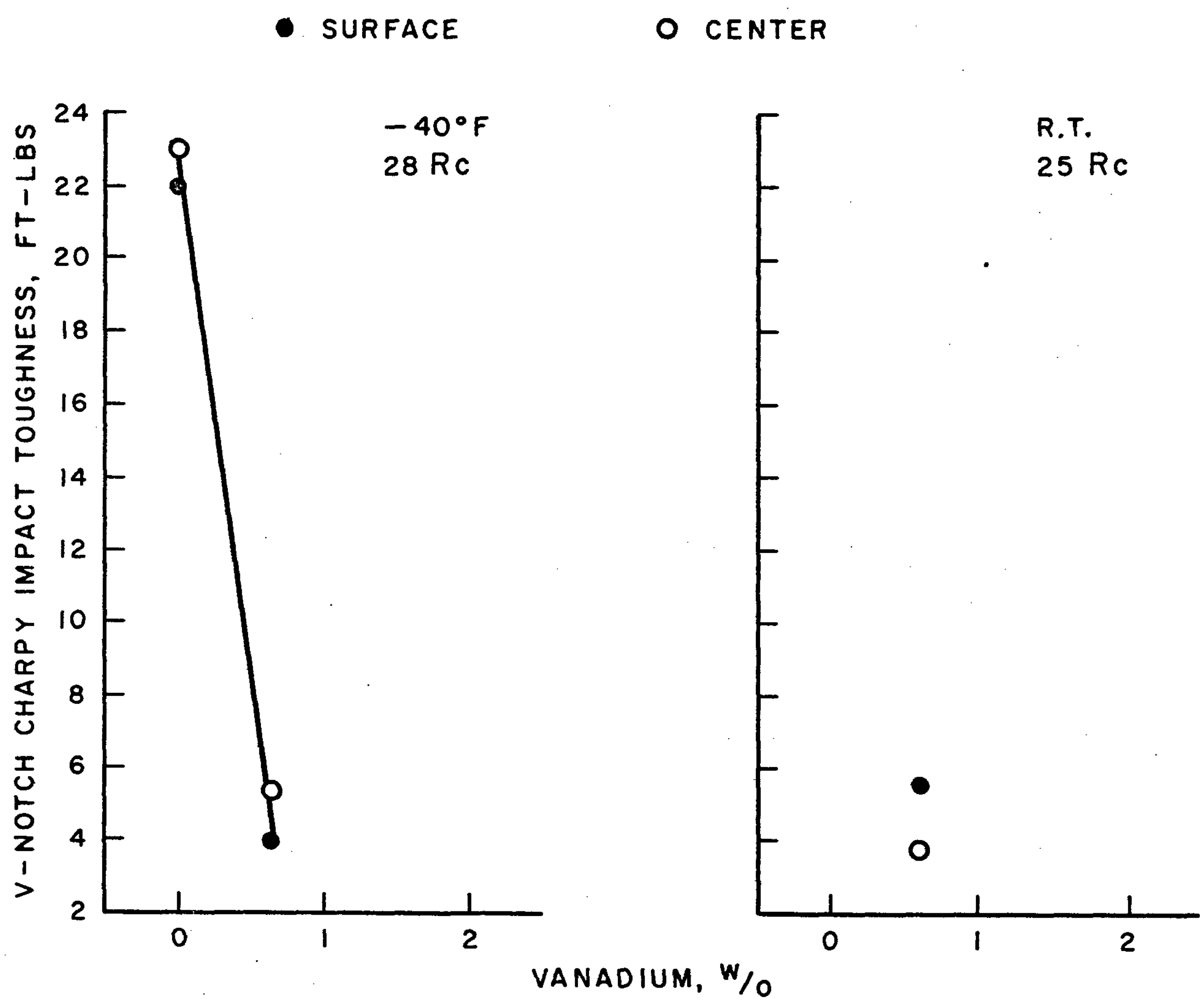


FIG. 14 INFLUENCE OF VANADIUM ON THE V-NOTCH CHARPY IMPACT TOUGHNESS IN A BASE COMPOSITION (NOMINAL) OF 1.5% Mn, 0.5% Ni, 1% Cr, 0.5% Mo, 0.5% Si, 0.18% C. STEEL AIR-QUENCHED AND TEMPERED TO INDICATED HARDNESS. TESTED AT INDICATED TEMPERATURE. FIVE-INCH SECTION THICKNESS.

TABLE III

INFLUENCE OF THE NUMBER OF ALLOYING ELEMENTS ON TOUGHNESS

Heat No.	Major Alloying Elements	Toughness at -40° F, ft-lb (Tempered Hardness)
18	2.4 Mn, 0.53 Ni, 1.06 Cr, 0.61 Mo	14-20 (28 Rc)
34	2.86 Mn, 0.62 Ni, 1.59 Cr	8-9 (22 Rc)
35	2.5 Mn, 2.27 Ni	11-12 (25 Rc)
36	4.65 Mn, 0.65 Ni	1.5-2 (29 Rc)

(b) There are only minor differences between toughness (at -40°F) of the 25 and 29 Rc tempered hardness levels.

(c) The -40°F toughness data suggests that, for each of the major alloying elements, there is an optimum amount in excess of which toughness drops. Thus the maximum Mn is about 2%, maximum Ni about 2.5%, maximum Cr about 1%, and maximum Mo about 1%. Of the minor elements, Si in excess of needs for deoxidation gives adverse results. Both B and V detract from toughness.

(d) There is no correlation between as-air-quenched hardness and toughness. It is definitely not true that toughness in the tempered state increases with as-air-quenched hardness. This point is in conflict with other work, but the reconciliation is probably that these structures are predominantly bainitic while, in the previous work, the structures were predominantly martensitic.

(e) Toughness at room temperature is generally about the same as -40°F. It seems likely, therefore, that in most cases, the transition from the ductile to brittle state is very gradual with temperature. There are singular exceptions in the cases of the highest Mn and Ni contents. It is also notable that the 2.4 Mn-2.3 Ni alloy (Heat No. 35) when accidentally tempered to 19 Rc gave about 55 ft-lb at room temperature.

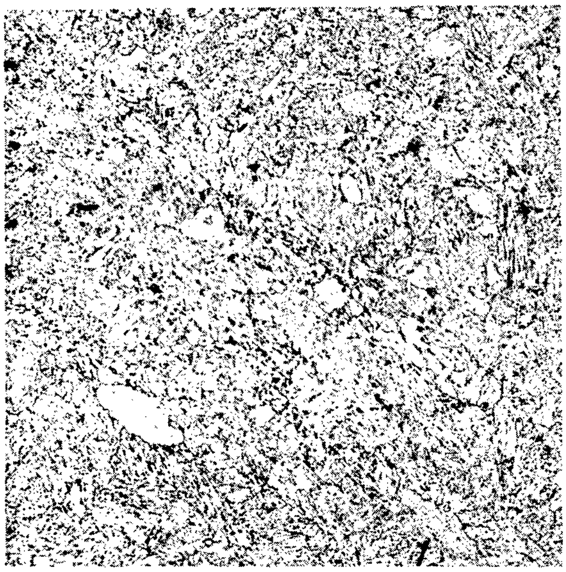
(f) Mn and Ni are most influential in developing high toughness, and the indication in Table III is that 0.5% Mo is advantageous. Chromium seems to serve very little purpose.

VI. STRUCTURE OF EXPERIMENTAL STEELS

In examining the microstructures of the experimental steels in their air-quenched and tempered state, it was consistently seen that no significant structural differences existed between the surface and the center of the 5-inch section.

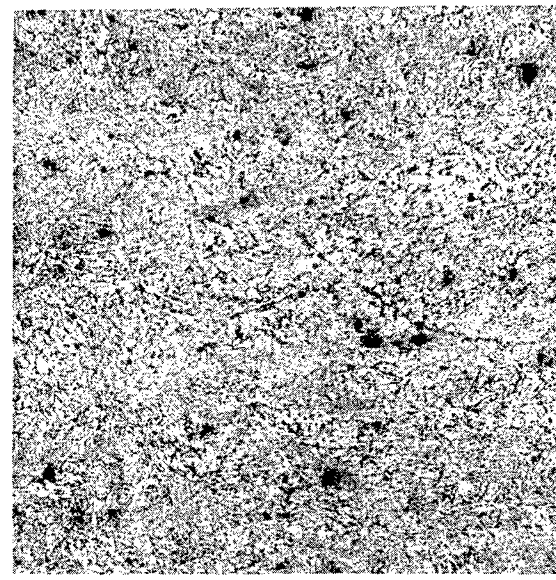
The structures themselves showed differences which correlate with the toughness measured at -40°F. The series of steels with increasing nickel content illustrates these factors quite well. Reference is made to Figures 15 and 16 representing 1.59, 2.09, 2.51, and 2.97% Ni.

At the lowest Ni content (1.59%), the structure contains two adverse conditions. There are regions of free ferrite (free of resolvable



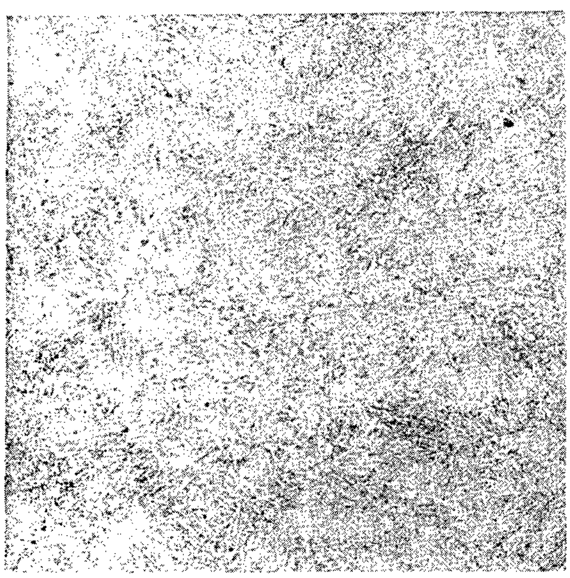
Neg. No. 22751

(a) 1.59% Ni (Heat No. 19)



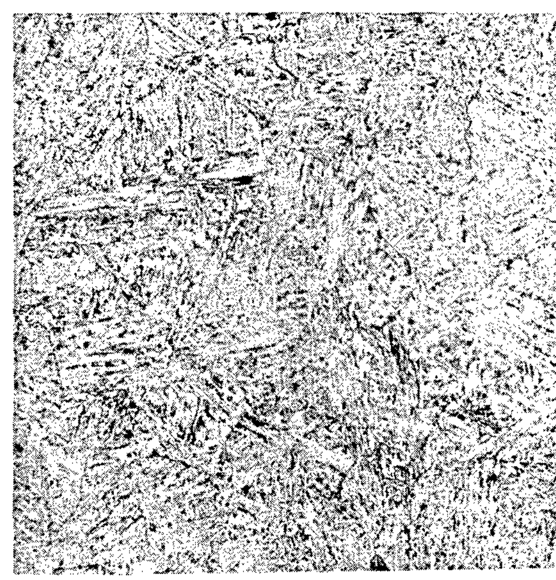
Neg. No. 22752

(b) 2.09% Ni (Heat No. 20)



Neg. No. 22753

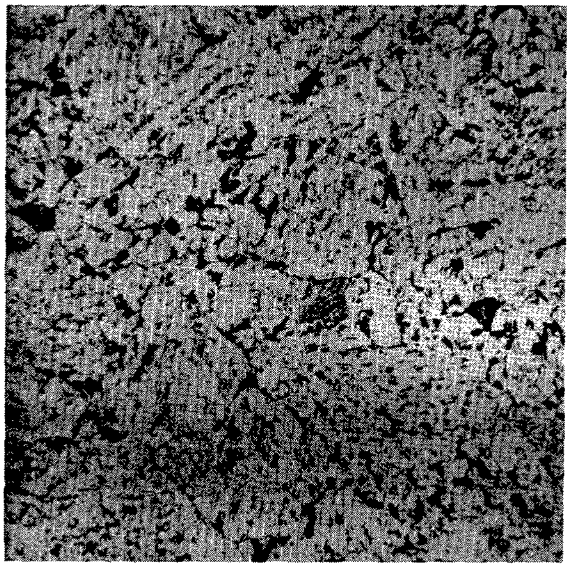
(c) 2.51% Ni (Heat No. 33)



Neg. No. 22754

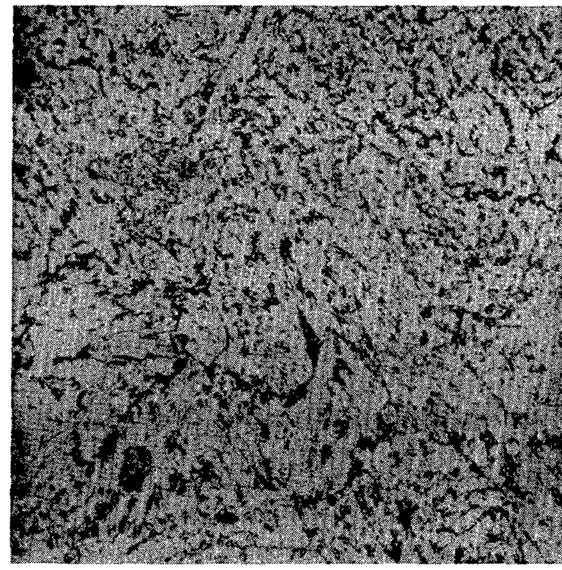
(d) 2.97% Ni (Heat No. 37)

FIG. 15 - MICROGRAPHS (X100) OF A SERIES OF STEELS WITH INCREASING NICKEL CONTENT. Air-quenched and tempered condition. At 27-30 Rc and -40°F test temperature, toughnesses of 5, 12, 21, and 11 ft-lb (average), respectively. Etchant: nital.



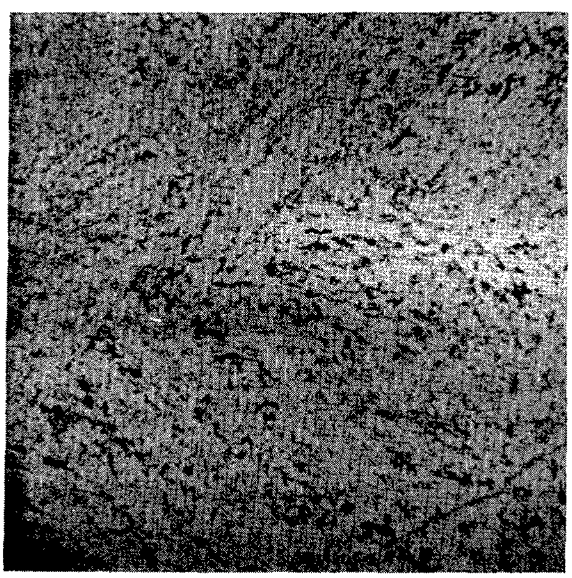
Neg. No. 22750

(a) 1.59% Ni (Heat No. 19)



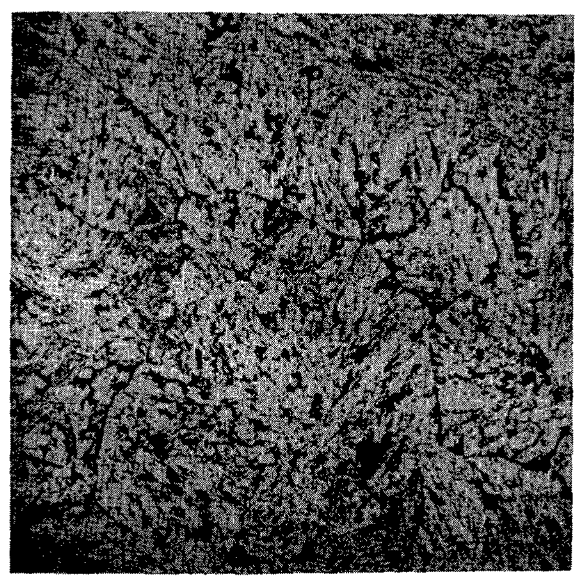
Neg. No. 22755

(b) 2.09% Ni (Heat No. 20)



Neg. No. 22756

(c) 2.51% Ni (Heat No. 33)



Neg. No. 22757

(d) 2.97% Ni (Heat No. 37)

FIG. 16 - MICROGRAPHS (X500) OF THE SAME SERIES AS FIGURE 15.

carbides) and a network of ferrite boundaries in the regions of dispersed carbides. The free ferrite is probably pre-eutectoid in nature. The ferrite boundary system reflects the fact that grain growth in the tempered structure has occurred. With 2.09% Ni there is less free ferrite, but the ferrite boundary network persists. At 2.51% Ni no free ferrite exists, and the structure is one of tempered lower bainite and martensite. There are no grain-boundary networks. This structure corresponds with the highest toughness in the series. With still higher Ni (2.97%) a new grain-boundary network is evident which is probably the boundaries of the austenite grains prior to quenching. Whether retained austenite actually persists is not certain, but grain-boundary delineation of this sort is generally associated with poor toughness as was encountered in the present case. Therefore, it is apparent that optimum toughness is associated with freedom from free ferrite and from resolvable grain boundary networks whether they be ferritic or erstwhile austenitic.

The fractured surfaces of the V-notch Charpy bars are not easily classified. There are certainly not fibrous, nor are they obviously cleavage type. Only at the optimum Mn and Ni compositions is there any evidence of shear lip on the fracture edges. A group of exemplary fractures is illustrated in Figure 17.

VII. EVALUATION OF SAND-CAST SLABS

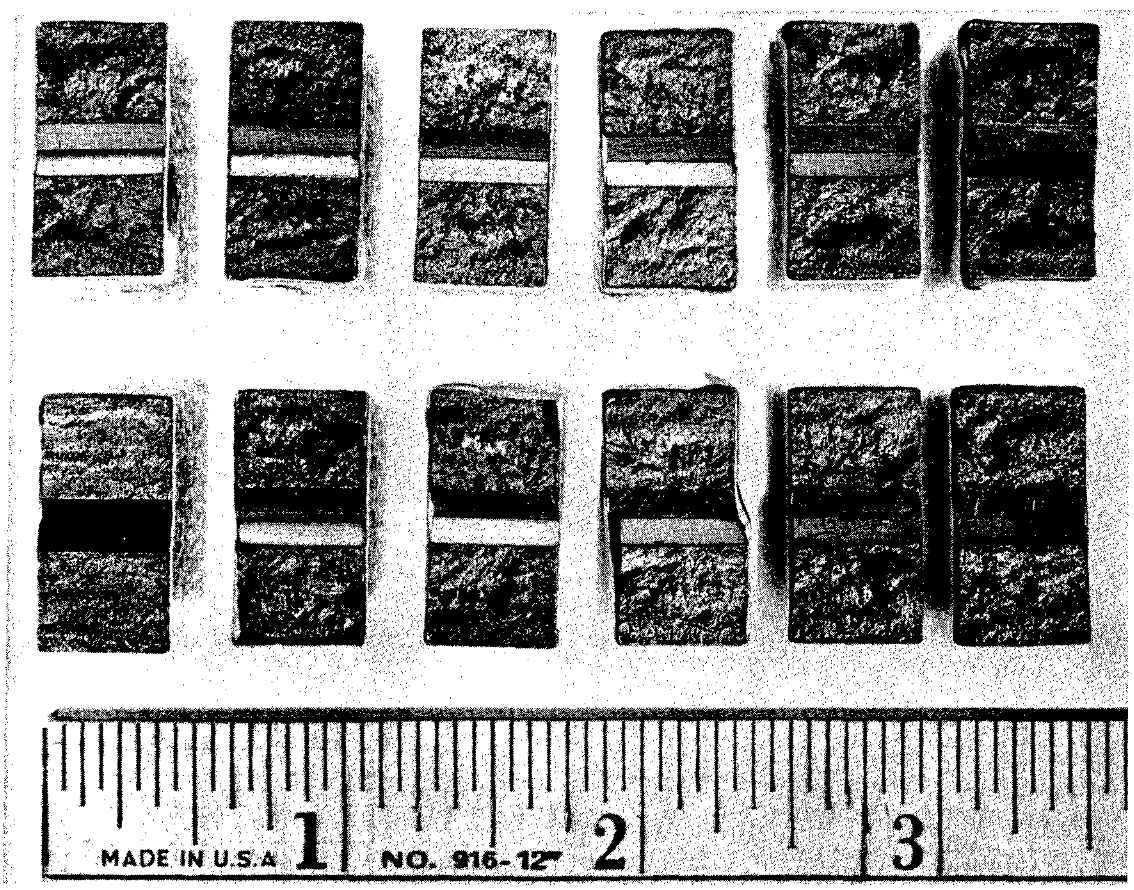
As a final phase of the program, it was intended that one steel composition of superior properties should be reproduced by air melting under slag and casting in the form of thick slabs in green sand molds. The alloy selected was to have the following nominal composition:

Mn	Ni	Cr	Mo	Si	C
1.9	0.5	1.0	0.5	0.5	0.18

There are actually two optimum alloy compositions, the other containing nominally:

Ni	Mn	Cr	Mo	Si	C
2.5	0.5	1.0	0.5	0.5	0.18

The choice of the high Mn alloy was based on its lower potential alloy costs.



Neg. No. 21684

FIG. 17 - APPEARANCE OF THE FRACTURED SURFACES OF A GROUP OF CHARPY BARS RANDOMLY SELECTED.

A pattern was made which permitted the casting of slabs of 5, 4, and 3-inch thickness and lateral dimensions of 18 in. x 18 in. The slabs were cast vertically with a large riser on one of the 18-in. thickness faces. The slabs were allowed to cool in the sand. Even in this state they were too hard to cut with a saw. Accordingly, the riser was cut off with a torch, and the slab was furnace annealed. It is important to point out that torch cutting worked without difficulty and without the formation of cracks in the steel. This points up the expectedly good weldability of steels at this low carbon level. The analyzed compositions of the three heats are given in Table IV.

TABLE IV

ANALYSIS OF THREE AIR-MELTED HEATS

Slab Thickness, inches	As-cast Hardness, Rc	Composition, w/o					
		C	Mn	Ni	Cr	Mo	Si
5	34	0.19	1.82	0.62	1.04	0.60	0.62
4	35	0.17	1.93	0.59	0.86	0.63	0.35
3	36	0.19	1.63	0.60	1.09	0.63	0.45

The slabs were austenitized and air-quenched in the manner previously used for the block and insert system. After tempering, a center slice of about 1-inch thickness was cut out for radiography and for the selection of test specimens. The radiographs are shown in Figures 18, 19, and 20. Some unsoundness was apparent in all of the slabs, particularly in the 5-inch thick one.

One slice from each slab was tempered directly from the as-cast condition to a hardness of 29 Rc. It will be noted that the as-cast hardnesses were 34-36 Rc. From these slices, Charpy test specimens were cut; the toughness measurements are recorded in Table V. While the toughnesses recorded are not particularly good, they were, nevertheless, appreciable.

FIG. 18 - RADIOGRAPH OF 5-INCH THICK SAND-CAST SLAB; 1/2-INCH THICK SLICE (RADIATING LINES ARE SAW MARKS.)

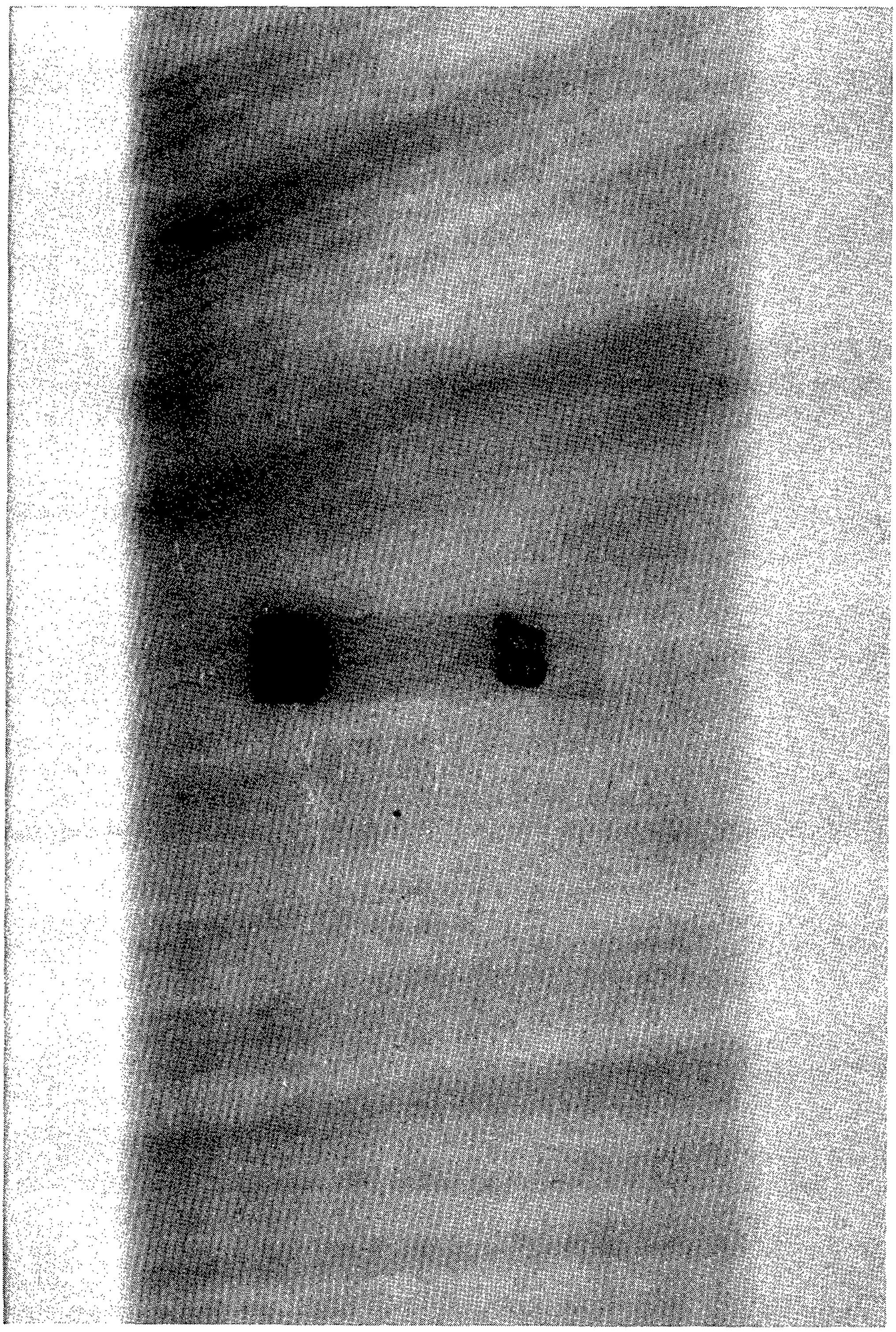


FIG. 19 - RADIOGRAPH OF 4-INCH THICK SAND-CAST SLAB; 1/2-INCH THICK SLICE.

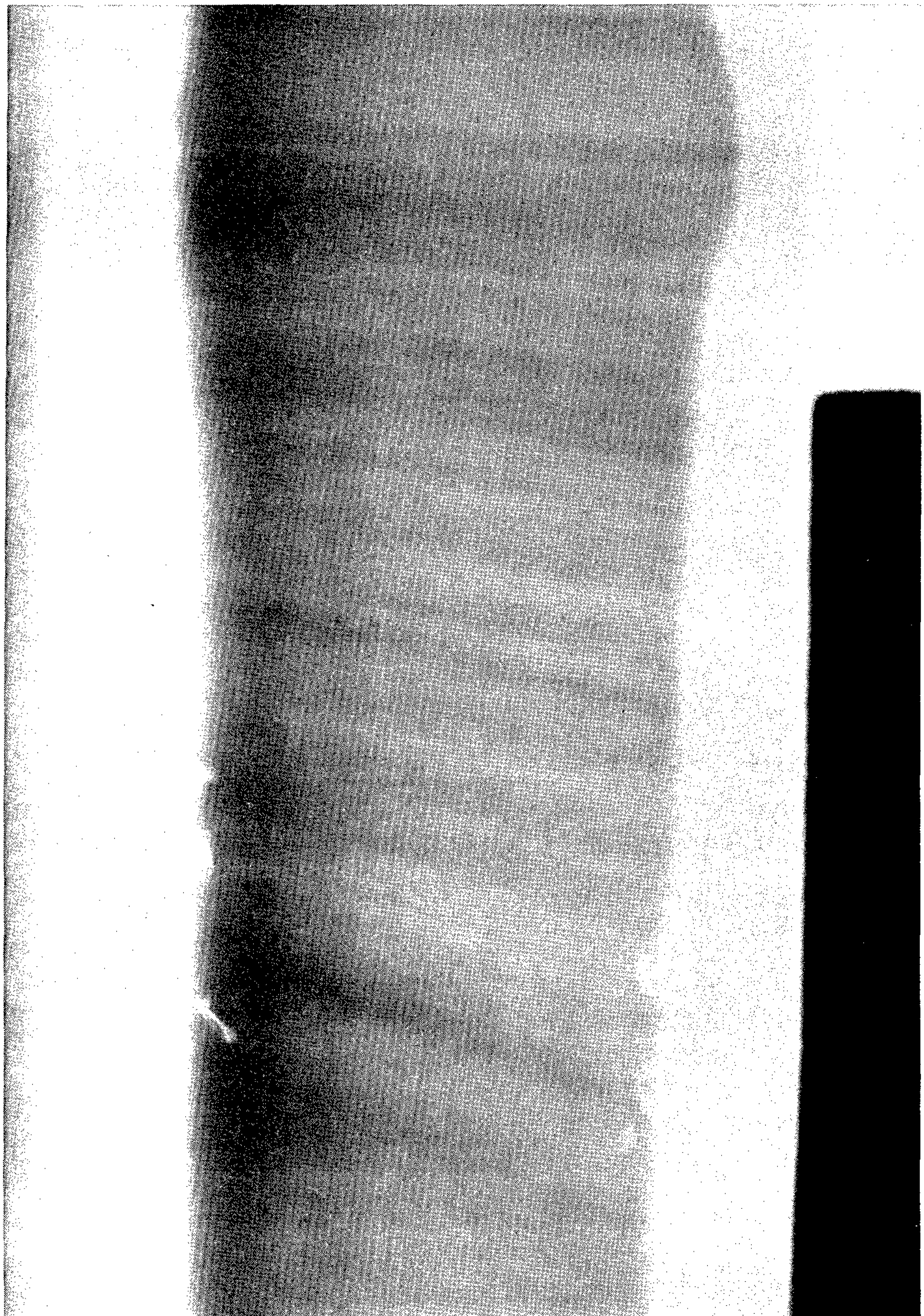


FIG. 20 - RADIOGRAPH OF 3-INCH THICK, SAND-CAST SLAB; 1/2-INCH THICK SLICE.

TABLE V

TOUGHNESS OF SAND-CAST, 1.9% MANGANESE STEEL TEMPERED FROM THE AS-CAST STATE TO 29 Rc

Slab Thickness, inches	Distance from Quenched Surface, inches	Toughness, ft-lb -40°F	Toughness, ft-lb R.T.
5	0.5	4	6, 16
	1	4, 10	13
	1.5	11, 12	12, 15
	2	10, 13	10, 15
	2.5	8, 10	12, 13
4	0.5	5, 7	8, 14
	1	6, 12	16, 18
	1.5	6, 7	10, 11
	2	5	10, 10
3	0.5	6	6, 7
	1	5, 6	7, 10
	1.5	8	4, 9

The remaining slab halves were re-austenitized at 1700°F and air quenched. Tempering was intended to yield a hardness of 22-24 Rc, but the 5-inch and 3-inch slab samples recorded 28-30 Rc. Specimens were cut from these slices and toughness measurements made. These are recorded in Table VI. The toughness proved to be not much better than as-tempered to the same hardness from the as-cast state. The remainder of the slabs were tempered back to 22-24 Rc and new specimens cut. These results are plotted in Figure 21, where it is apparent that considerable improvement in toughness is realized. In fact, these values come close to armor requirements.

It will be noted that both steeper gradients and more fluctuation occur in the sand-cast material than was experienced in the small experimental heats. This is probably a reflection of the inadequate soundness of these castings, and improvement could be expected. The average values of toughness are equal to or better than the smaller experimental heats indicating that the coarse grain size does not introduce any deleterious effects. The tensile properties of the material at 22-25 Rc are summarized in Table VII. Some of the anomalously low ductilities indicate again the presence of unsoundness in the centers of the slabs.

The microstructures of the hardened and tempered slabs are shown in Figure 22, where it may be seen that a uniform bainitic structure has been developed. There are some evidences of prior austenite grain boundaries.

VIII. SUMMARY

This program has concerned itself with the influence of alloying on the toughness of steel under a very special set of circumstances. These circumstances involve the cast state, a thickness dimension of 5 inches, a hardening operation by air quenching, and toughness testing primarily at -40°F. These specific conditions describe in laboratory terms the qualifications of heavy cast armor for military vehicles.

The 5-inch section dimension and the air-quenching condition preclude the generation of predominantly martensitic structures. By setting an initial condition for further test that the steel shall be capable of air hardening throughout the section to at least 30 Rc, the scope of alloying

TABLE VI

TOUGHNESS OF SAND-CAST, 1.9% MANGANESE STEEL AIR-HARDENED AND TEMPERED TO 28-30 Rc

Slab Thickness, inches	Distance from Quenched Surface, inches	Toughness, ft-lb -40°F	Toughness, ft-lb R.T.
5	0.5	13.5	5
	1	10, 11	8
	1.5	13	7, 8
	2	11, 12	2, 4
	2.5	5, 9	1, 10
3	0.5	11, 14	15, 15
	1	7, 9	4, 5
	1.5	4, 9	2, 5

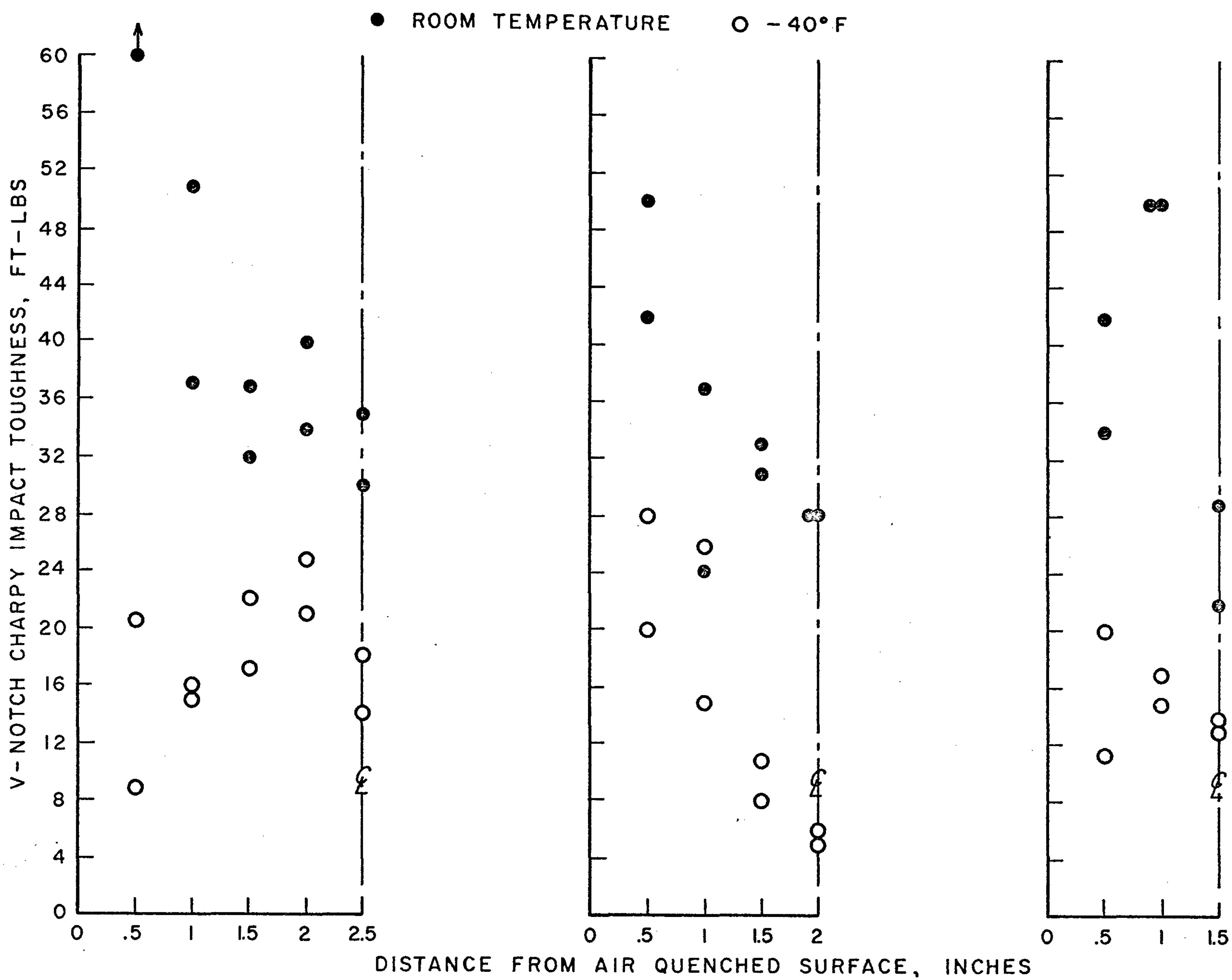


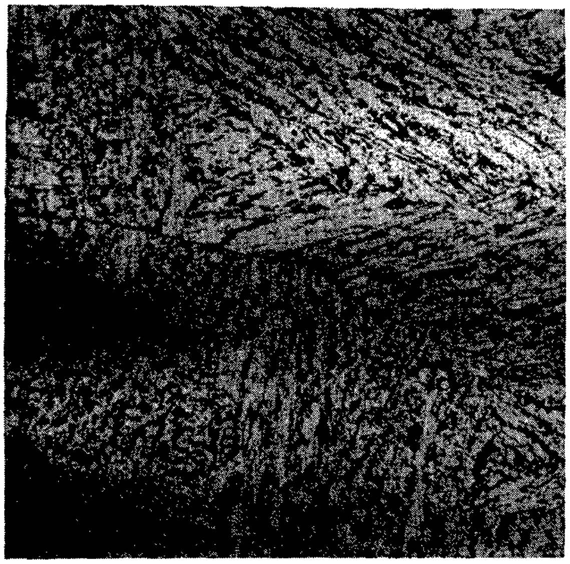
FIG. 21 TOUGHNESS OF SAND CAST SLABS, AIR-HARDENED AND TEMPERED TO 22-24 Rc.

TABLE VII

TENSILE PROPERTIES OF SAND-CAST SLABS*
AIR-HARDENED AND TEMPERED TO 22-25 Rc

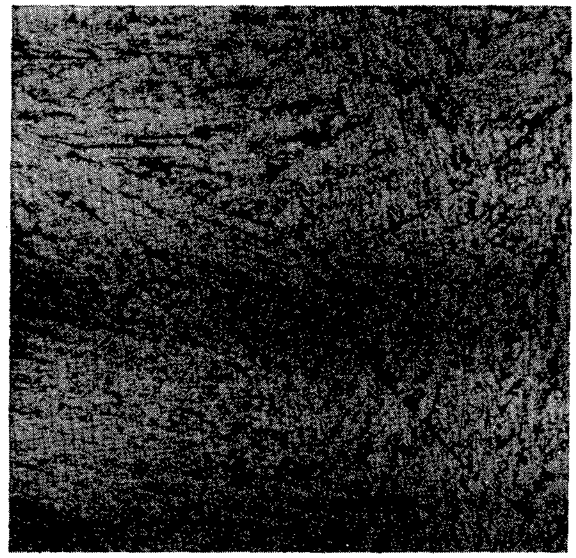
Slab Thickness, inches	Distance from Air-Quenched Surface, inches	UTS, psi	Yield Strength, psi	Elong., %	RA, %
5	1/2	108,900	89,100	10	21.5
	1	110,000	90,500	12.5	20.5
	1 1/2	112,000	88,000	10.5	18
4	1/2	115,900	88,500	21	41
	1	116,300	89,700	12	15.5
	1 1/2	105,400	87,500	5	6
3	1/2	110,400	89,200	15.5	41
	1	108,900	88,000	10	19
	1 1/2	105,800	87,000	16	13.5

* See Table IV.



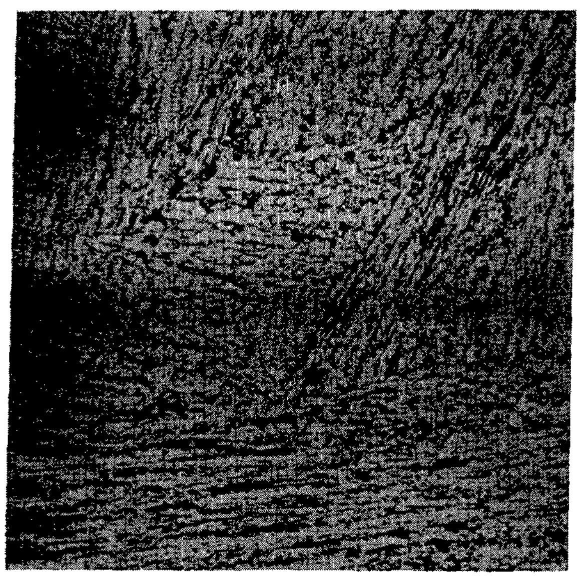
Neg. No. 22758

(a) 5-inch Slab



Neg. No. 22760

(b) 4-inch Slab



Neg. No. 22759

(c) 3-inch Slab

FIG. 22 - MICROGRAPHS (X500) OF SAND-CAST SLABS HAVING NOMINAL COMPOSITION: 1.9% Mn, 0.5% Ni, 1.0% Cr, 0.5% Mo, 0.5% Si, 0.18% C. Etchant: nital.

essentially precludes also the existence of pearlitic structures. This study, therefore, relates to the influence of alloying on the toughness of structures which are predominantly lower bainite.

Within the context of section dimensions, quench severity, and microstructure, it has been shown that there is a clear optimum relationship between carbon content and toughness. A preferred carbon content of about 0.18% has been established with toughness falling off on either side of this optimum. The permissible range about this optimum carbon content has not been established. A carbon content of 0.18% is significantly lower than has been commonly used in cast armor applications.

While a lower carbon content is not particularly welcome to the foundryman because of the necessity for higher melt temperatures, it should otherwise be generally welcome for the relative freedom from cracking hazards which it brings. Basically, the lower carbon content dictates that the hardest state which can be produced cannot exceed about 45 Rc. This is quite sufficient because armor plate is invariably tempered back to 20-30 Rc. But martensite of only 45 Rc hardness has appreciable toughness compared to higher carbon-higher hardness equivalents. Therefore, such factors as non-uniform transformation, thermal stresses, and local welding operations do not present as much of a cracking hazard. These remarks have been amply borne out in the behavior and experiences recorded in this program.

With total alloy contents of 3-6%, air quenching produces uniform hardening in section thicknesses at least up to 5 inches. In general, hardness and microstructures were uniform throughout. This was also largely true for toughness although there were some exceptions which may be due to center-section unsoundness. Hardenability under these conditions must be defined in terms of the absolute level of hardness attainable by air quenching.

By independent variation of the content of individual alloying species, it was possible to show that substantial differences in ability to produce high as-quenched hardnesses exist. Of the major alloying elements Mn is the most powerful hardener followed by Mo but with upper limit restrictions on the latter. Of the minor alloying elements, B is effective but only above some minimum amount.

Within the context of these lower bainite structures, it has been definitely shown that high toughness in the tempered state does not follow upon higher, as-quenched hardness; thus whereas as-quenched hardness continues to increase with increasing alloy content (except in the case of Mo additions), the toughness of the tempered steel reaches a maximum. For progressive Mn additions, this maximum occurs at about 2% Mn and for Ni additions at about 2.5% Ni. This is an important point because it establishes that unlimited alloying is totally undesirable.

The optimum alloy content correlates with the disappearance of apparently carbide-free ferrite and grain boundaries--of either ferrite or prior austenite. The ideal structure for high toughness has a fine, uniform structure with no evidences of long continuous interfaces.

From the systematic study phase, the superior alloy was chosen for further evaluation. This preferred composition is nominally:

Mn	Ni	Cr	Mo	Si	C
1.9%	0.5	1.0	0.5	0.5	0.18

This composition is not radically different from others used in cast armor applications. The carbon content is definitely lower and the Mn content is somewhat higher. A second analysis providing equally good toughness had the following nominal composition:

Ni	Mn	Cr	Mo	Si	C
2.5	0.5	1.0	0.5	0.5	0.18

This outcome is especially interesting because the alloy content comes close to the time-honored Krupp analysis for wrought armor plate. The major difference is the lower carbon level.

The former alloy was air-melted and cast into 5, 4, and 3-inch thick slabs using green sand molds. The sand-cast metal, in spite of obvious center unsoundness, gives as good or better mechanical properties as the more carefully melted and chill-cast experimental heats. This alloy is capable of sustaining about 18-20 ft-lb impact energy at -40°F and 30-60 ft-lb at room temperature at a tempered hardness of 22-24 Rc. It is believed that some of the lower impact values experienced in the center regions of the slab could have been improved with a sounder casting.

This alloy could be regarded as a general-purpose cast armor steel--that is, it can provide an acceptable toughness under conditions of very thick section and very mild quench but certainly much better toughness if smaller sections and/or more severe quench are used. General indications are that this alloy is not prone to cracking in heat treatment or flame cutting. It should be weldable using filler rod of the same or similar composition.

IX. LOGBOOKS AND PERSONNEL

Data presented in this report are contained in ARF Logbooks No. 11019, 11185, 10744, 11686, and 12223. Much of the work reported herein was conducted by Mr. Clarence Carter, Assistant Metallurgist.

Respectfully submitted,

W. Rostoker
Metals and Ceramics Research

Tech Rev: JFR

APPENDIX

MEASUREMENT OF QUENCH SEVERITY IN AIR COOLING

Cooling curves have been taken under typical conditions of forced air cooling at three positions in specimens inserted in the block. The cooling curves are shown in Figure 23 (a, b, c). Note the thermal arrests at 750°-650°F. These obviously indicate the occurrence of a lower bainite or martensitic transformation. They do not, however, interfere with the determination of quench severity. The cooling curves of temperature vs. time have been converted to relative temperature vs. relative time using an average thermal diffusivity of 0.65 $in.^2/min$. These experimental curves are plotted in Figure 24 (a, b, c) against the calibration curves taken from Russell's tables (see Austin*). These three separate comparisons permit independent determination of H. The values obtained are all, within the accuracy of determination, of the magnitude of 0.08.

* J. B. Austin, Flow of Heat in Metals, ASM (1942).

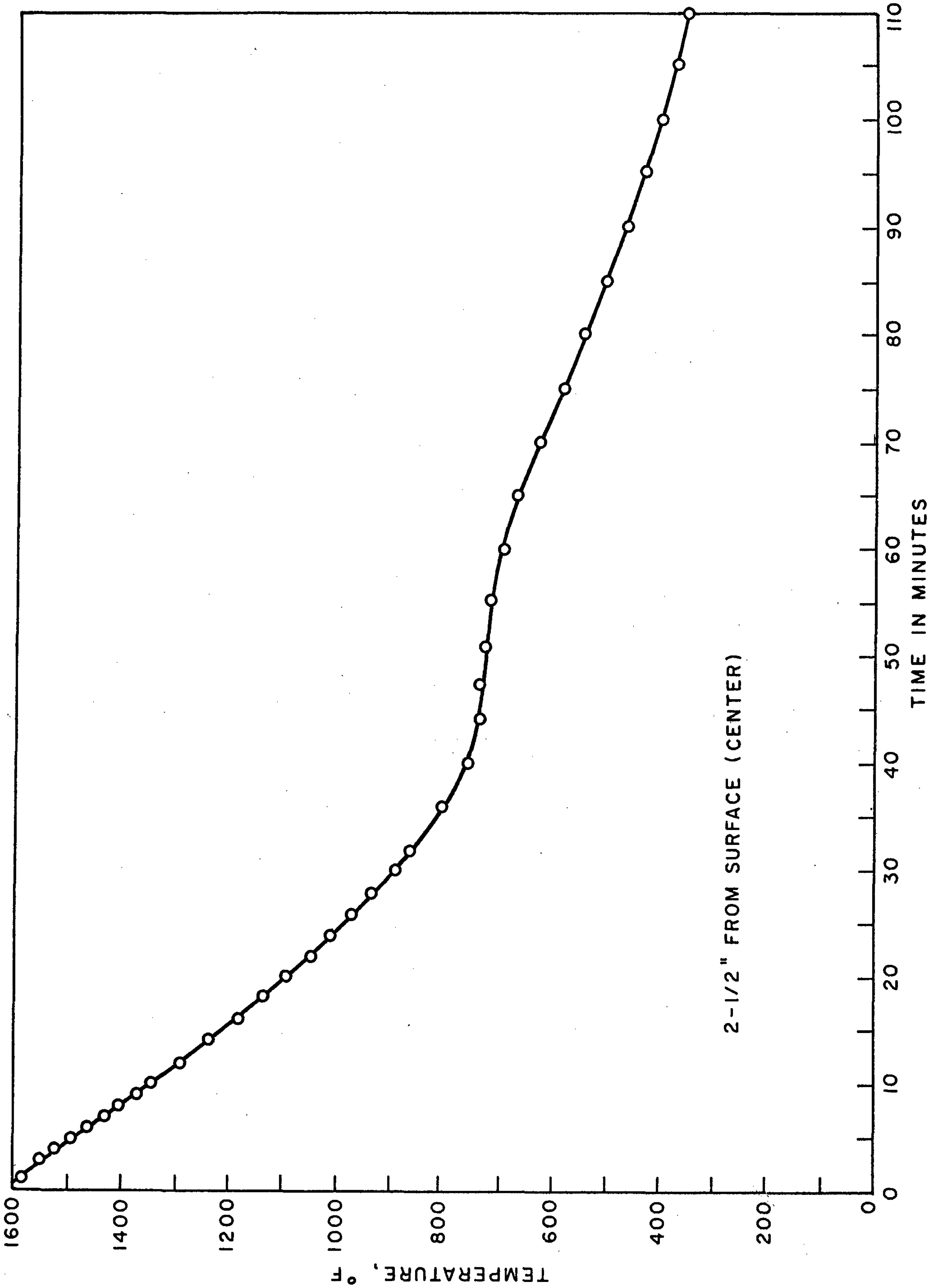


FIG. 23 (a) COOLING CURVES IN FORCED AIR FOR A 0.17%C-4.5% ALLOY STEEL.

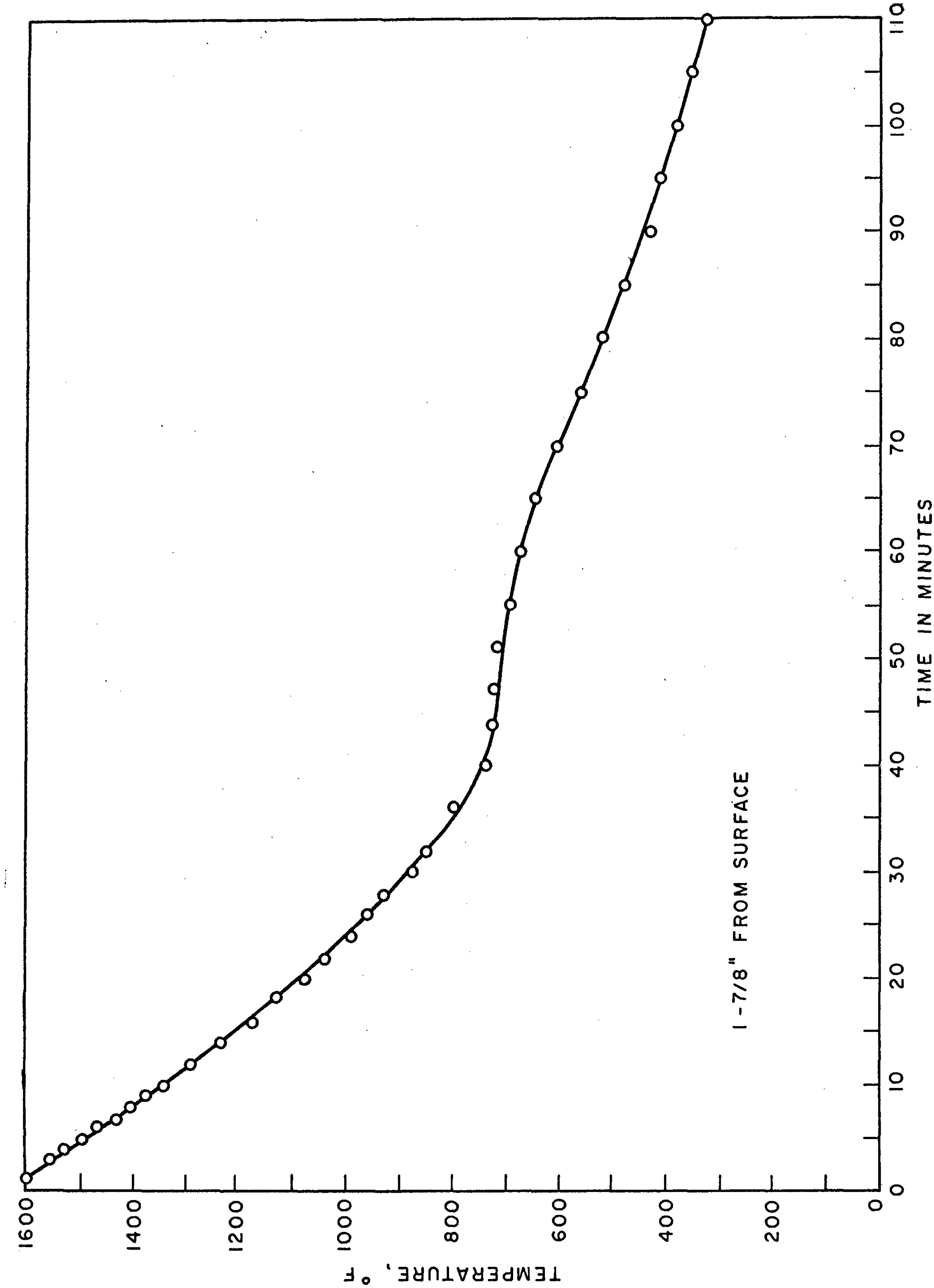


FIG. 23 (b) COOLING CURVES IN FORCED AIR FOR A 0.17%C-4.5% ALLOY STEEL.

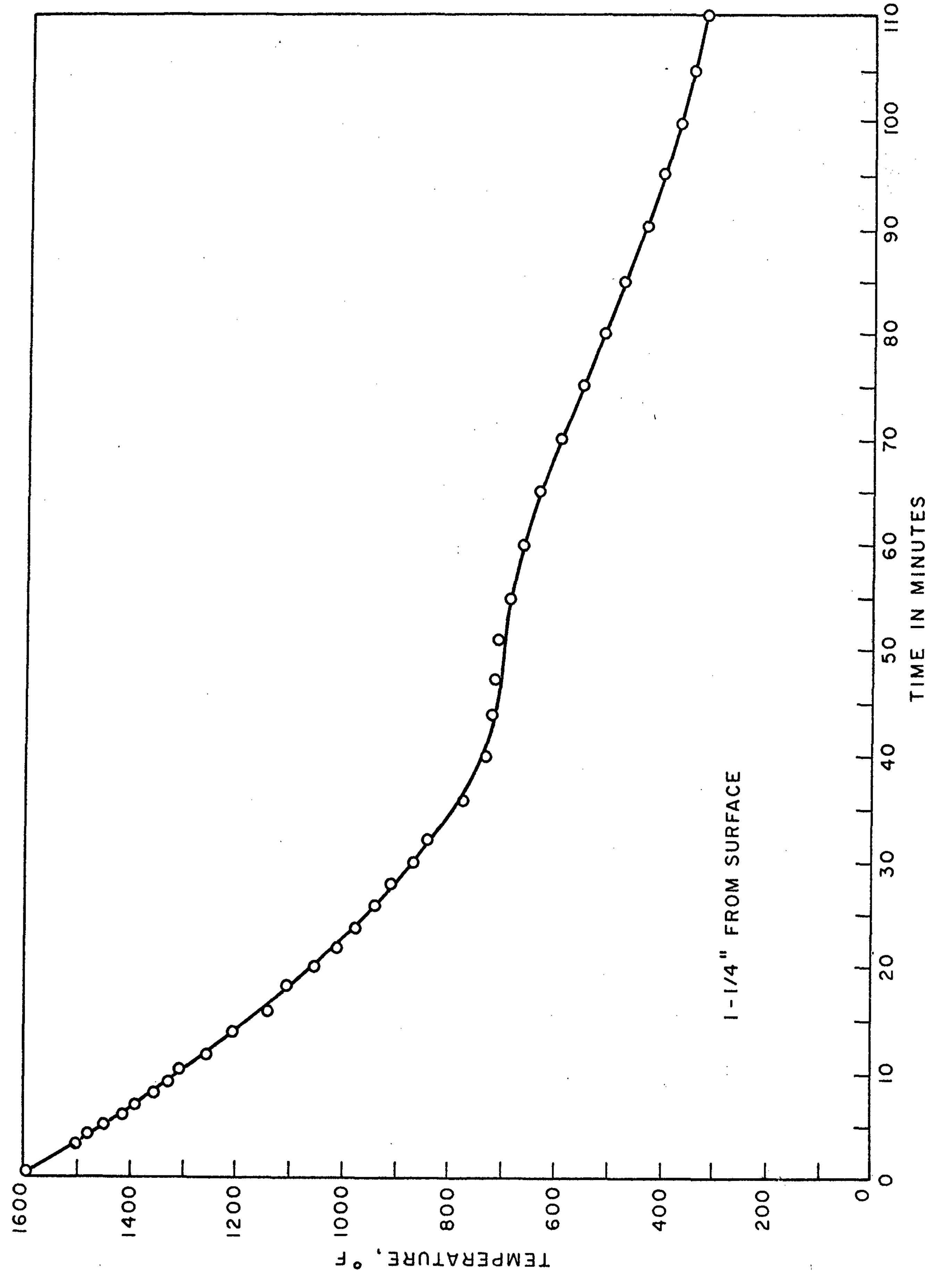


FIG. 23 (c) COOLING CURVES IN FORCED AIR FOR A 0.17% C - 4.5% ALLOY STEEL.

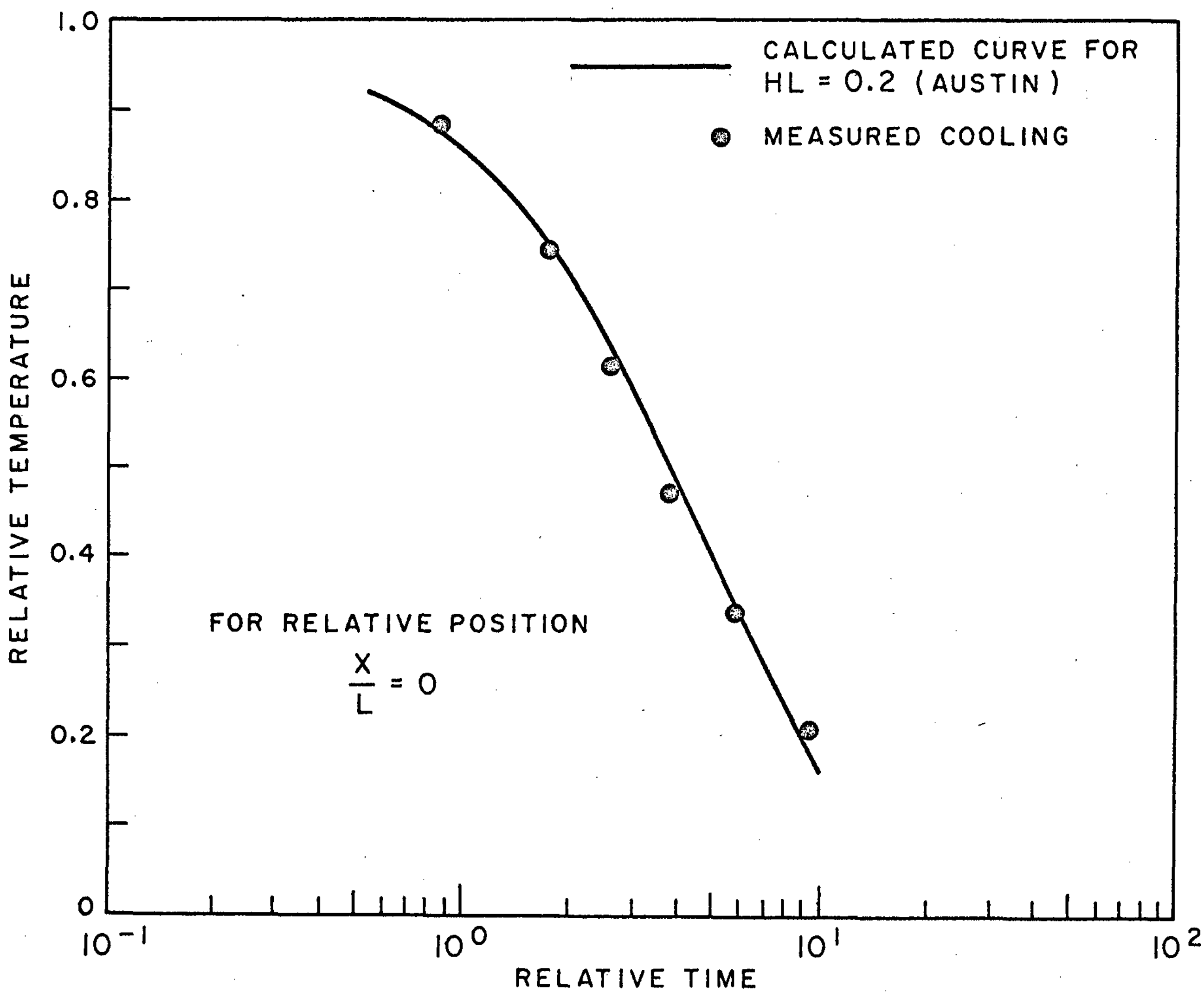


FIG. 24 (a) DETERMINATION OF QUENCH SEVERITY OF MOVING AIR IN STEEL PLATE FIVE INCHES THICK.

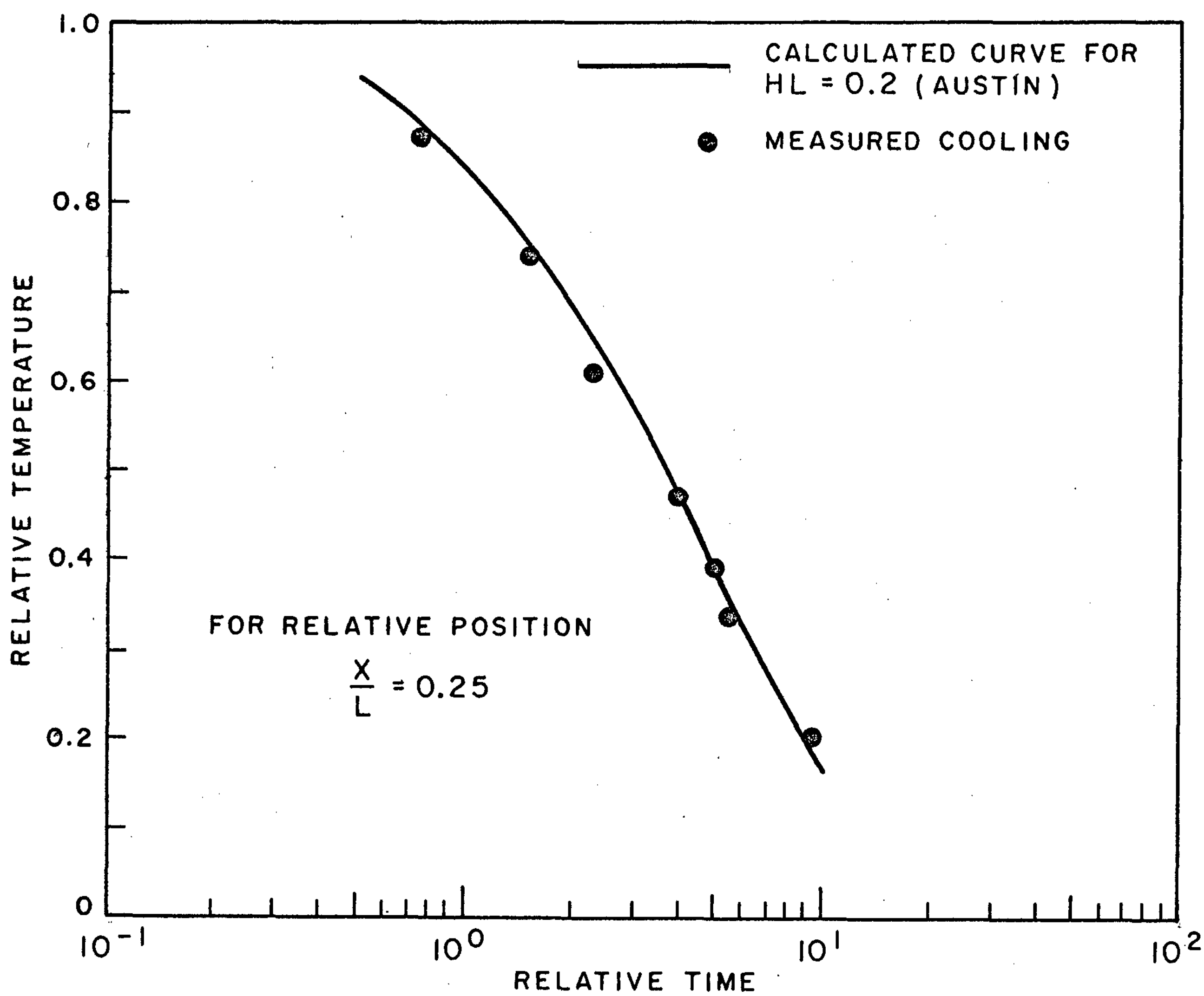


FIG. 24 (b) DETERMINATION OF QUENCH SEVERITY OF MOVING AIR IN STEEL PLATE FIVE INCHES THICK.

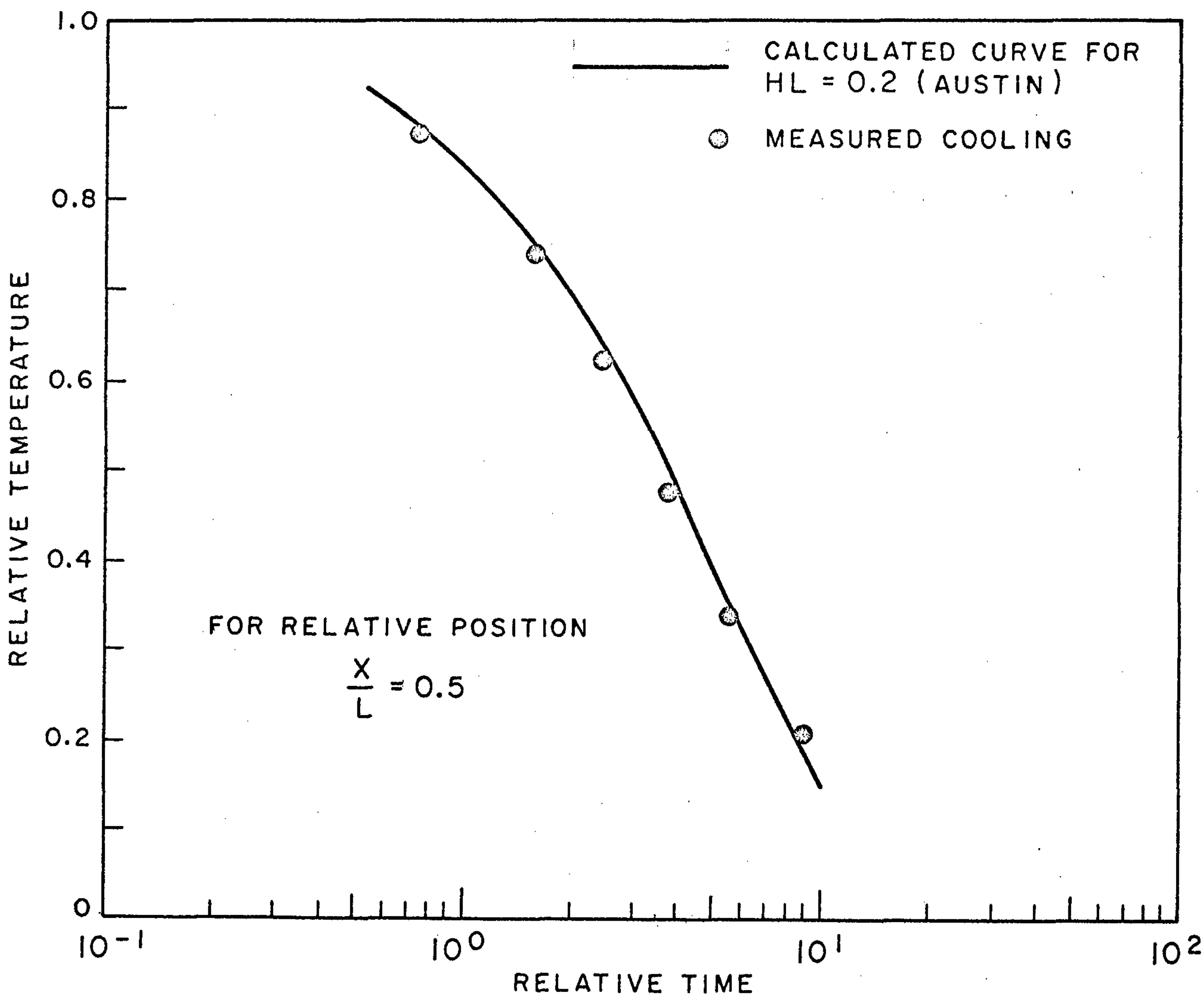


FIG. 24 (c) DETERMINATION OF QUENCH SEVERITY OF MOVING AIR IN STEEL PLATE FIVE INCHES THICK.