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APPENDIX A

Estimations of Metallurgical Characteristics



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APPENDIX A

Estimations of Metallurgical Characteristics

I. Cooling Curves

Estimated time-temperature curves for the cooling at the center and at the surface of 3-inch and 6-inch thick plates given direct, delayed, interrupted, and combination delayed and interrupted quenches are shown in Figures A-1 to A-8. These curves were calculated from the tables of Russell,¹ and are, therefore, subject to the same assumptions as those tables. The severity of water quench H^2 was taken² as 1 inch⁻¹ and of air-cool as .02 inch⁻¹ while the thermal diffusivity of the steel was considered³ to be .009 square inches per second.

The behavior of "equalization" following the interruption of a quench is not covered by Russell's tables, and, therefore, was deduced for this work, under the simplifying assumption that the temperature distribution along the thickness of the plate at the moment of interruption can be considered to take the simple form of a constant plus one-half cycle of a cosine curve. The details of the calculation will not be given here, but it may be noted that, for the value of thermal diffusivity mentioned, the characteristic time in seconds for the temperature difference to decrease to $\frac{1}{2}$ its value is found to be 2.8 times the square of the thickness in inches, while it falls to 10 per cent its value in 6.2 times the square of thickness and to one per cent in 12.0 times the square. For a 6-inch plate, these times are about 100 seconds, 3 minutes 40 seconds and 7 minutes respectively. The results are included in Figures A-3, A-4, A-7 and A-8.

It must be remembered that the cooling curves of Figures A-1 to A-8 are necessarily calculated for particular severities of quench. The actual severities will vary from plant to plant. Moreover, several of the approximations used by Russell are undoubtedly not very close. The cooling curves given are, therefore, to be considered rough estimates only.

II. Steel Characteristics

The preliminary calculations for the various types of steel selected for this program included estimated critical and austenitizing temperatures, martensite temperature ranges, Jominy hardenability, and isothermal transformation diagrams ("S-Curves").

¹Russell in his tables uses the symbol h which is equal to $2H$.

1. T. F. Russell; "Some Mathematical Considerations on the Heating and Cooling of Steel". Iron and Steel Institute, Alloy Steels Research Comm., First Report, 149-187 (1936).
2. M. A. Grossman and M. Asinow; "Hardenability and Quenching". The Iron Age, 145, (Number 18), 45 (May 2, 1940).
3. M. Asinow, W. F. Craig, M. A. Grossmann; "Correlation between Jominy Test and Quenched Round Bars". S.A.E. Journal, 49, 292 (1941).

Before computing the austenitizing temperatures, the minimum temperature (A_{e3}) at which the equilibrium structure is austenite alone was estimated upon the basis of the commonly accepted iron-carbon diagram¹ and the data concerning the effect of the alloying elements upon this diagram which are summarized by Bain.² It was found that the equilibrium temperature would probably not be over 1470°F. (See Table AI.) Experience indicated, however, that considerably higher temperatures would be required to obtain solution of the alloy carbides within the selected time of four hours. The austenitizing temperatures listed in Table AI and in the body of the report were predicted on the basis of this experience.

The calculated temperatures for the beginning (M_s) of the martensite reaction were obtained from Greninger's³ measurements on iron-carbon alloys and the results of various workers^{4,5,6} on the effect of alloying elements, making the assumption that the effects of the alloying elements are additive. In order to estimate the temperatures of the end (M_f) of the martensite transformation, the data of Payson and Savage⁷ concerning the difference between the M_s and the M_f temperatures were used. Table AI shows the M_s and M_f temperatures estimated on these bases.

The predicted range (high-side composition and low-side composition) of the Jominy end-quench hardenability curves for each type of steel is given in Figures A-9 to A-13. These estimates are based upon interpolation among and extrapolation from the various Jominy curves available for similar compositions, including those in the published literature, those found in reports locally available, and those determined at this Laboratory. The predicted isothermal transformation diagrams (S-curves), Figures A-14 to A-18, represent

1. S. Epstein; "Alloys of Iron and Carbon, I - Constitution", McGraw-Hill, 96 (1936).
2. E. C. Bain; "Functions of the Alloying Elements in Steel". ASM, 234-274 (1939).
3. A. B. Greninger; "The Martensite Thermal Arrest". Trans. ASM, 30, 1-26 (1942).
4. H. H. Chiswick and A. B. Greninger; "Influence of Nickel, Molybdenum, Cobalt, and Silicon on the Kinetics and Arⁿ Temperatures of the Austenite to Martensite Transformation in Steels". Trans. ASM, 32, 483-520 (1944).
5. P. Payson and C. H. Savage; "Martensite Reactions in Alloy Steels". Trans. ASM, 33, 261-280 (1944).
6. J. V. Russell and F. T. McGuire; "A Metallographic Study of the Decomposition of Austenite in Manganese Steels". Trans. ASM, 33, 103-125 (1944).
7. P. Payson and C. H. Savage; "Martensite Reactions in Alloy Steels". Trans. ASM, 33, 261-290 (1944).

the averaged estimates of two people, using data from four sources^{1,2,3,4}. The diagrams were intended for the mean composition of each type. The A_{c1} , M_s and M_f temperatures shown are taken from Table AI. There is some doubt⁵ as to the time at which the formation of primary ferrite begins in the range 850-1200°F.; it is possible that a smooth curve should be drawn connecting the "noses" at 1200° and at 850°F., and that the "bay" at 1000°F. for the beginning and end of cementite formation does not apply to the start of primary ferrite precipitation.

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1. United States Steel Corporation, Research Laboratory; "Atlas of Isothermal Transformation Diagrams". U. S. Steel Corp. of Delaware, 1943.
 2. E. S. Davenport; "Isothermal Transformation in Steels". Trans. ASM, 27, 837-886 (1939).
 3. A. E. Troiano; "Progress Report on Investigation of the Metallographic and Physical Properties of New Types of Gun Steels (OD-34-3)". National Defense Research Comm. Report M-181, Watertown Arsenal Report 313/34-2. 1943.
 4. Crucible Steel Corp. of America, Atha Works. Private communication.
 5. A. R. Troiano; loc. cit,

TABLE AI

Estimated Transformation Temperatures

<u>Composition Type</u>	<u>A_{c3}, °F.</u>	<u>Austenitizing °F.</u>	<u>M_s, °F.</u>	<u>M_f, °F.</u>
I	1440-1465	1600	625-675	150-225
II	1445-1470	1625	575-650	75-150
III	1445-1470	1625	575-650	75-150
IV	1430-1465	1650	500-575	0-75
V	1440-1465	1675	475-575	-25-+75

FIGURE A-1
(CALCULATED)
3" PLATE

DIRECT WATER-QUENCH FROM 1650°F TO 75°F

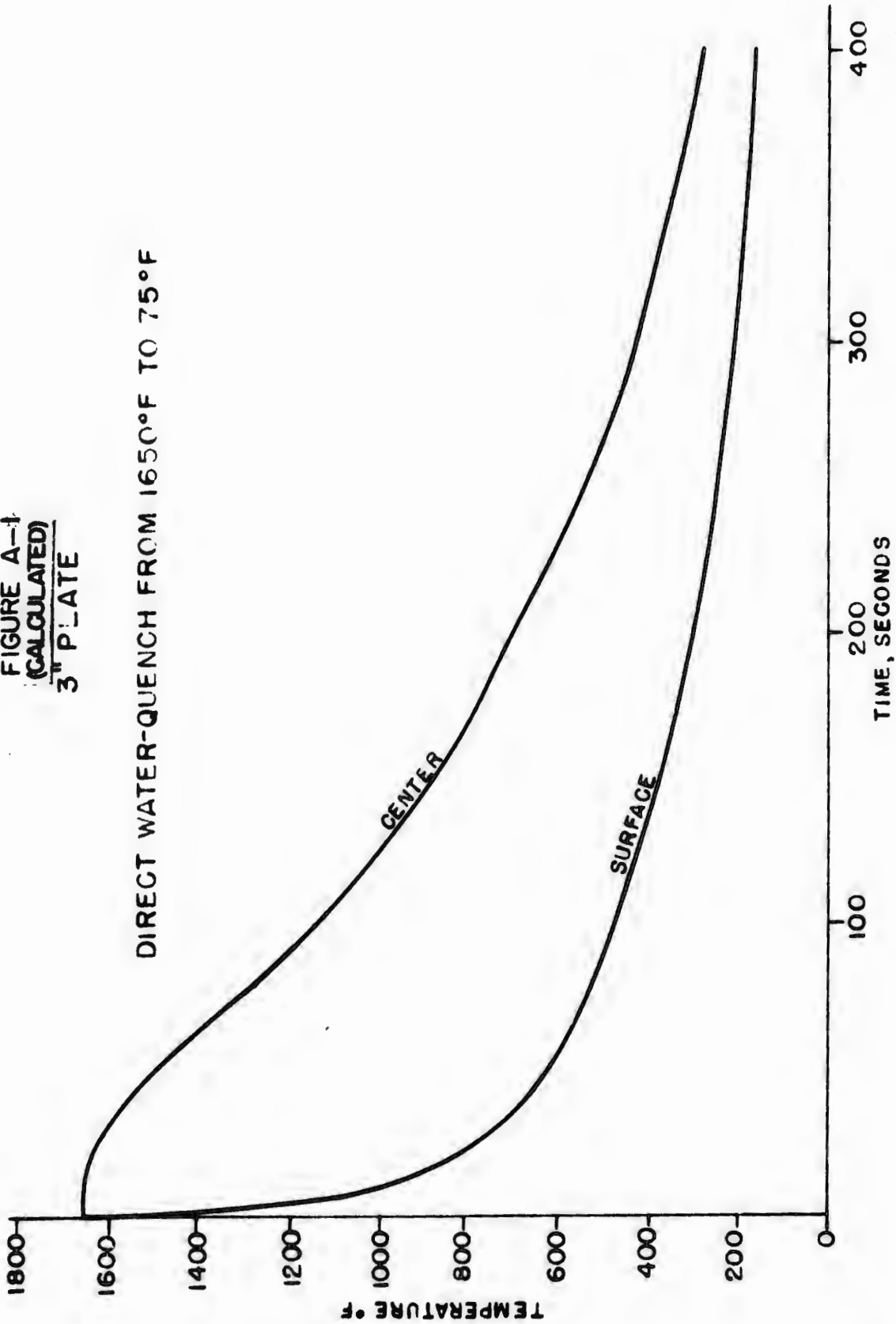


FIGURE A2
(CALCULATED)
3" PLATE

DELAYED QUENCH:- AIR-COOLED FROM 1650°F TO 1020°F.
WATER-QUENCHED FROM 1020°F TO 75°F.

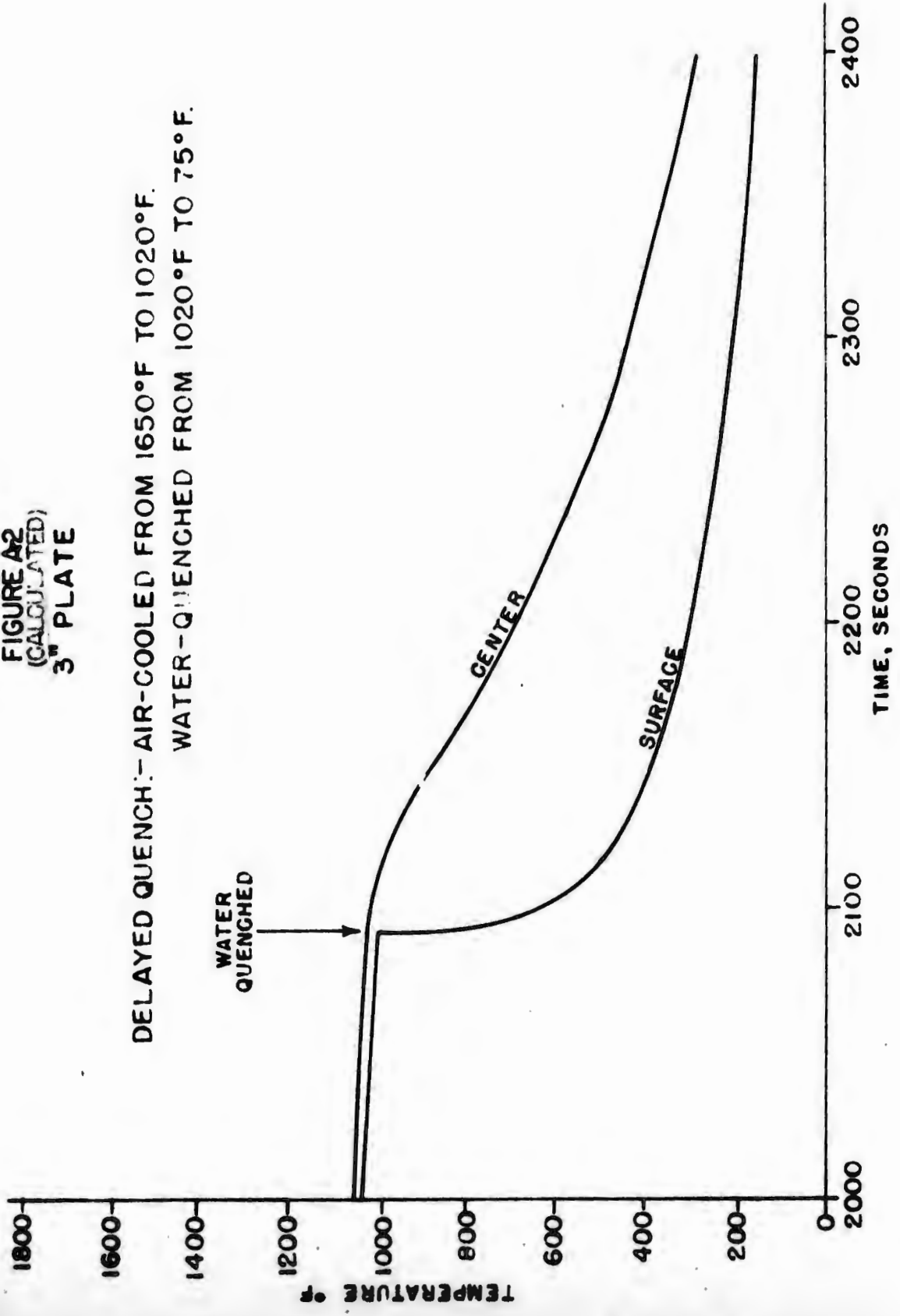


FIGURE A-3
(CALCULATED)
3" PLATE

INTERRUPTED Q'JENCH: - QUENCHED FROM 1650°F INTO
WATER AT 75°F.
INTERRUPT WHEN CENTER AT
650°F.
AIR-COOLED TO 75°F.

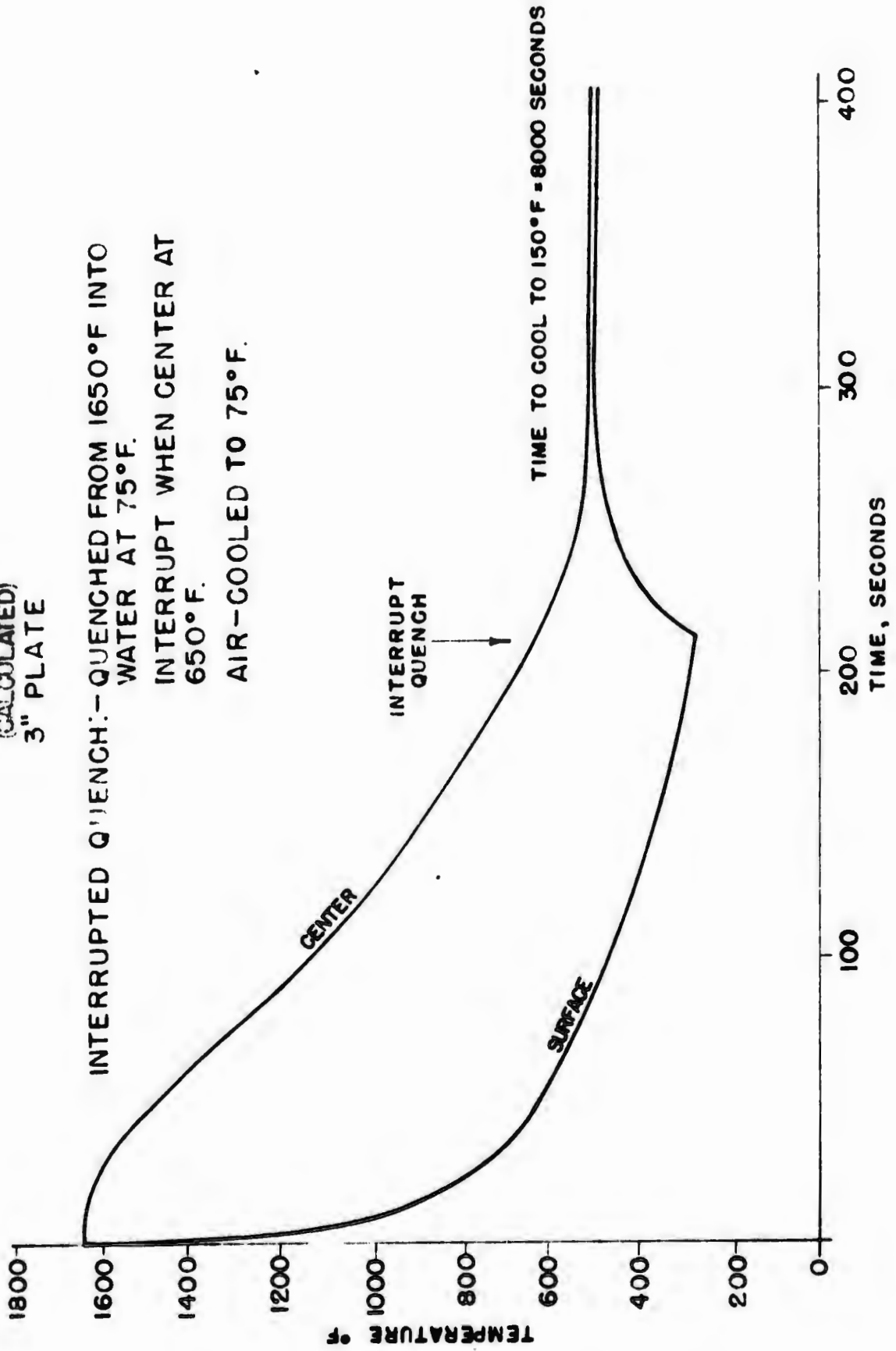


FIGURE A-4
(CALCULATED)
3" PLATE

DELAYED AND INTERRUPTED QUENCH—:
AIR-COOLED FROM 1650°F TO 1020°F.
QUENCHED FROM 1020°F INTO WATER
AT 75°F.
INTERRUPT WHEN CENTER AT 650°F.
AIR-COOLED TO 75°F.

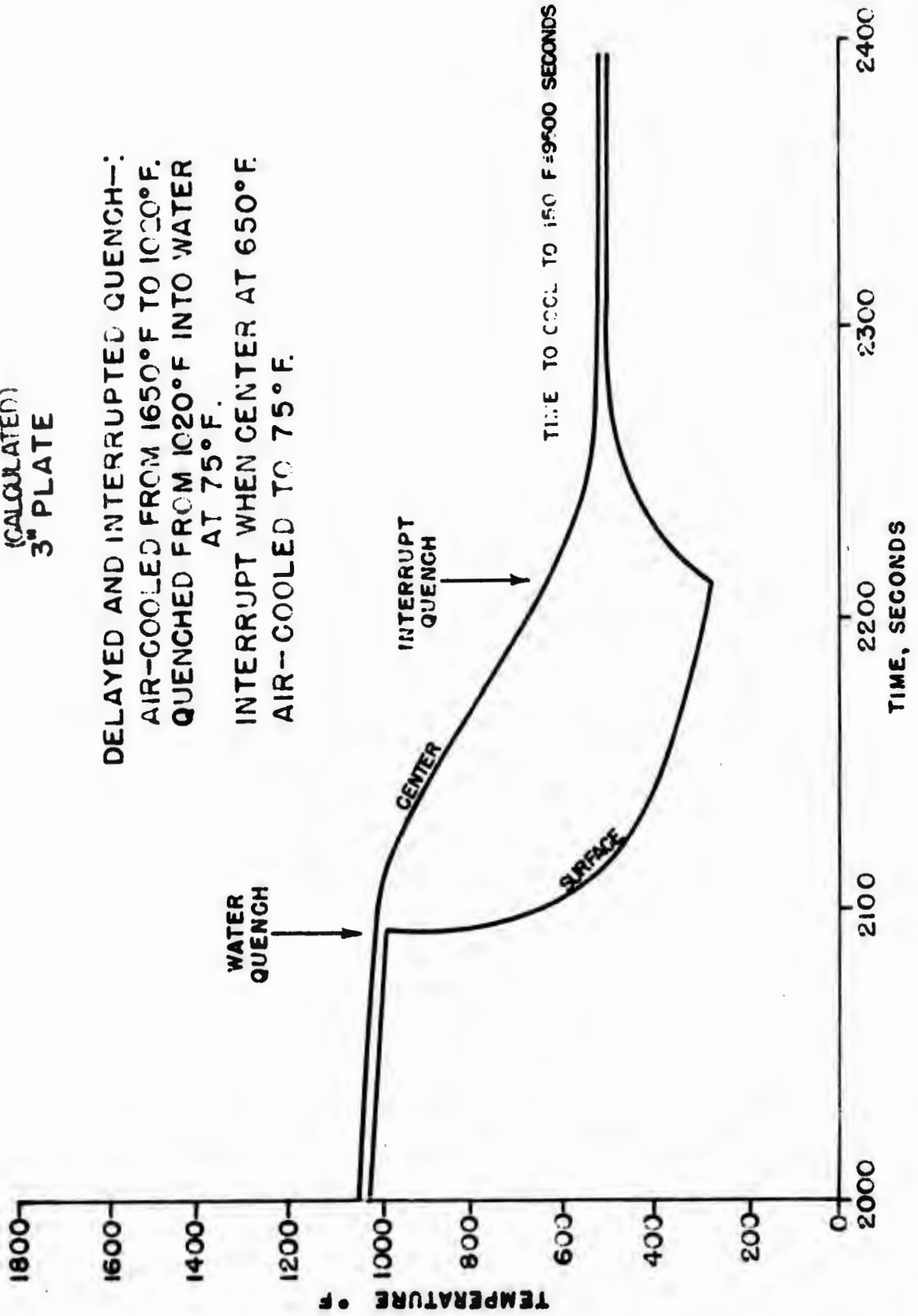


FIGURE A-5
(CALCULATED)
6" PLATE

DIRECT WATER QUENCH FROM 1650° TO 75°F

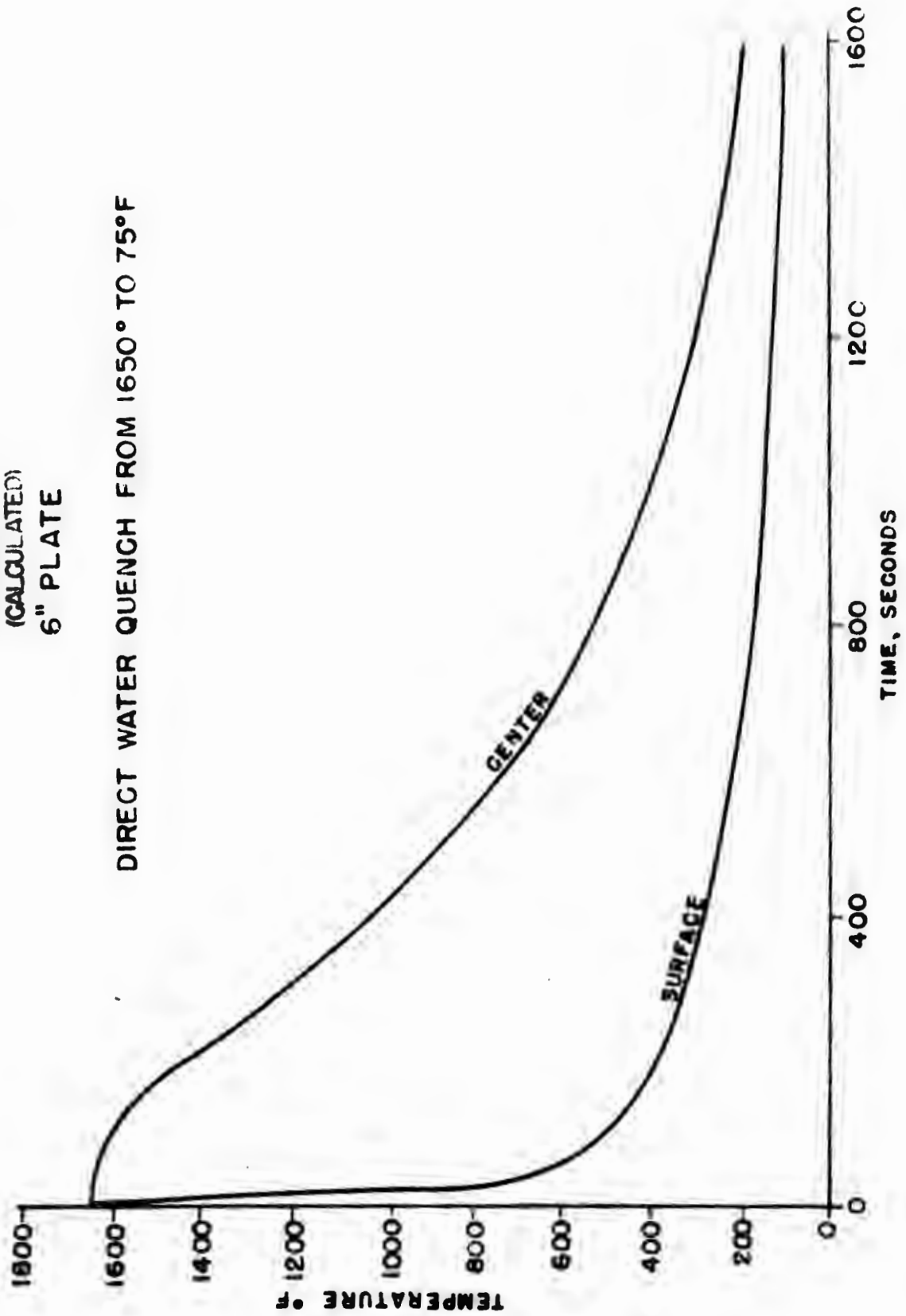


FIGURE A-6
(CALCULATED)
6" PLATE

DELAYED QUENCH: AIR-COOLED FROM 1650°F TO 1020°F.
WATER QUENCHED FROM 1020°F TO 75°F.

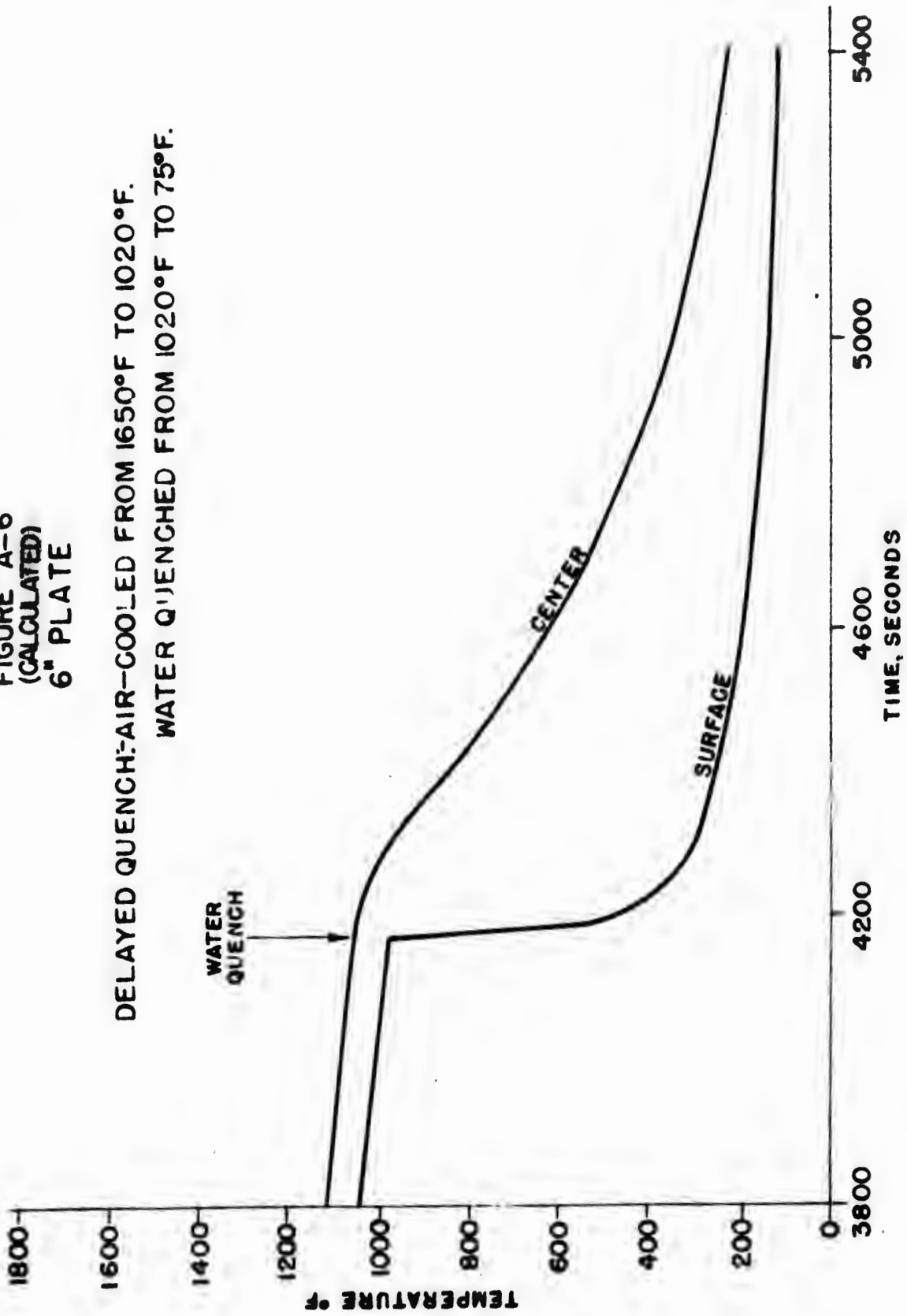


FIGURE A-7
(CALCULATED)
6" PLATE

INTERRUPTED QUENCH

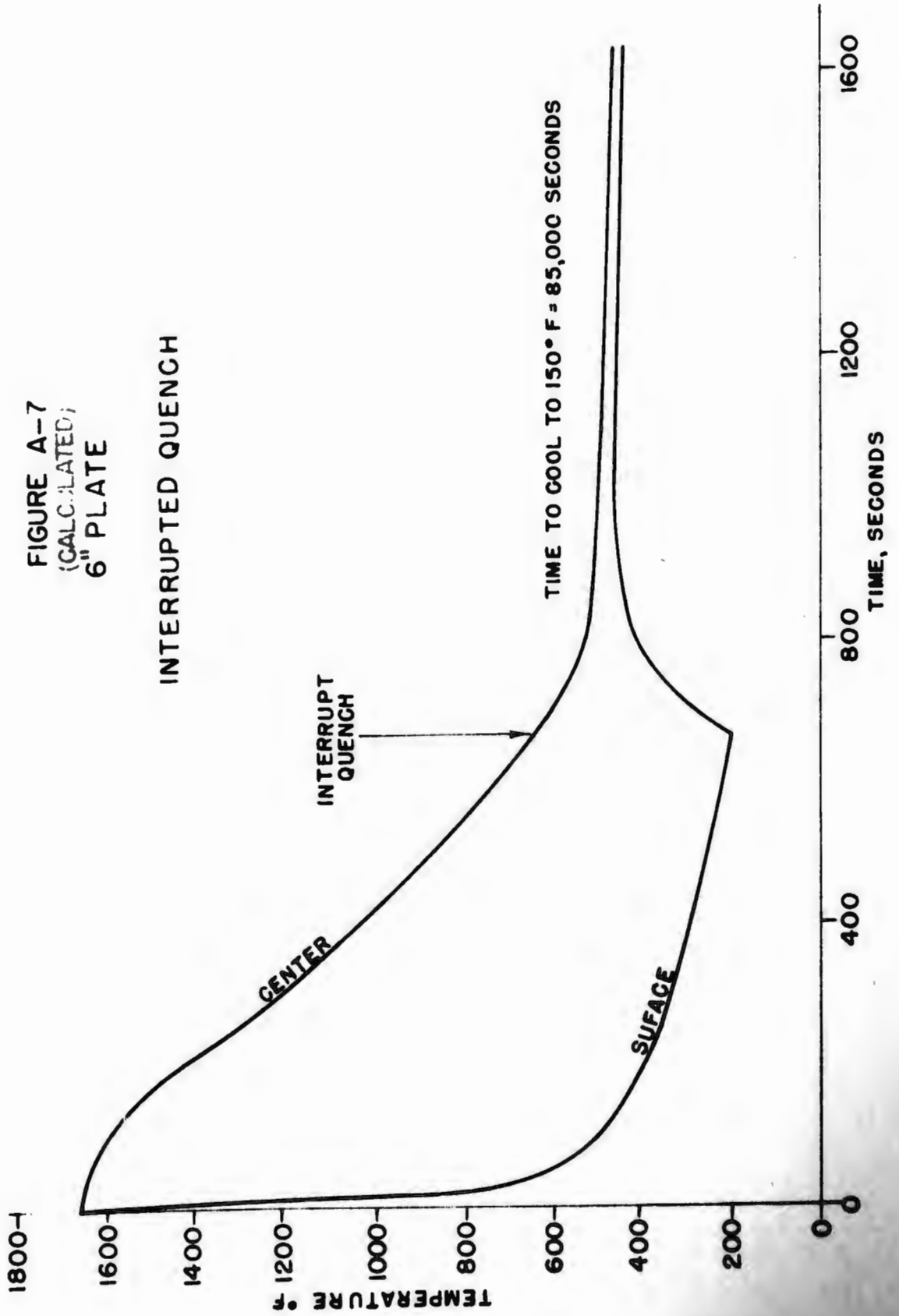


FIGURE A-8
(CALCULATED)
6" PLATE

DELAYED AND INTERRUPTED QUENCH

AIR-COOLED FROM 1650°F TO 1020°F.
QUENCHED FROM 1020°F, INTO WATER AT 75°F.
INTERRUPT WHEN CENTER AT 650°F.
AIR-COOLED TO 75°.

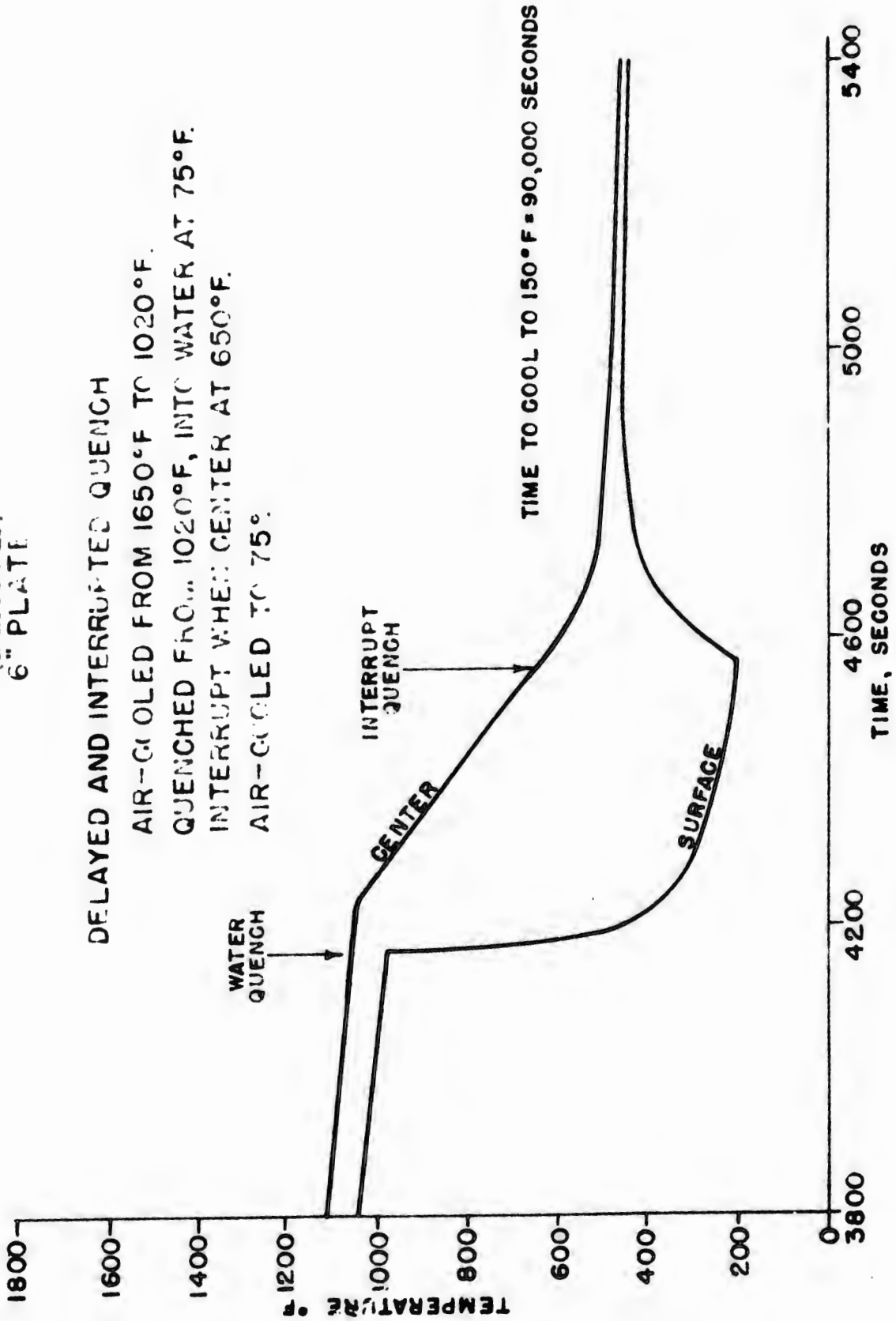


FIGURE A-14
ISOTHERMAL TRANSFORMATION DIAGRAM (ESTIMATED)

COMPOSITION I

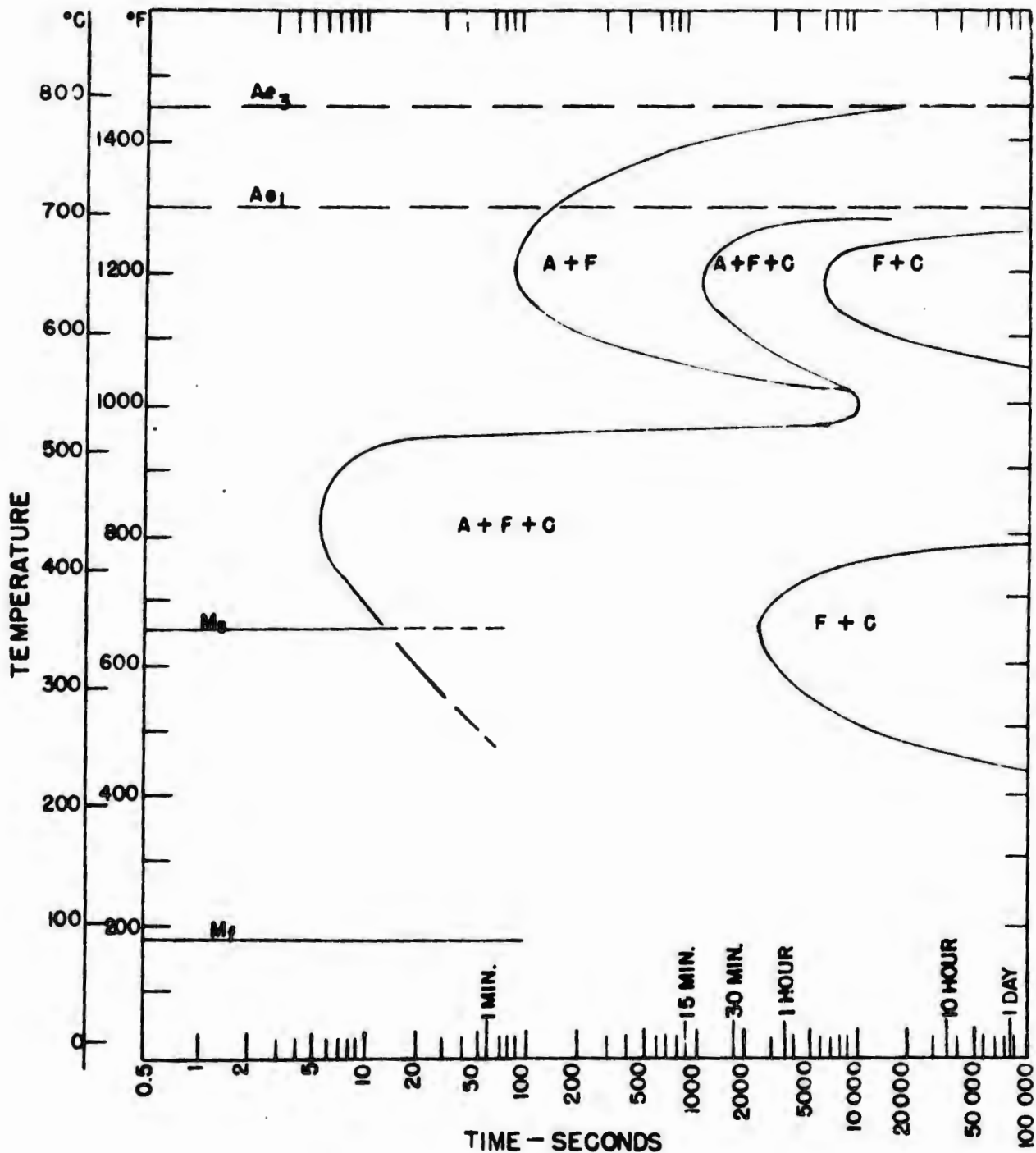


FIGURE A-15
ISOTHERMAL TRANSFORMATION DIAGRAM (ESTIMATED)

COMPOSITION II

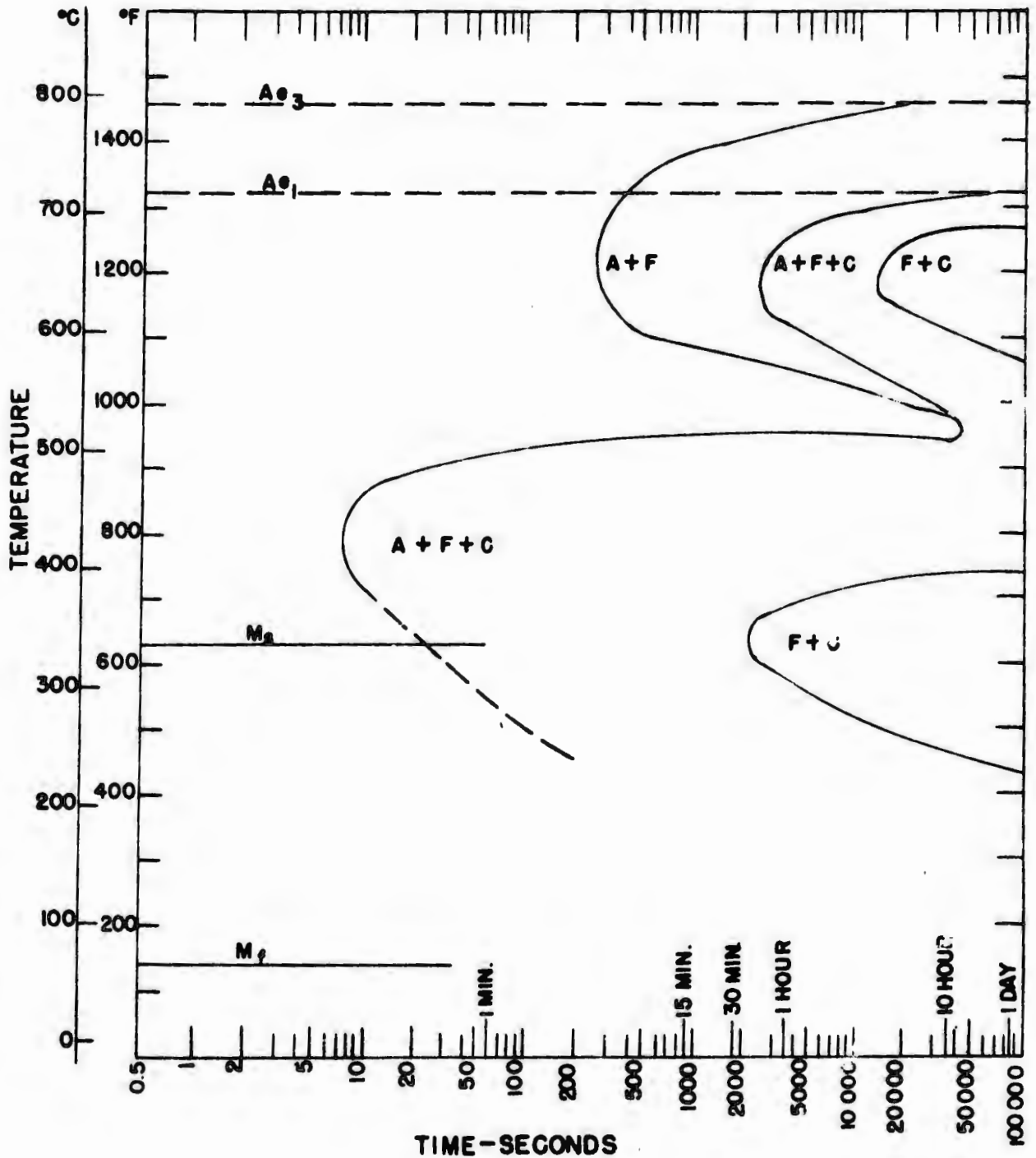


FIGURE A-16
 ISOTHERMAL TRANSFORMATION DIAGRAM (ESTIMATED)
 COMPOSITION III

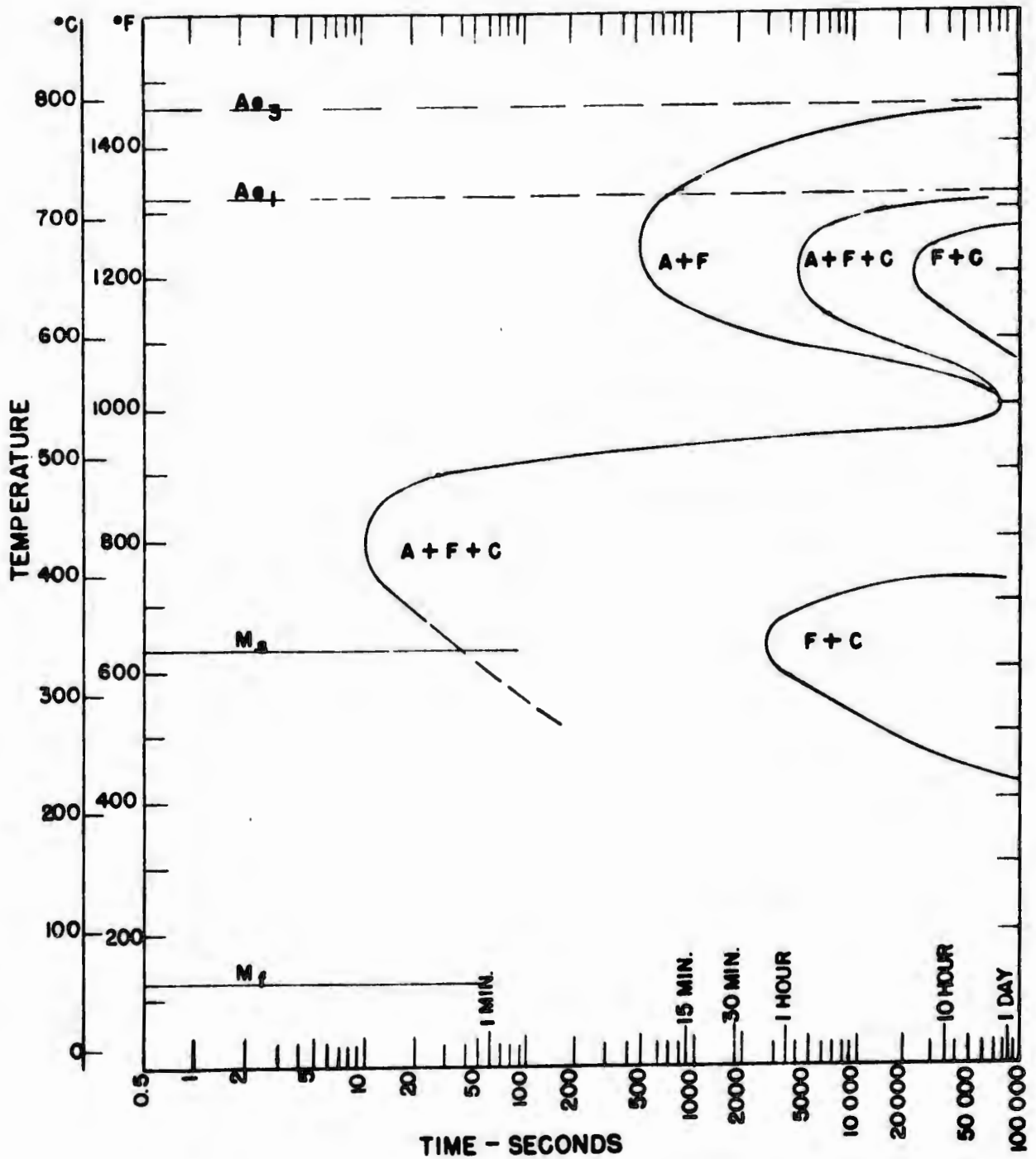


FIGURE A-17
 ISOTHERMAL TRANSFORMATION DIAGRAM (ESTIMATED)
 COMPOSITION IV

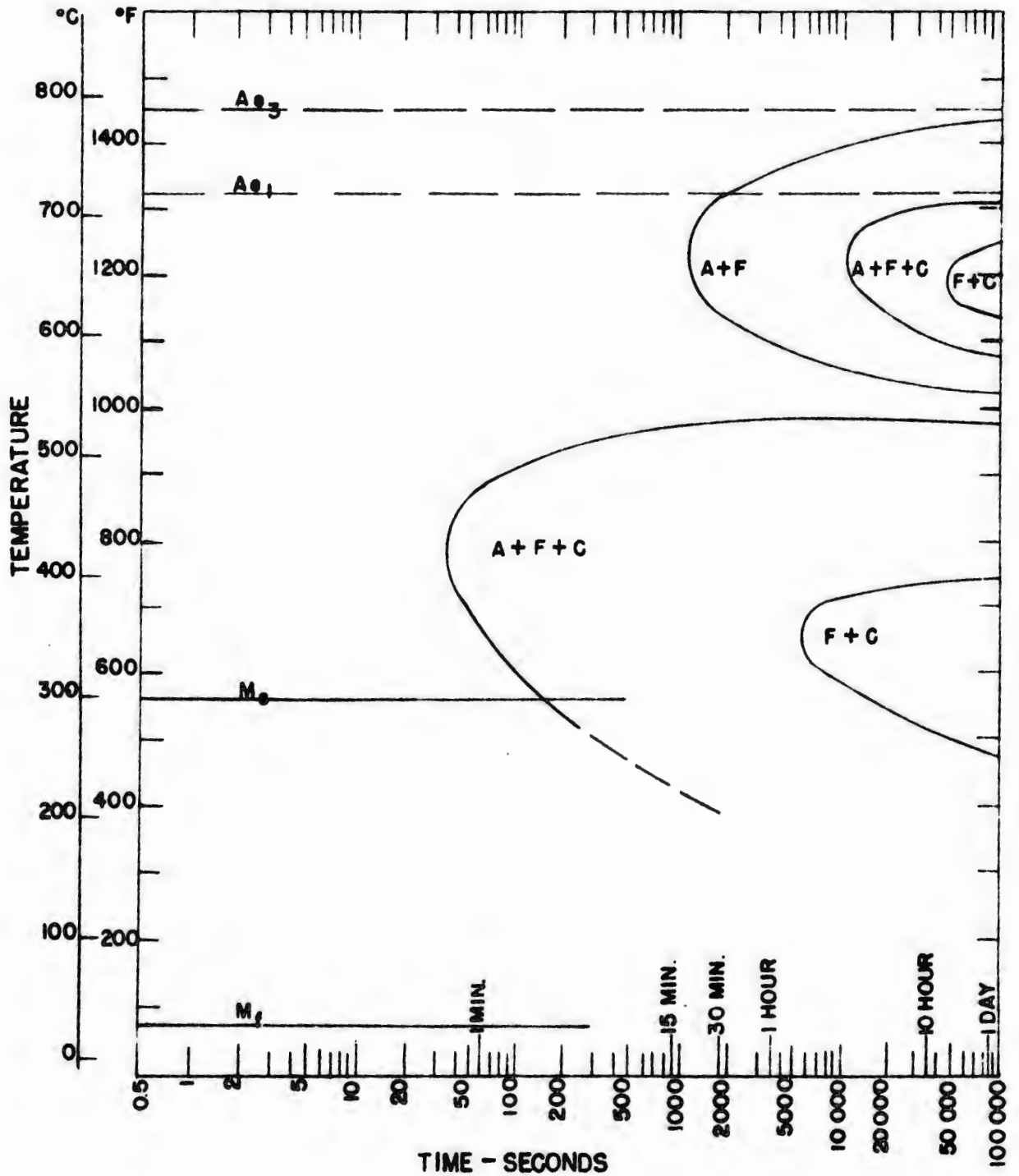
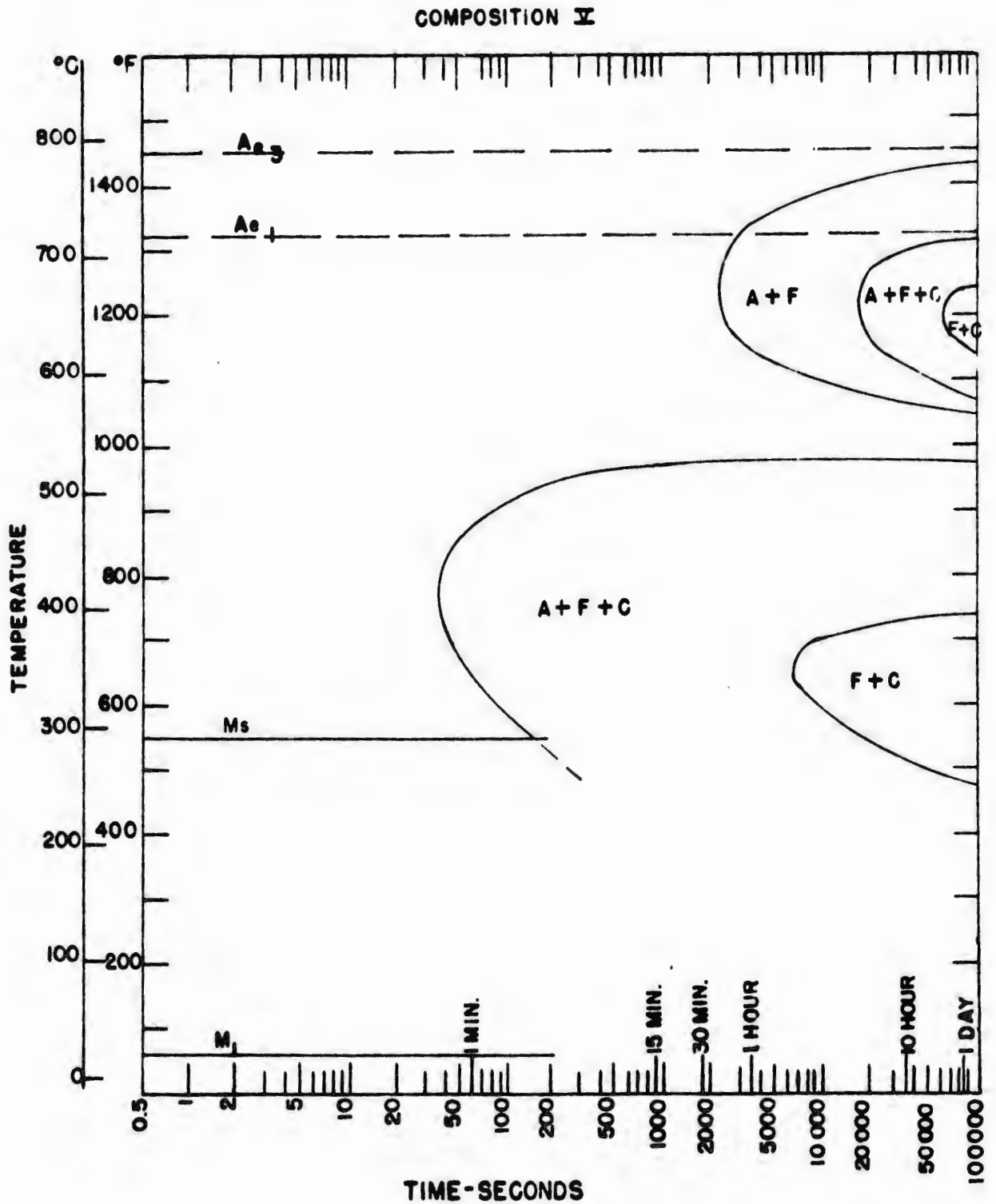


FIGURE A-18
ISOTHERMAL TRANSFORMATION DIAGRAM (ESTIMATED)



APPENDIX B

MATERIALS

C

APPENDIX B

Materials

I. Experimental Castings

Data covering the designs, analyses, melting practices, and normalizing heat treatments of the initial twenty-two heats are contained in Section III of the body of the report.

Detailed drawings of the locations of the test specimens machined from the vertical sections flame-cut from the plates are contained in Figures B1 through B7. Spectroscopic test bars and chips for chemical analysis were machined from areas lying halfway between the surfaces and the midsections of the plates. In several instances more 1.9" diameter and 0.95" diameter insert bars were machined from the remaining sections of the plates whenever additional heat treatments were required.

II. Additional Castings

As a result of the heat treatments performed upon the experimental castings of higher alloy contents, it became apparent that temper brittleness is a factor which must be taken into consideration when designing alloys for the heavier sections. Therefore, it was decided to make three more castings containing increasing amounts of molybdenum to determine if additional quantities of this element could counteract the susceptibility to temper brittleness.

Since heat No. 16 was found to possess the highest degree of susceptibility to temper brittleness this composition was selected as the base for the three new heats. The molybdenum contents were chosen as 0.60%, 0.80% and 1.00% respectively, while the chromium contents were successively reduced by 0.20% for each 0.20% increase in molybdenum content, see Table B1, which contains the specified, ladle, and actual analyses of the three heats.

The three heats were cast into 30" long ingots varying in cross-section from 8" x 8" at the top to 6½" x 6½" at the bottom, Figure B8. The ingots averaged 475 pounds in weight. The ingots were normalized and tempered as follows:

<u>Temperature</u>	<u>Hrs. Rise</u>	<u>Hrs. Soak</u>	<u>Coolant</u>
1950°F.	8	10	Air
1250°F.	5	10	Air

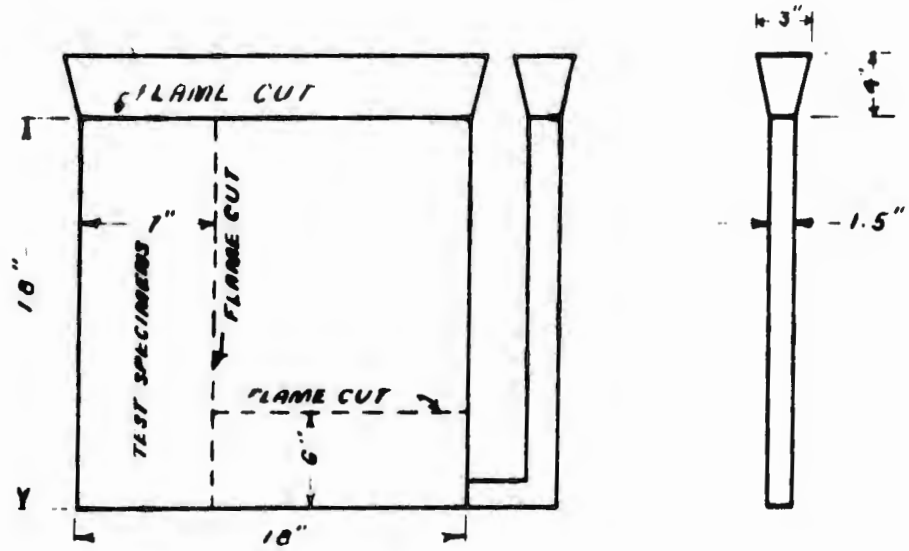
Two discs were cut from the bottoms of each ingot, Figure B8, from which were machined Charpy impact blanks, temper bars, chips for chemical analysis, and bars for heat treatments to determine the susceptibility to temper brittleness.

TABLE BI

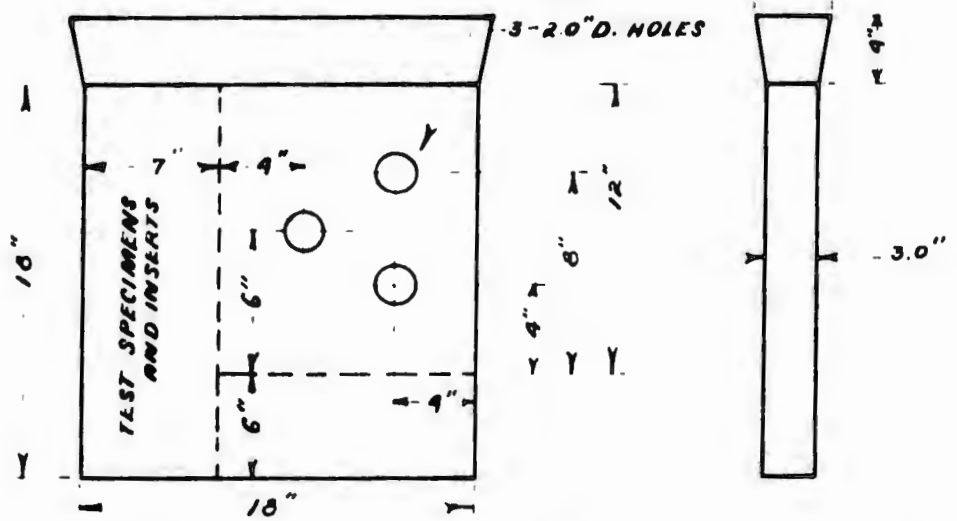
Chemical Analyses of Additional Castings

*S - Specified Analysis
L - Ladle Analysis
A - Actual Analysis

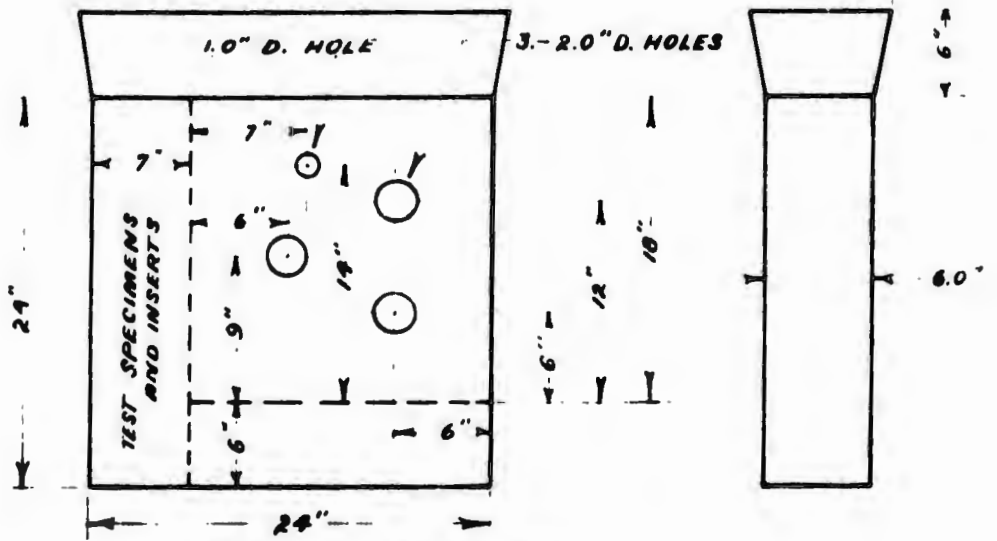
<u>Heat No.</u>		<u>C</u>	<u>Mn</u>	<u>Si</u>	<u>S</u>	<u>P</u>	<u>Ni</u>	<u>Cr</u>	<u>Mo</u>
23	*S	.30	1.50				3.00	2.20	.60
	L	.275	1.50	.51	.020	.012	3.05	2.23	.60
	A	.265	1.44	.55	.019	.010	3.09	2.22	.61
24	S	.30	1.50				3.00	2.00	.80
	L	.29	1.48	.40	.020	.012	3.27	2.05	.83
	A	.29	1.39	.41	.019	.011	3.15	2.06	.84
25	S	.30	1.50				3.00	1.80	1.00
	L	.295	1.41	.41	.019	.012	3.29	1.82	1.01
	A	.29	1.41	.43	.018	.010	3.21	1.79	1.02



1 1/2" THICK CAST PLATES



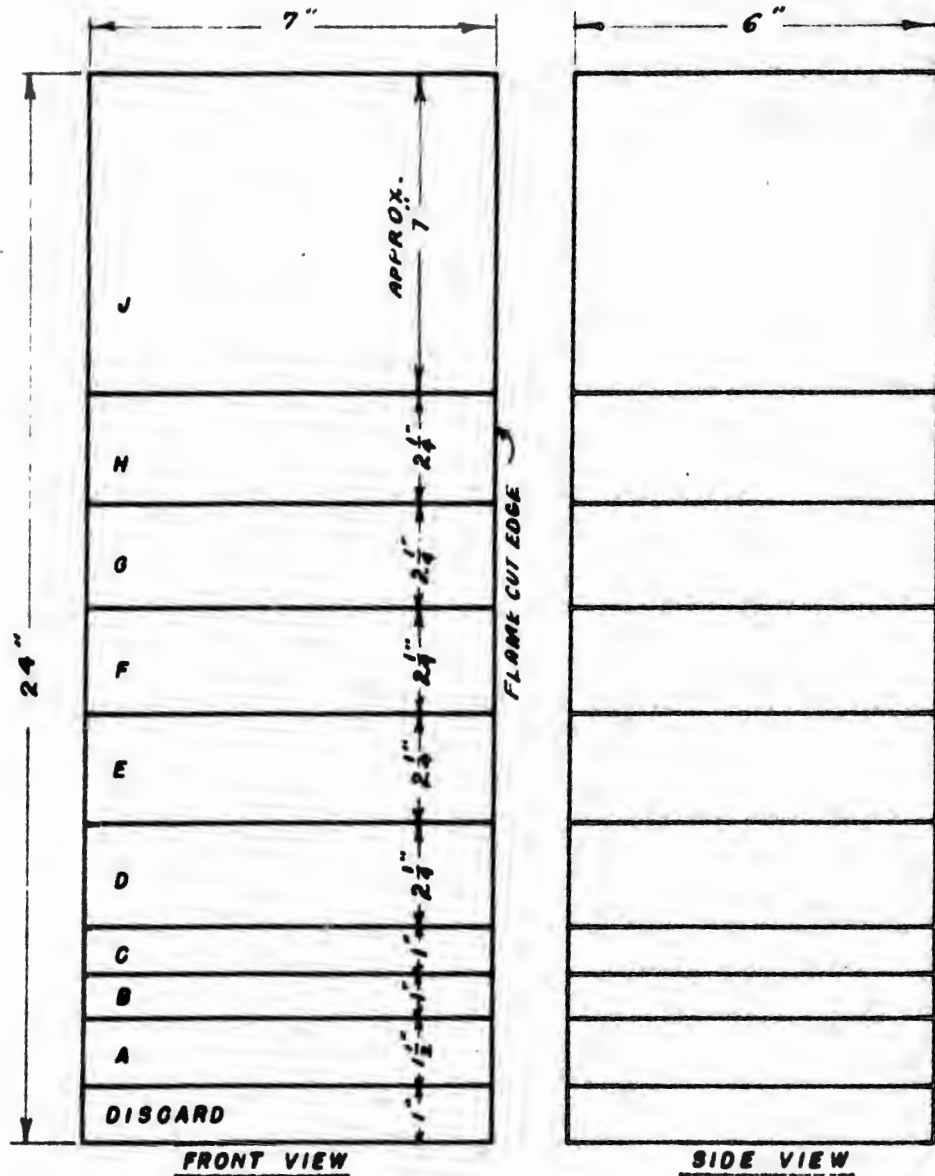
3" THICK CAST PLATES



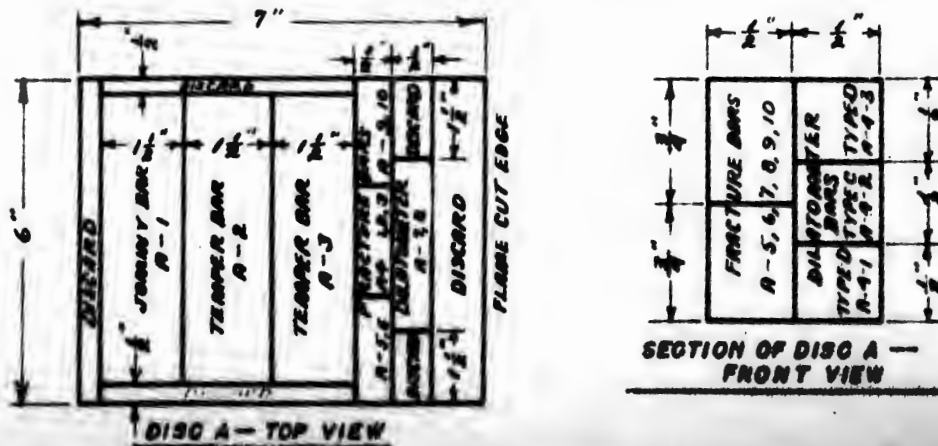
6" THICK CAST PLATES

LAYOUT OF EXPERIMENTAL CAST ARMOR PLATES

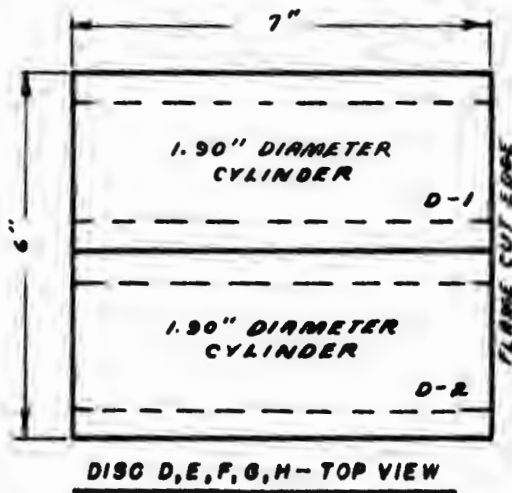
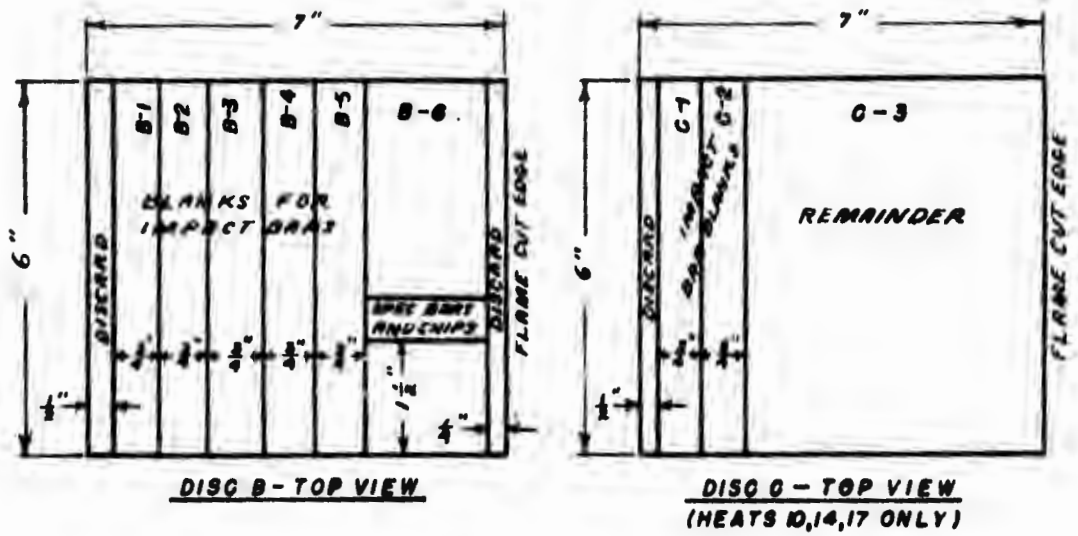
FIGURE B2



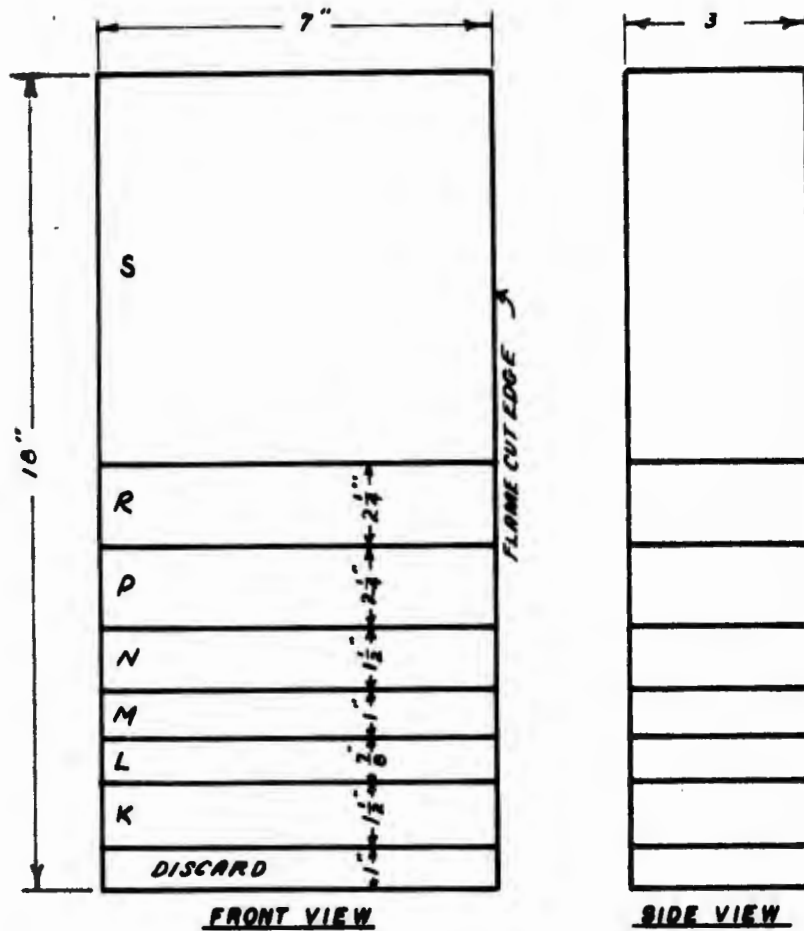
24 x 7 x 6" SECTION FLAME CUT FROM 6" THICK PLATES



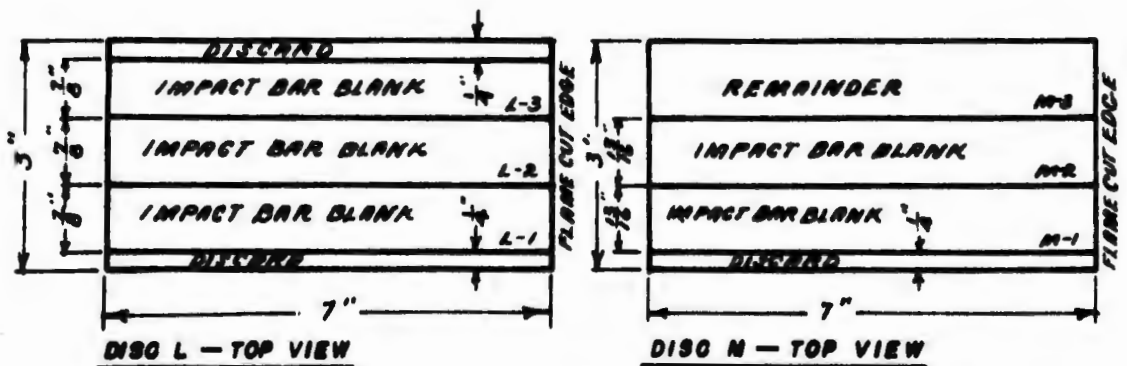
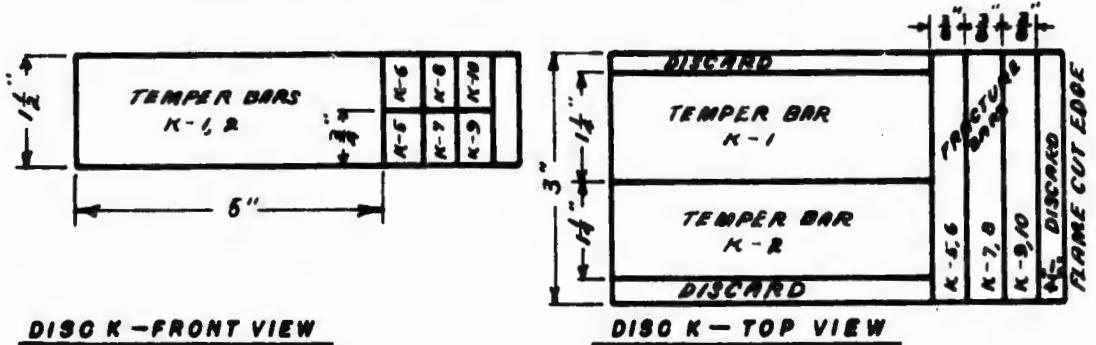
LOCATIONS OF TEST SPECIMENS FROM 6" THICK CAST PLATES



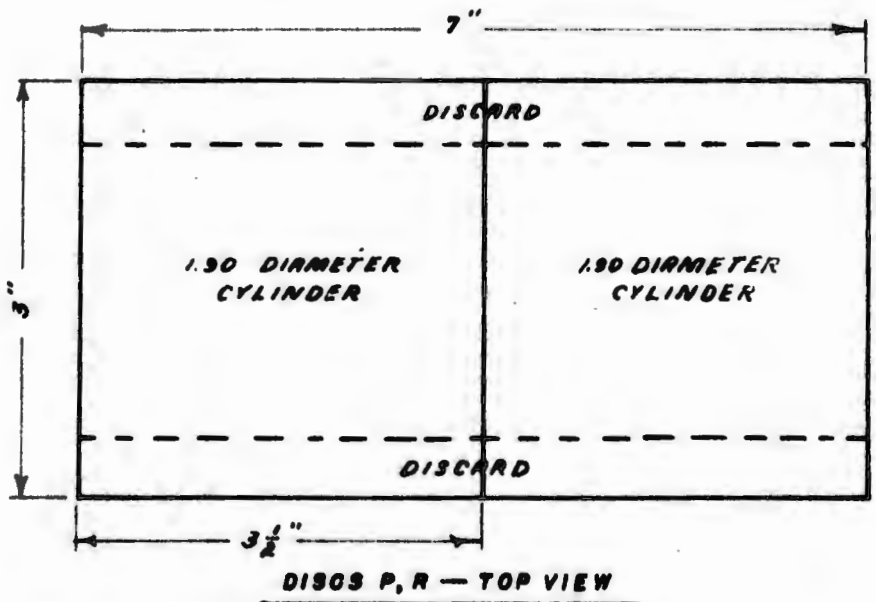
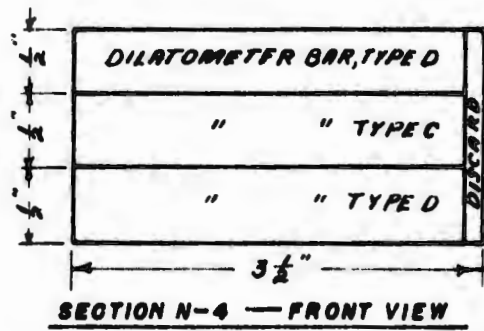
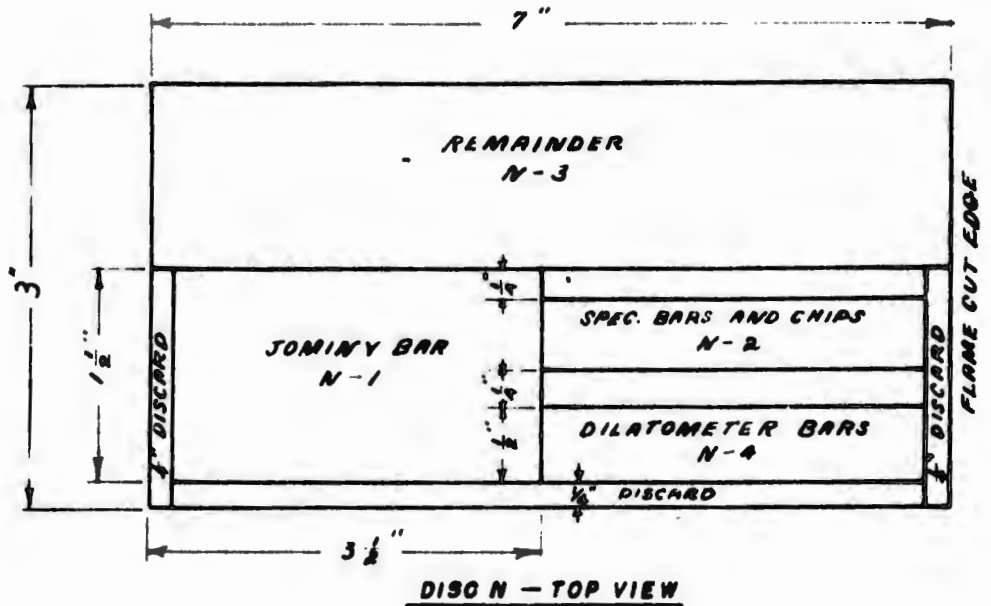
LOCATIONS OF TEST SPECIMENS FROM 6" THICK CAST PLATES



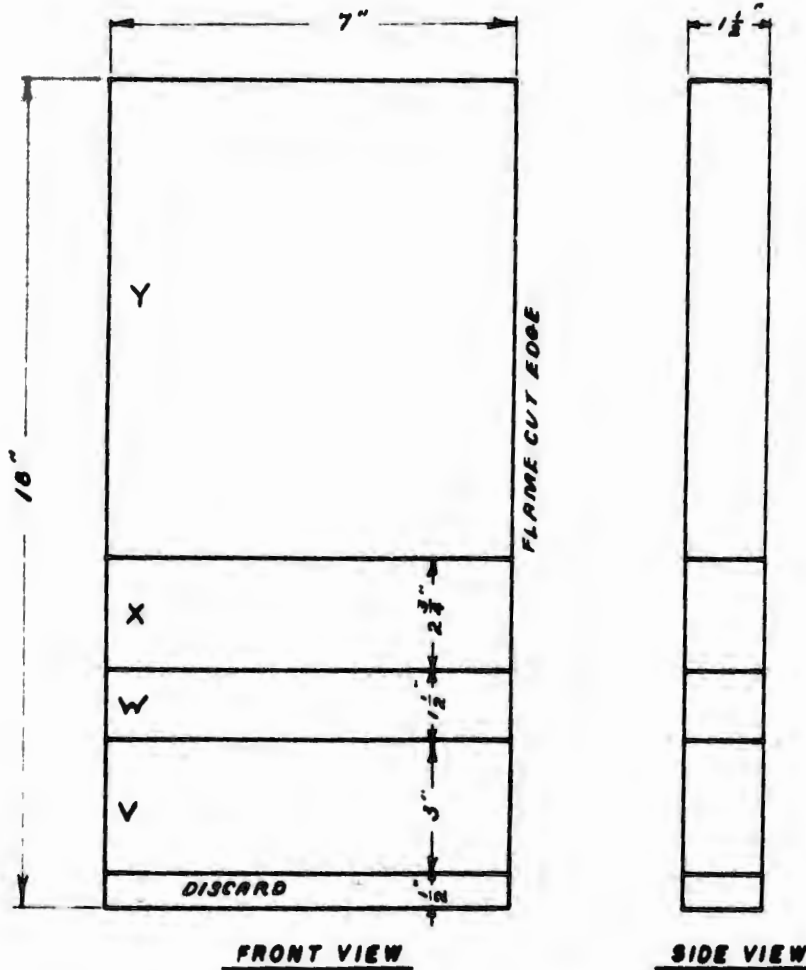
18"x7"x3" SECTION FLAME CUT FROM 3" THICK PLATES



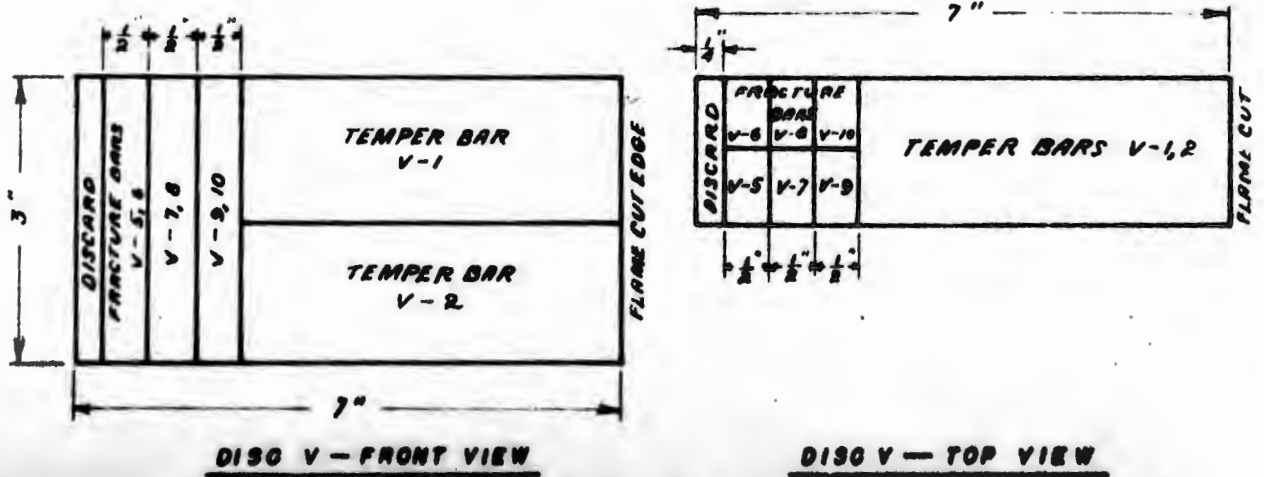
LOCATIONS OF TEST SPECIMENS FROM 3" THICK CAST PLATES



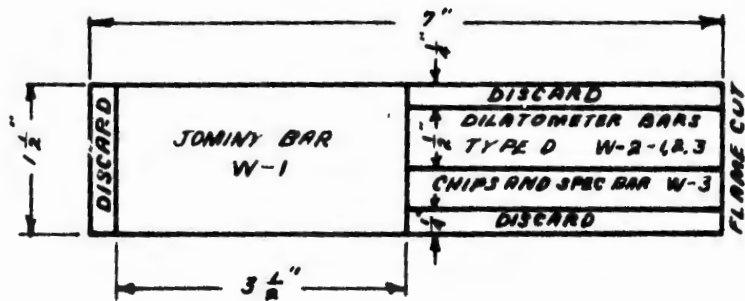
LOCATIONS OF TEST SPECIMENS FROM 3" THICK CAST PLATES



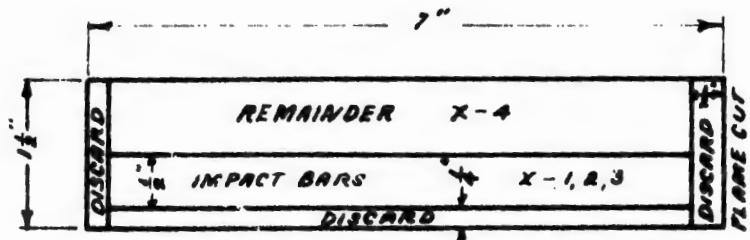
18"x7"x1 1/2" SECTION FLAME CUT FROM 1 1/2" THICK PLATES



LOCATIONS OF TEST SPECIMENS FROM 1 1/2" THICK CAST PLATES

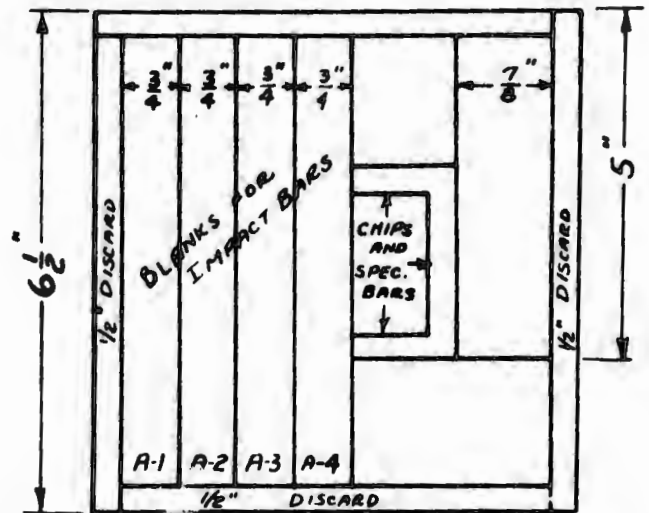
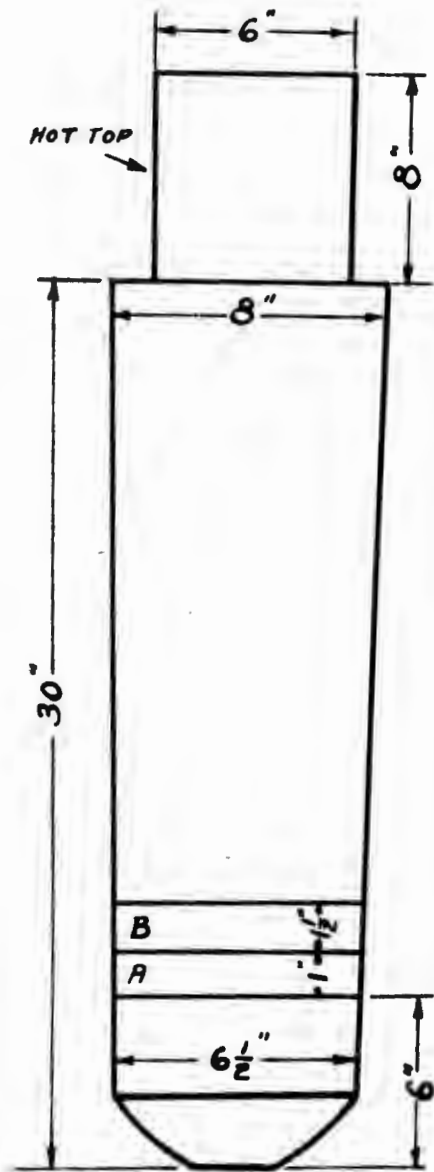


DISC W — TOP VIEW

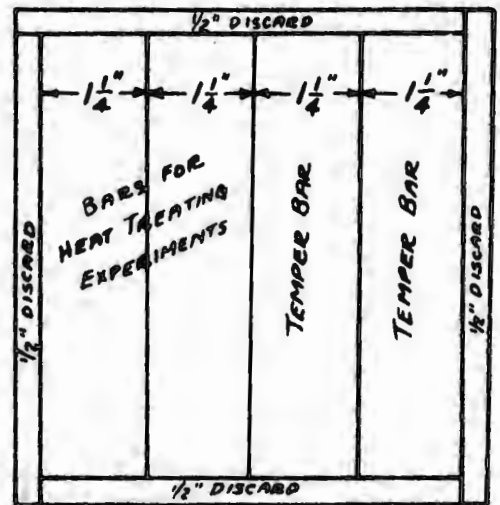


DISC X — TOP VIEW

LOCATIONS OF TEST SPECIMENS FROM $1\frac{1}{2}$ " THICK
CAST PLATES



DISC A



DISC B

EXPERIMENTAL INGOTS
HIGH MOLYBDENUM HEATS NOS. 23, 24, 25

APPENDIX C

AUSTENITIZING TREATMENTS

APPENDIX C

Austenitizing Treatments

I. Scope of Austenitizing Heat Treatments

Before any heat treatments could be performed upon small sections to be used for the determination of the optimum base properties of the experimental castings, it was necessary to select the proper austenitizing temperature for each composition which would result in the formation of a homogeneous austenite of minimum practicable grain size.

The importance of securing complete carbide solution prior to quenching cannot be overemphasized. In steels of medium carbon content such as the subject castings, the presence of undissolved carbides seriously detracts from the hardenability of the steel, not only because of the resultant lowering of the carbon and alloy contents of the austenite, but also because of the provision of nuclei around which transformation to intermediate or high temperature decomposition products may occur. Digges¹ and Williams² have showed the ill effects of incomplete carbide solution and austenite heterogeneity upon hardenability.

II. Materials and Test Procedure

Six specimens varying in size from 1/2" x 1/2" x 2" to 3/4" x 3/4" x 3" were cut from each of the twenty-one castings of various compositions, and were heated to temperatures within the range of 1550°F. to 1750°F. in steps of either 25° or 50° intervals. After four hours at temperature the specimens were either oil or water quenched, depending upon the alloy content, to obtain as complete martensitization as possible. The specimens were notched in the middle and fractured. The fracture grain sizes were estimated by comparison with a set of the B. F. Shepherd Fracture Grain Size Standards. Sections for microscopic examination were prepared, etched for 2 minutes in a saturated solution of picric acid in ethyl alcohol, and examined at a magnification of X1000 for the presence of undissolved carbides and any other sign of austenite heterogeneity. Picral was selected as the etchant because the martensitic background was but slightly attacked while the carbides were sharply delineated; the high degree of contrast greatly assisting in rating the specimens with respect to carbide solution.

The specimens from heats Nos. 1, 2, 4, and 5 were originally oil quenched, and a bright crystalline fracture indicative of incomplete quench hardening was obtained when the specimens were fractured for grain size determination. New specimens were consequently prepared and were water quenched from the austenitizing temperature, after which the specimens were found to be satisfactorily quench hardened.

-
1. T. G. Digges; "Transformation of Austenite on Quenching High Purity Iron-Carbon Alloys". Trans., ASM, 28 (1940), 575-607.
 2. G. T. Williams; "Hardenability Variations in Alloy Steels—Some Investigations with the End-Quench Test". Trans., ASM, 28 (1940), 157-185.

III. Results and Discussion

The results of the fracture grain size ratings and the microscopic examination are presented in Table CI. All steels maintained a fine grain size up to the highest austenitizing temperatures employed, in no case being coarser than fracture grain size #5-6.

In general, the austenitizing temperatures selected for subsequent heat treatment were chosen as 25 to 50°F. higher than the lowest quenching temperatures which produced a homogeneous martensite, but in no case was the selected temperature allowed to exceed 1725°F. This latter temperature, because of considerations regarding the life of furnace refractories, distortion upon quenching, etc., was believed to represent the maximum practicable austenitizing temperature for industrial application. The data upon which the selection of the austenitizing temperatures were based are contained in Table CII.

Photomicrographs of the structures produced in a typical low alloy and a typical high alloy steel upon quenching from various austenitizing temperatures are shown in Figures C1 and C2. It is of interest to note that in the low alloy steel no undissolved carbides could be detected by visual microscopic examination in the specimen quenched from 1600°F. The superior sensitivity of the photographic emulsion, however, reveals some small carbides, see Figure C1. It was thus fortunate that the austenitizing temperatures were chosen as 25 to 50°F. higher than the lowest quenching temperatures which produced martensite free of undissolved carbides, the rating being based upon visual examination at a magnification of X1000.

TABLE OI

Fracture Grain Size and Degree of Austenite

Homogeneity Resulting from a Four Hour Hold

<u>Heat No.</u>	<u>Specimen No.</u>	<u>Austenitizing Temp. °F.</u>	<u>Coolant</u>	<u>Fracture Grain Size</u>	<u>Microstructure</u>
1	1X5	1550	Water	6	Few undissolved carbides.
	1X6	1575	"	6-7	Very few undissolved carbides.
	1X7	1600	"	6-7	Homogeneous martensite.
	1X8	1625	"	6-7	" "
	1X9	1650	"	6	" "
	1X10	1675	"	5-6	" "
2	2N5	1550	Water	7	Very few undissolved carbides.
	2N6	1575	"	7	" " " "
	2N7	1600	"	7	Homogeneous martensite.
	2N8	1625	"	7	" "
	2N9	1650	"	7	" "
	2N10	1675	"	7	" "
3	3K5	1550	Oil	6-7	Very few undissolved carbides.
	3K6	1600	"	6-7	" " " "
	3K7	1625	"	7	Homogeneous martensite.
	3K8	1650	"	6-7	" "
	3K9	1700	"	7	" "
	3K10	1750	"	6	" "
4	4X5	1550	Water	7	Few undissolved carbides.
	4X6	1575	"	7	Very few undissolved carbides.
	4X7	1600	"	6-7	Homogeneous martensite.
	4X8	1625	"	7	" "
	4X9	1650	"	7	" "
	4X10	1675	"	7	" "
5	5N5	1550	Water	6-7	Few undissolved carbides.
	5N6	1575	"	6	Very few undissolved carbides.
	5N7	1600	"	6	Homogeneous martensite.
	5N8	1625	"	6-7	" "
	5N9	1650	"	6-7	" "
	5N10	1675	"	6-7	" "
6	6K5	1550	Oil	7	Very few undissolved carbides.
	6K6	1600	"	7	Homogeneous martensite.
	6K7	1625	"	6	" "
	6K8	1650	"	7	" "
	6K9	1700	"	6-7	" "
	6K10	1750	"	6	" "

TABLE CI (Continued)

Heat No.	Specimen No.	Austenitizing Temp. °F.	Coolant	Fracture Grain Size	Microstructure
7	7K5	1550	Oil	7	Many undissolved carbides.
	7K6	1600	"	7	Few undissolved carbides.
	7K7	1625	"	7	Very few undissolved carbides.
	7K8	1650	"	7	Homogeneous martensite.
	7K10	1700	"	7	" "
8	8K5	1550	Oil	7-8	Many undissolved carbides.
	8K6	1600	"	7	Few undissolved carbides.
	8K7	1625	"	7-8	Very few undissolved carbides.
	8K8	1650	"	7	Homogeneous martensite.
	8K9	1675	"	7	" "
	8K10	1700	"	7	" "
9	9K5	1550	Oil	7	Many undissolved carbides.
	9K6	1600	"	7	" " "
	9K7	1625	"	7	Few undissolved carbides.
	9K8	1650	"	7	Very few undissolved carbides.
	9K9	1675	"	7	Homogeneous martensite.
	9K10	1700	"	7	" "
10	10A5	1550	Oil	6-7	Few undissolved carbides.
	10A6	1600	"	6-7	Very few undissolved carbides.
	10A7	1625	"	7	" " " "
	10A8	1650	"	7	Homogeneous martensite.
	10A9	1700	"	7	" "
	10A10	1750	"	7	" "
12	12A5	1550	Oil	7	Many undissolved carbides.
	12A6	1600	"	7	Few undissolved carbides.
	12A7	1625	"	7	" " "
	12A8	1650	"	7	Very few undissolved carbides.
	12A9	1675	"	7	Homogeneous martensite.
	12A10	1700	"	7	" "
13	13A5	1550	Oil	7	Many undissolved carbides.
	13A6	1600	"	7	" " "
	13A7	1625	"	7	" " "
	13A8	1650	"	6-7	Few undissolved carbides.
	13A9	1675	"	7	" " "
	13A10	1700	"	7	Very few undissolved carbides.
14	14A5	1600	Oil	7	Few undissolved carbides.
	14A6	1625	"	7	" " "
	14A7	1650	"	6	Very few undissolved carbides.
	14A8	1675	"	6	Homogeneous martensite.
	14A9	1700	"	6	" "
	14A10	1725	"	6	" "
15	15A5	1600	Oil	6-7	Few undissolved carbides.
	15A6	1625	"	6-7	" " "
	15A7	1650	"	6	Very few undissolved carbides.
	15A8	1675	"	6-7	" " "
	15A9	1700	"	6-7	Homogeneous martensite.
	15A10	1725	"	6-7	" "

TABLE CI (Continued)

Heat No.	Specimen No.	Austenitizing Temp., °F.	Coolant	Fracture Grain Size	Microstructure
16	16A5	1600	Oil	6-7	Few undissolved carbides.
	16A6	1625	"	6-7	" " "
	16A7	1650	"	6	Very few undissolved carbides.
	16A8	1675	"	6-7	" " " "
	16A9	1700	"	6-7	Homogeneous martensite.
	16A10	1725	"	7	" "
17	17A5	1550	Oil	7	Many undissolved carbides.
	17A6	1600	"	7	Few undissolved carbides.
	17A7	1625	"	7	" " "
	17A8	1650	"	7	Very few undissolved carbides.
	17A9	1675	"	7	Homogeneous martensite.
	17A10	1700	"	7	" "
18	18A5	1550	Water	6-7	Few undissolved carbides.
	18A6	1600	"	7	" " "
	18A7	1625	"	7	Homogeneous martensite.
	18A8	1650	"	7	" "
	18A9	1700	"	6	" "
	18A10	1750	"	6	" "
19	19A5	1550	Water	7	Few undissolved carbides.
	19A6	1600	"	7	" " "
	19A7	1625	"	7	Homogeneous martensite.
	19A8	1650	"	6-7	" "
	19A9	1700	"	6	" "
	19A10	1725	"	5-6	" "
20	20A5	1550	Water	6-7	Many undissolved carbides.
	20A6	1600	"	6-7	Few undissolved carbides.
	20A7	1625	"	7	Very few undissolved carbides.
	20A8	1650	"	7	" " " "
	20A9	1700	"	6-7	Homogeneous martensite.
	20A10	1750	"	6-7	" "
21	21A5	1550	Oil	7-8	Many undissolved carbides.
	21A6	1600	"	8	Few undissolved carbides.
	21A7	1625	"	7-8	Very few undissolved carbides.
	21A8	1650	"	8	" " " "
	21A9	1700	"	7-8	Homogeneous martensite.
	21A10	1750	"	8	" "
22	22A5	1550	Oil	7-8	Many undissolved carbides.
	22A6	1600	"	7-8	" " "
	22A7	1625	"	8	Few undissolved carbides.
	22A8	1650	"	8	Very few undissolved carbides.
	22A9	1675	"	7-8	Homogeneous martensite.
	22A10	1700	"	7-8	" "

TABLE CII

Selection of Proper Austenitizing Temperatures

<u>Heat No.</u>	<u>Lowest Temperature Resulting in Formation of Homogeneous Martensite upon Quenching - °F.</u>	<u>Selected Austenitizing Temperature - °F.</u>
1	1600	1650
2	1600	1650
3	1625	1650
4	1600	1650
5	1600	1650
6	1600	1650
7	1650	1700
8	1650	1700
9	1675	1725
10	1650	1675
12	1675	1725
13	Very few carbides out of solution at 1725°F.	1725
14	1675	1725
15	1700	1725
16	1700	1725
17	1675	1725
18	1625	1650
19	1625	1650
20	1700	1700
21	1700	1725
22	1675	1725

APPENDIX D

Tempering treatment

APPENDIX D

Tempering Treatment

As indicated above, it had been decided to make all Charpy impact tests upon material tempered to a hardness of 260 Brinell (26 Rockwell C). It was therefore, necessary to determine, for each heat, the tempering temperature which would give this hardness.

Tempering temperatures were determined with the aid of a gradient tempering furnace, similar to that described by Troiano.¹ This is an electrically heated vertical tube furnace with the bottom of the tube closed. The element winding is so arranged that the temperature decreases continuously from the bottom to the top of the tube. Construction is such that a sample may be placed in one position only. A sample consists of a "temper bar" having a one-inch diameter and a four-inch length. The bar is austenitized, quenched and cold-treated as desired (see Table III), then placed in the tube of the furnace, which has previously been heated to the selected temperature range. The sample comes to temperature in about one and one-half hours, is held there for the selected tempering time (four hours in the present case), is automatically removed from the furnace, and is cooled in water.

Two opposite longitudinal flats are then ground on the temper bar and Rockwell hardness measurements are made at 1/8 inch spacings all along these flats. Hardness can then be plotted as a function of length, as shown in Figure D-1. From the plot, the position at which the desired hardness (here 26 Rockwell C) occurred is selected. To convert this position to temperature, reference is made to a temperature-versus-position calibration chart prepared by measuring the temperature with thermocouples welded to a number of positions along the length of a dummy temper bar. (Figure D-2 is a sample.) The tempering temperature found in this way should then give the desired hardness when applied for the chosen tempering time to fully quenched material from the same heat as the temper bar. Preliminary tests indicated that the Charpy impact blanks tended to run slightly harder than predicted, (probably because of uncertainties in temperature calibration of the furnace used), so, for the later heats, the estimate of temperature obtained from the temper bar was increased by 5°F. A more complete description of the operation of the gradient furnace, will be found elsewhere.²

Since the gradient furnace supplies a gradient of only 50°F. in the range of temperatures needed on the heats under consideration, the desired hardness was not always obtained on the first trial. Another temper bar was then used, and the control setting on the thermocouple potentiometer which controlled the gradient furnace was changed so as to shift the temperature range obtainable.

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1. A. R. Troiano; "Investigation of the Metallographic and Physical properties of New Types of Gun Steels". O.S.R.D. Report M-66, 1943.
 2. L. D. Jaffe and P. Terris; "Construction, Control Equipment, and Operation of Gradient Tempering Furnace". Watertown Arsenal Laboratory Report 635/1. In Preparation.

Whenever the control setting was changed, the first temper bar used at the new setting had a thermocouple welded 1/4 inch from the hot end to check the calibration. The rest of the calibration could be calculated when the temperature at 1/4 inch was known, since the temperature differences between various points on the bar varied but little with control temperature.

Some difficulty was at first encountered in obtaining valid hardness readings, because of surface decarburization during tempering. (The gradient furnace is not provided with atmosphere control.) To eliminate this, it was decided to grind the flats to a depth of .100". Since there were some indications that dry grinding heated the bars sufficiently to affect the hardness, all grinding was done wet.

Occasional slow fluctuations occurred in the temperature within the tube. The cause of these fluctuations is not known, but they appear to be associated with atmospheric humidity. To minimize error from this source, the practice of checking the calibration (at one position) once a day was adopted.

In the case of heats 19, 21, 22, 24, and 25, it was found that no temperature below the critical would reduce the hardness to the desired Rockwell C 26 within the specified four-hour tempering time. Tempering temperatures for these heats were therefore taken as a few degrees below the critical, which was indicated by the hardness of the temper bar beginning to increase with temperature. These temperatures were expected to give a hardness of approximately Rockwell C 30.

The tempering temperatures selected on the basis of temper bar results are given in Table DI, as well as in the body of this report.

TABLE DI

Treatment and Results of Temper Bars

Heat No.	TREATMENT			RESULTS
	Austenitized 4 Hours at (° F.)	Quench in	Cooled to (° F.)	Rockwell C 26 When Tempered 4 Hours at (° F.)
1	1650	Water	70	1155
2	1650	Water	70	1175
3	1650	Oil	70	1205
4	1650	Water	70	1165
5	1650	Water	70	1155
6	1650	Oil	70	1210
7	1700	Oil	-100	1220
8	1700	Oil	-100	1220
9	1725	Oil	-100	1210
10	1675	Oil	-100	1225
12	1725	Oil	-320	1195
13	1725	Oil	-320	1200
14	1725	Oil	-320	1180
15	1725	Oil	-320	1230
16	1725	Oil	-320	1230
17	1725	Oil	-100	1205
18	1650	Oil	-100	1225
19	1650	Oil	-320	1205*
20	1700	Oil	-100	1210
21	1725	Oil	-320	1205*
22	1725	Oil	-320	1205*
23	1750	Oil	-320	1210
24	1750	Oil	-320	1205*
25	1750	Oil	-320	1215*

*Rockwell C 26 could not be obtained; temperature indicated is that giving minimum hardness (a few degrees below critical range).

FIGURE D-1
TYPICAL TEMPER BAR CURVE
 BAR 17A2

$$\frac{1''}{4} = 27.4 \text{ MV} = 1218^\circ \text{F.}$$

$$\text{GRADIENT} = \frac{17''}{8} = -18^\circ$$

TEMPERING TEMPERATURE = 1200°

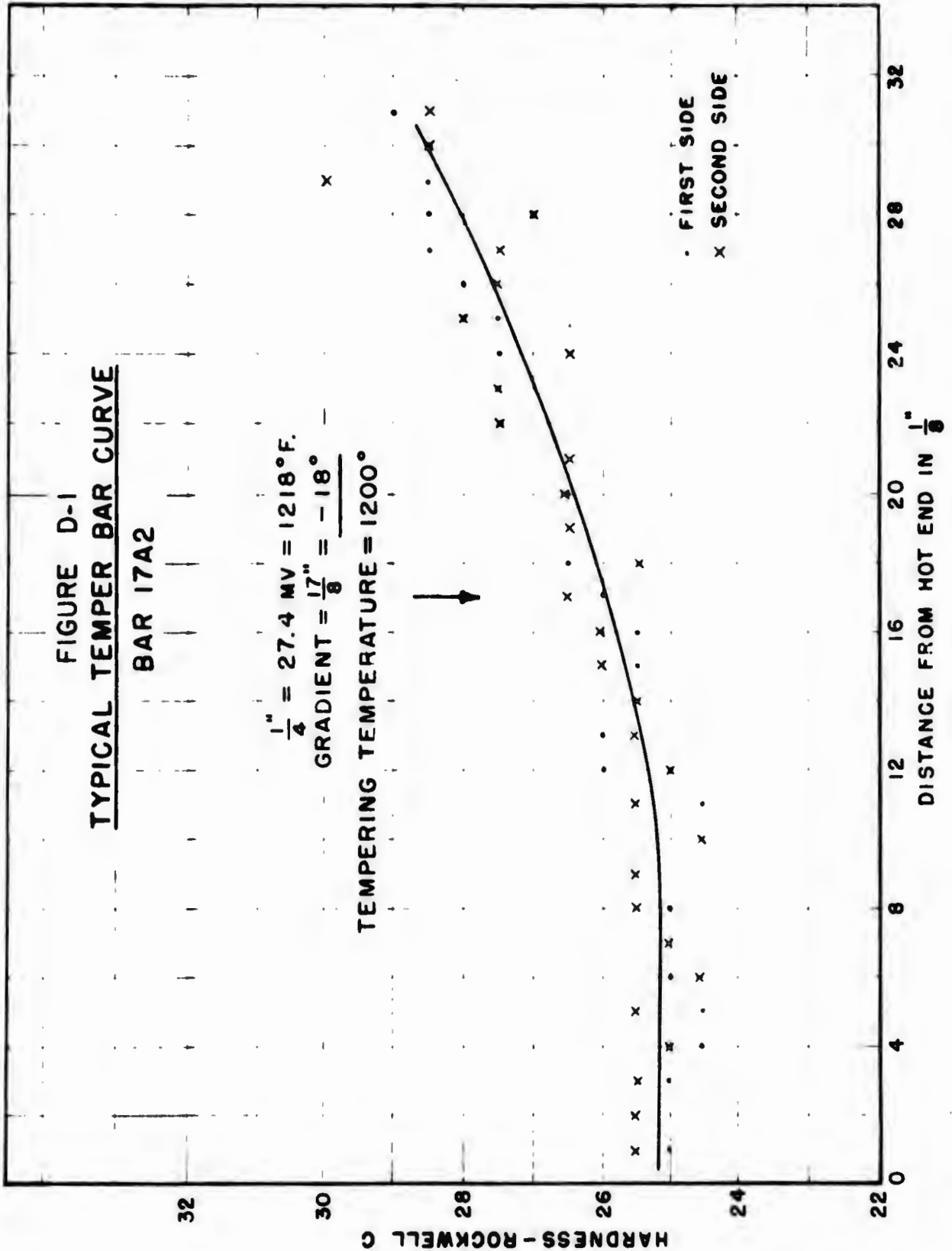
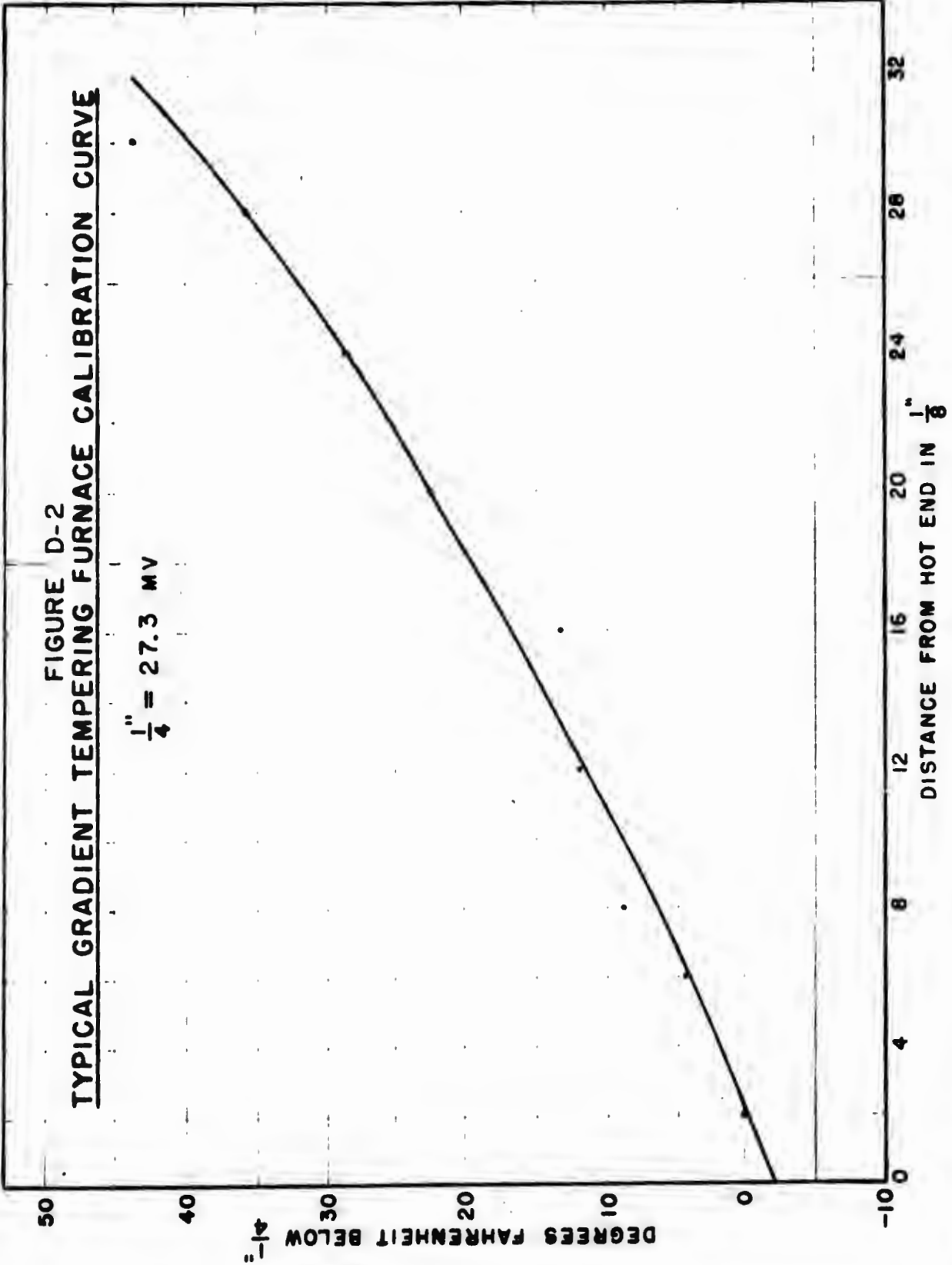


FIGURE D-2
TYPICAL GRADIENT TEMPERING FURNACE CALIBRATION CURVE

$\frac{1''}{4} = 27.3 \text{ MV}$



APPENDIX E

Jominy Results

APPENDIX E

Jominy Results

I. Samples Investigated.

- A. Jominy bars machined from each of the experimental castings. These specimens, three inches in length and one inch in diameter, were austenitized for four hours at the temperatures determined by the study described in Appendix C and end-quenched in water using a standard Jominy fixture. Hardness data and metallographic data obtained from the as-quenched samples are given in Table E I, in Figures E 1, E 2, E 3, E 4, E 5, E 6, E 7, and in Figure 1 (body of report).
- B. Six additional Jominy bars from heat 6. The bars, of standard dimensions, were austenitized as described under A. but were subjected to special cooling treatments prior to the end-quenching in water. The cooling schedules are outlined in Table E IV. Hardness data and metallographic data obtained from the as-quenched samples are contained in Tables E II and E III.
- C. Jominy bar from heat 22 tempered for 1/2 hour at 500° F. This bar was one of the group austenitized, end-quenched, and studied as described under A. above. It was given a subsequent slight tempering in order to permit clarification of the interpretation of some of the as-quenched microstructures. The microstructure observed after tempering is shown in Figure E 8.
- D. Jominy bar from heat 6 tempered under the conditions determined by the study described in Appendix D, that is, for four hours at 1210° F. This bar was one of the group austenitized, end-quenched and studied as described under A. above. It was given the subsequent tempering treatment in order to ascertain if the intermediate transformation product observed on the as-quenched sample may be detected after tempering. The tempered microstructure is shown in Figure E 9.

II. Procedure.

- A. Hardness Study.
- Sample Preparation - Carburized and decarburized metal was ground from the samples in this manner:
 - Removal of .010 inches from the radius on a centerless grinder
 - Removal of .040 inches* from each of two opposite faces on a wet, horizontal surface grinder
 - Method of Surveying Sample - Rockwell "C" hardness values were obtained along one face at fixed distances in sixteenths of an inch from the quenched end. These distances are indicated in Table E III. Burrs were eliminated from the hardness indentations by wet grinding to a depth of a few thousandths of an inch.

* Hardness values fluctuated from layer to layer but became constant at this depth of cut. The bar from heat 6 was ground an additional .020 inches and no substantial change was found in the data obtained both by a hardness survey and a microstructural survey.

Another survey was then made at equivalent distances along the second face. Hardness values were thus obtained on representative Jominy bars from all the experimental castings. They are plotted in Figure E 1. Hardness values were obtained similarly on the six additional Jominy bars from heat 6. They appear in Table E III.

B. Metallographic Study

1. Sample Preparation - One face of each sample on which hardness values had been determined was prepared for microscopic examination. The method used was similar to that outlined in a previous report.¹ It is believed that insufficient heating occurred during polishing to temper the quenched microstructures.
2. Etching - All samples were etched for about 15 seconds in 1% nital. This practice was established after some preliminary study of the structures obtained with both nital and picral on the steels under investigation. Surveys of amounts of intermediate transformation products revealed by both etches in bars of two of the lower alloy heats, 3 and 6*, showed that they could be used interchangeably for this purpose. All the steels studied and especially those high in nickel content were much more resistant to picral than to nital. The latter revealed simultaneously the structures of the intermediate transformation products and the background structure of untransformed microconstituents whereas the former failed to depict similar evidence clearly and completely. On the basis of this effect 1% nital was selected for the present procedure.**
3. Method of Surveying Microstructure - To facilitate observation of the microstructure at fixed distances from the quenched end and along the complete length of the Jominy bar, a special sample holder was attached to the stage plate of the microscope stand. The holder consists of a V-block in which a specimen is fastened securely by means of a set screw. The block is capable of displacement in two directions, at right angles, displacements being read off by means of millimeter scales.

1. M. Norton: "Metallographic Polishing." - Watertown Arsenal Report 130/3 (1935).

* The comparison estimates recorded for heat 6 are given in Table E I.

** The decision was made with full knowledge of the descriptions of the merits and limitations of picral contained in the following publications:

- (1) Berglund: "Metallographers' Hand Book of Etching" Pitman & Sons, N.Y. (1931)
- (2) Portevin and Bastien: "Réactifs D'Ahaque Métallographique" Dunod, Paris (1937)
- (3) Vilella: "Metallographic Technique for Steel" - A.S.M., Cleveland (1938)
- (4) A.S.T.M. Standards Part I 1939
- (5) A.S.M. Metals Handbook 1939

Three separate surveys of the microstructure along the length of each bar were made at a magnification of approximately 500 diameters. This was done by moving the sample holder to predetermined positions read off on the millimeter scale and by recording the percentage of intermediate transformation product, if any, visible in the field at each position. The fixed positions, converted to sixteenths of an inch, appear at the heads of columns in Table E I. Survey No. 1 was made along the center of a bar. Surveys No. 2 and No. 3 were made along parallel, longitudinal areas 1/2 mm. to the right and left of center. Data were obtained in this manner on Jominy bars from all the experimental castings. They are recorded in Table E I and plotted in Figure E 1. Similarly, data were obtained on the six additional Jominy bars from heat 6. They are recorded in Table E II.

III. Results.

- A. As-quenched Jominy Bars from Experimental Heats. Data found by hardness and microstructural surveys of these specimens are presented in Figure E 1. Rockwell "C" hardness values and percentages* of intermediate transformation product are plotted versus distance from the quenched end of the bar. The occurrence of intermediate transformation product, an indication that the specimen did not harden throughout the three-inch length, is recorded for heats 1, 2, 3, 4, 5, 6, 7, 8, 9 and 20. This product was not observed in bars from heats 10, 12, 13, 14, 15, 16, 17, 18, 19, 21 and 22. From the curves of Figure E 1, it may be seen that the hardness values do not generally reflect the presence of the intermediate transformation product until it occurs in relatively large amounts. As much as 30% of the microconstituent may cause no significant change in hardness.

The amounts of intermediate transformation product observed microscopically, according to the procedure described previously, in bars from heats 1, 2, 3, 4, 5, 6, 7, 8, 9 and 20 are recorded completely in Table E I. Determinations were rounded off to the nearest 5%. Values smaller than 5% are listed without alteration. Because of segregation in the steels, duplicate results were not obtained for two surveys made at different locations along the same bar. If more than one series of surveys was made, however, the resulting averages from each series were similar. Likewise, when two bars from the same heat were surveyed, the resulting averages did not differ greatly. The results from two bars from heat 1 are presented in Table E I and illustrate the reproducibility of the surveys. As mentioned previously the averaged estimated percentages of intermediate transformation product were roughly equivalent whether the structure was revealed with nital or with picral etches. Table E I gives data for heat 6 after using these two reagents.

* Figures used are the average values listed in Table E I.

The intermediate transformation product, recorded in Figure E 1 and in Table E I and referred to throughout this report, is best defined by means of photomicrographs which illustrate it in relation to the untransformed microstructure reported here as martensite. Figure E 3 (X1000) depicts the microstructures at 1/16, 9/16, and 42/16 inches from the quenched end of a heat 8 Jominy bar. The structure in A seems to be bona fide martensite. In B, the martensitic outlines persist but there is a suggestion of carbide precipitation in some of the larger needles. In C, a distinctly different structure is visible, some portions of it being indicated by white arrows. This represents the intermediate transformation product 3% of which is reported* for the sample at an equivalent distance from the quenched end. The background in C is similar to the structure in B and appears to be martensite with slight carbide precipitation. Figure E 6 (X1000) shows the microstructures at 4/16, 18/16 and 34/16 inches from the quenched end of a heat 20 bar. The description just given for the microstructures in Figure E 3 applies also to those in Figure 6 except that the amount of intermediate transformation product is much greater in Figure E 6 C than in Figure E 3 C. For this sample of heat 20, 30% of the product was reported at the 34/16 inch location.

A large number of photomicrographs illustrating the microstructures of a Jominy bar from heat 6 are presented in Figure 1 (body of report) and in Figure E 2. They are intended to serve the following purposes:

1. To exemplify increasing amounts of intermediate transformation product.
2. To show the appearance of the product at high magnification.
3. To permit comparison of the product as revealed by nital and by picral etchants.

Figures 1 D, F, J, M (X1000) portray areas at 9/16, 15/16, 26/16 and 33/16 inches from the quenched end of the bar and exhibit increasing amounts of intermediate transformation product. Percentages of the product reported for equivalent locations on this sample are 1, 2, 10 and 20. The appearance of the product at high magnification is illustrated in Figures 1 E, G, H, I, K, L, N and P. The areas in Figures 1 E, G and H contain very small patches occurring in the vicinity of grain boundaries. The structure of the product is displayed more clearly where it exists in larger patches as in Figures 1 K, L, N and P. Figures E 2 B, E, G, H (X1000) show increasing amounts of intermediate transformation product as revealed by a picral etch. These areas should be compared with those of Figures 1 D, F, J, M which were photographed at equivalent locations on the same bar after a nital etch. At first glance the increasing amount of product, represented by dark etching areas, may be appraised more quickly than when nital etch is used. More careful scrutiny indicates that the presence of the first small patches near the quenched end is not definitely distinguishable from the background structure and that much of the detail of the background structure itself is indistinct.

* Note that visual estimates of the product were made at a magnification of 500 diameters; photomicrographs were made at 1000 diameters.

Figures E 4 (X1000) E 5 (X1000) and E 7 (X1000) illustrate the microstructures observed at the two ends and center of Jominy bars from heats 17, 19 and 22—typical heats in which the intermediate transformation product did not occur. The presence of 100% martensite was reported for all of these areas. In Figures E 5 C and E 7 C, there is an unexplained non-etching background material which possibly may be retained austenite. In Figure E 4 B and C, there is a suggestion of carbide precipitation in the martensitic structure similar to that shown in Figures E 3 and E 6.

B. Jominy Bars from Heat 22 Tempered $\frac{1}{2}$ Hour at 500°F. Figure E 8 shows the microstructure of this sample after the indicated tempering treatment. The locations are comparable to those of the areas on the as-quenched bar from the same heat, displayed in Figure E 7. Study of the photomicrographs in Figure E 8 discloses that

1. The carbide particles precipitated by this mild tempering are, in general, too fine to be resolved distinctly at the magnification employed.
2. The structure is the same at both ends and at the center of the bar intimating that the non-etching background material of Figure E 7 C responded to the treatment just as did the martensitic areas.
3. The martensite needles which, on the as-quenched bar from this heat, were clear cut and free of visible carbides (see Figure E 7) have persisted to some extent have become less distinct and now contain finely precipitated carbides. They seem to be analogous to that microconstituent which was observed on some of the as-quenched bars and which, up to this point, has been described as martensite with a suggestion of carbide precipitation. (See Figures E 3, E 4, E 6 and Figure 1 (body of report).) It would now appear reasonable to call this structure slightly tempered martensite.

Further discussion of the foregoing observation is pertinent. The occurrence of tempered martensite in some of the quenched Jominy bars is feasible when it is considered that: (1) the cooling rate of a Jominy sample is fairly slow below about 700°F, and (2) the beginning of the martensite transformation for most of these steels, as determined by the study described in Appendix F, is sufficiently above 500°F, that the initially formed martensite can conceivably become mildly tempered before cooling is completed. It should be noted, finally, that the microstructures in Figures E 5 and E 7, typifying heats 19 and 22, do not resemble slightly tempered martensite and that the beginning of the martensite transformation for these steels is reported to occur at 550°F. and 470°F, respectively, temperatures lower than those for the other heats.

Structures similar to this slightly tempered martensite and claimed to have been produced isothermally, have been shown elsewhere^{1,2,3}. There appears to be uncertainty as to its true nature. One suggestion, that it is a low-temperature Bainite, may be correct. If so, then the evidence obtained in the present study indicates that low-temperature Bainite and slightly tempered martensite are indistinguishable microscopically.

- C. Jominy Bar from Heat 6 Tempered 4 Hours at 1210°F. The intermediate transformation product observed in some of the as-quenched Jominy bars examined in this investigation may possibly be associated with the undesirable conditions contributing to inferior properties in some of the steels when heat treated as full sized plates (see body of report). Since such steels would not ordinarily be checked for microconstituents until they had been subjected to final heat treatment, it is important to know if evidence of the existence of the intermediate transformation product persists sufficiently during the tempering operation to be detectable microscopically. For this reason, the Jominy bar from heat 6 was tempered 4 hours at 1210°F.—the temperature determined for this steel by the study described in Appendix D.

The photomicrographs of Figure E 9 (X1000) illustrate the resulting microstructures at locations equivalent to those photographed on the same bar, as-quenched. (See Figure 1, body of report.) Comparison of the areas in Figures 1 B, D, F, J, M, which contain varying amounts of intermediate transformation product, with those in Figure E 9 suggests that the structure of the tempered intermediate transformation product is not readily differentiated, at this magnification, from the structure of tempered martensite.

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1. Vilella; "Metallographic Technique for Steel" - ASM Cleveland, 1938.
 2. Davenport; "Isothermal Transformation in Steel" - Trans. ASM Vol. XXVII, No. 4, Dec. 1939.
 3. Cruciger & Vilella; "The Isothermal Transformation of Case-Carburized SAE 4815" - Trans. ASM Vol. XXXII, 1944.

TABLE EI

MICROSTRUCTURAL SURVEY OF JOMINY BARS CONTAINING INTERMEDIATE TRANSFORMATION PRODUCT

HEAT NO.	SURVEY NO.	% INTERMEDIATE TRANSFORMATION PRODUCT AT INDICATED DISTANCES IN SIXTEENTHS OF AN INCH FROM QUENCHED END OF JOMINY BAR																
		1	3	4	5	6	8	9	11	13	15	19	23	26	30	34	38	41
1	1	—	—	—	5	40	40	40	40	40	60	60	80	90	95	80	95	95
	2	—	—	5	25	20	15	40	50	50	60	50	85	80	60	70	85	80
	3	—	—	—	30	20	60	50	50	50	60	70	85	80	90	70	70	95
	AVERAGE	—	—	2	20	25	40	45	45	45	60	60	85	85	80	75	85	90
1	1	—	—	1	2	20	50	55	40	50	60	95	60	90	60	95	80	70
	2	—	—	—	10	25	40	50	50	80	60	85	85	80	85	80	85	50
	3	—	—	—	—	10	30	40	50	60	60	90	60	80	70	85	80	70
	AVERAGE	—	—	—	4	20	40	50	45	65	60	90	70	85	70	85	80	60
2	1	—	—	—	—	1	10	10	—	40	25	60	70	50	90	50	50	60
	2	—	—	—	—	2	10	5	30	40	50	60	30	80	60	90	25	10
	3	—	—	—	—	1	15	30	40	40	15	—	40	40	80	90	90	80
	AVERAGE	—	—	—	—	1	10	15	25	40	30	60	45	55	75	75	55	50
3	1	—	—	—	1	1	10	1	25	40	25	25	30	50	70	60	40	80
	2	—	—	—	—	—	10	15	25	25	5	10	60	50	70	70	70	50
	3	—	—	—	—	—	10	5	15	20	40	40	25	40	60	50	70	40
	AVERAGE	—	—	—	1	1	10	10	20	30	25	25	40	50	70	60	60	60
4	1	—	—	—	—	1	15	20	30	50	10	10	80	90	70	50	40	80
	2	—	—	—	—	5	20	—	40	40	2	60	50	80	90	25	90	85
	3	—	—	1	2	5	30	5	50	30	40	50	40	30	60	90	70	40
	AVERAGE	—	—	1	1	4	20	10	40	40	20	40	55	70	75	55	70	70
5	1	—	—	—	—	15	10	40	40	40	40	25	60	70	60	80	40	30
	2	—	—	—	—	1	—	10	40	40	30	40	10	70	40	40	60	50
	3	—	—	—	10	10	5	10	30	40	40	60	80	60	70	80	80	50
	AVERAGE	—	—	—	3	10	5	20	35	40	35	40	50	65	60	65	60	45

TABLE E I

MICROSTRUCTURAL SURVEY OF JOMINY BARS CONTAINING INTERMEDIATE TRANSFORMATION PRODUCT

HEAT NO.	SURVEY NO.	% INTERMEDIATE TRANSFORMATION PRODUCT AT INDICATED DISTANCES IN SIXTEENTHS OF AN INCH FROM QUENCHED END OF JOMINY BAR																
		1	3	4	5	6	8	9	11	13	15	19	23	26	30	34	38	41
		6	1	—	—	—	—	—	—	—	1	—	2	2	5	10	10	25
2	—		—	—	—	—	1	1	2	—	2	2	2	10	5	30	10	10
3	—		—	—	—	—	1	1	1	—	2	1	2	10	15	5	5	5
AVERAGE	—		—	—	—	—	1	1	1	—	2	2	3	10	10	20	10	5
6*	1	—	—	—	—	—	1	2	5	—	1	2	5	15	30	25	5	10
	2	—	—	—	—	—	1	2	1	2	10	2	20	15	25	25	5	2
	3	—	—	—	—	—	1	2	2	1	25	15	5	35	15	25	15	10
	AVERAGE	—	—	—	—	—	1	2	3	1	10	5	10	20	25	25	10	5
7	1	—	—	—	—	—	—	—	—	—	2	—	—	2	—	—	20	—
	2	—	—	—	—	—	—	—	—	—	—	1	—	5	15	10	2	25
	3	—	—	—	—	—	—	—	—	—	1	—	5	—	5	1	25	30
	AVERAGE	—	—	—	—	—	—	—	—	—	1	—	2	2	5	4	15	20
8	1	—	—	—	—	—	—	—	—	2	—	1	—	—	—	—	—	10
	2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	5	10	—
	3	—	—	—	—	—	—	—	—	—	1	7	7	—	1	—	1	—
	AVERAGE	—	—	—	—	—	—	—	—	—	1	—	3	3	—	—	2	4
9	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	5	5
	2	—	—	—	—	—	—	—	—	—	—	1	—	—	—	1	5	—
	3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2	1
	AVERAGE	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	3	2
20	1	—	—	—	—	—	—	—	—	—	—	—	—	—	1	25	10	15
	2	—	—	—	—	—	—	—	—	—	—	1	5	10	—	30	25	25
	3	—	—	—	—	—	—	—	—	—	—	—	10	10	2	20	20	20
	AVERAGE	—	—	—	—	—	—	—	—	—	—	—	5	5	1	30	20	20

* SAME AS PREVIOUS BAR BUT WITH 1% PICRAL ETCH.

TABLE E I

MICROSTRUCTURAL SURVEY OF STEP-AND DELAY-QUENCHED JOMINY BARS FROM HEAT NO. 6

**% INTERMEDIATE TRANSFORMATION PRODUCT AT INDICATED
DISTANCES IN SIXTEENTHS OF AN INCH FROM QUENCHED
END OF JOMINY BAR**

BAR NO.	SURVEY NO.	1	3	4	5	6	8	9	11	13	15	19	23	25	30	34	38	41
6T1	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2	—	—
	3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	AVERAGE	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	—
6T2	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	10	—
	2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	15	—
	3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	25	—	—
	AVERAGE	—	—	—	—	—	—	—	—	—	—	—	—	—	—	10	10	—
6T3	1	—	—	—	—	—	—	—	—	—	—	1	—	—	—	—	10	—
	2	—	—	—	—	—	—	—	—	—	—	1	—	—	—	—	—	10
	3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	15
	AVERAGE	—	—	—	—	—	—	—	—	—	—	1	—	—	—	—	3	10
6T5	1	—	—	—	—	—	—	—	—	—	—	—	—	5	—	15	15	20
	2	—	—	—	—	—	—	—	—	—	—	—	—	—	2	15	25	30
	3	—	—	—	—	—	—	—	—	—	—	—	—	5	—	10	—	15
	AVERAGE	—	—	—	—	—	—	—	—	—	—	—	—	3	1	15	15	20
6T6	1	—	—	—	—	—	—	—	—	—	—	—	10	—	15	15	25	30
	2	—	—	—	—	—	—	—	—	—	—	—	5	10	15	—	40	5
	3	—	—	—	—	—	—	—	—	—	—	—	—	15	—	40	5	—
	AVERAGE	—	—	—	—	—	—	—	—	—	—	—	5	10	10	20	25	10
6T7	1	—	—	—	—	—	—	—	—	—	—	—	—	10	—	—	30	5
	2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	15	—	—
	3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	20	10	5
	AVERAGE	—	—	—	—	—	—	—	—	—	—	—	—	3	—	10	15	3

TABLE E II

MICROSTRUCTURAL SURVEY OF STEP-AND DELAY-QUENCHED JOMINY BARS FROM HEAT NO. 6

BAR NO.	SURVEY NO.	% INTERMEDIATE TRANSFORMATION PRODUCT AT INDICATED DISTANCES IN SIXTEENTHS OF AN INCH FROM QUENCHED END OF JOMINY BAR.																
		1	3	4	5	6	8	9	11	13	15	19	23	26	30	34	38	41
ST8	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	-	-	-	-	-	-	-	-	-	-	-	-	15	1	-	25	5
	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	AVERAGE	-	-	-	-	-	-	-	-	-	-	-	-	5	-	-	10	1
ST9	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	3	-	-	-	-	-	-	-	-	-	-	-	2	-	-	5	2	-
	AVERAGE	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-
ST12	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10	-	30
	2	-	-	-	-	-	-	-	-	-	-	-	-	5	-	5	-	25
	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10	-	20
	AVERAGE	-	-	-	-	-	-	-	-	-	-	-	-	1	-	10	-	25

TABLE E III																								
HARDNESS SURVEY OF STEP - AND DELAY - QUENCHED JOMINY BARS FROM HEAT NO. 6																								
BAR NO.	ROCKWELL "C" HARDNESS VALUES AT INDICATED DISTANCES IN SIXTEENTHS OF AN INCH FROM QUENCHED END OF JOMINY BAR																							
	1	2	3	4	5	6	7	8	9	10	12	14	16	18	20	23	24	31	32	39	40			
6 T 1	56.5	54.5	55.0	53.5	53.5	54.5	53.6	53.5	53.0	52.5	52.5	52.5	52.5	52.5	52.5	52.0	52.5	52.5	52.5	52.5	50.5	50.5	51.5	
6 T 2	53.5	51.5	51.5	52.5	52.5	51.5	51.5	51.5	51.5	52.5	51.5	51.5	51.5	51.5	51.5	50.5	48.5	48.5	48.5	47.5	47.5	47.5	47.5	
6 T 3	55.5	54.5	54.5	54.0	53.5	52.5	52.5	53.0	54.0	53.0	52.5	52.5	52.5	52.5	51.5	51.5	52.0	52.5	52.5	52.5	52.5	52.5	52.5	53.0
6 T 5	54.0	54.5	53.0	52.0	52.5	52.5	52.5	50.5	51.5	52.0	50.5	51.5	51.0	50.5	52.5	51.0	52.5	50.5	50.5	49.0	49.0	49.0	49.0	49.0
6 T 6	55.5	54.5	54.0	53.5	53.0	53.5	52.5	54.0	53.5	53.5	52.5	52.0	52.0	51.5	52.5	50.5	52.5	50.5	52.5	52.5	50.0	48.5	47.5	47.5
6 T 7	55.5	55.0	54.0	53.0	53.5	52.5	52.5	51.5	51.5	51.0	51.5	51.5	51.5	51.5	52.0	51.5	52.0	51.5	51.5	51.0	51.0	51.0	51.0	51.0
6 T 8	54.5	54.5	54.5	53.5	53.5	53.5	52.5	52.5	52.5	52.5	52.5	52.5	52.5	51.5	51.5	52.0	51.5	51.5	51.5	51.5	51.5	51.5	51.5	51.5
6 T 9	56.5	56.5	55.5	54.5	55.5	54.5	53.5	54.5	54.5	54.5	54.5	53.5	52.0	52.5	51.5	52.0	52.5	51.5	53.5	52.0	52.0	51.5	52.5	52.5
6 T 12	54.5	53.5	53.0	53.5	53.5	53.5	53.5	51.5	50.5	51.5	51.5	52.5	51.5	52.0	51.0	51.5	52.0	51.0	51.5	52.0	51.0	51.5	50.5	50.5
	54.0	53.5	53.0	53.5	52.5	52.5	52.5	51.0	52.0	51.0	51.5	51.5	51.0	51.0	51.0	52.5	51.5	52.5	50.5	51.5	52.5	50.5	48.5	50.5

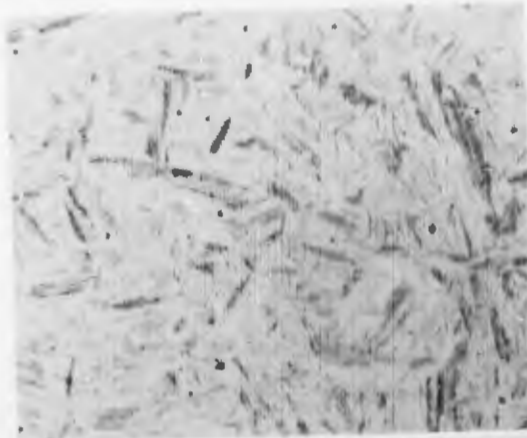
TABLE E IV**HEAT TREATMENT OF STEP-AND DELAY-QUENCHED JOMINY BARS FROM HEAT NO. 6****ALL BARS AUSTENITIZED AT APPROXIMATELY 1650°F, COOLED AND HELD AT TEMPERATURES AS INDICATED BELOW AND THEN END-QUENCHED IN WATER.**

BAR NO.	COOLING PRACTICE	
	TEMPERATURE	TIME AT TEMPERATURE
6 T 1	1000 °F (SALT)	5 MINUTES
6 T 2	"	10 MINUTES
6 T 3	"	20 MINUTES
6 T 12	"	40 MINUTES
6 T 5	"	1 HOUR 20 MINUTES
6 T 6	"	2 HOUR 40 MINUTES
6 T 7	"	5 HOUR 30 MINUTES
6 T 8	AIR-COOLED TO 1000°F — TRANSFERED TO SALT AT 1000°F — HELD 5 MINUTES	
6 T 9	FURNACE COOLED AT 18°F/MINUTE TO 1000°F — TRANSFERED TO SALT AT 1000°F — HELD 5 MINUTES.	

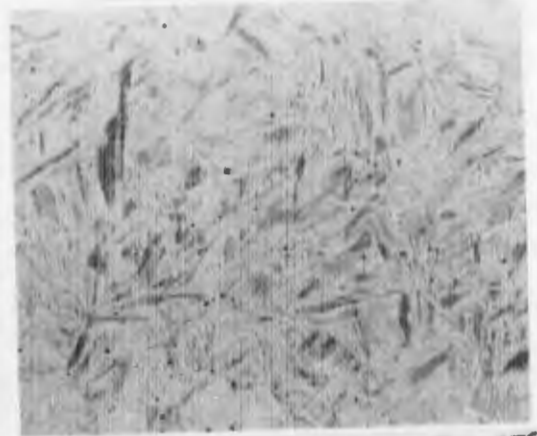
FIGURE C-1

Effect of Austenitizing Temperature upon Degree of Carbide Solution in Low Alloy Steel

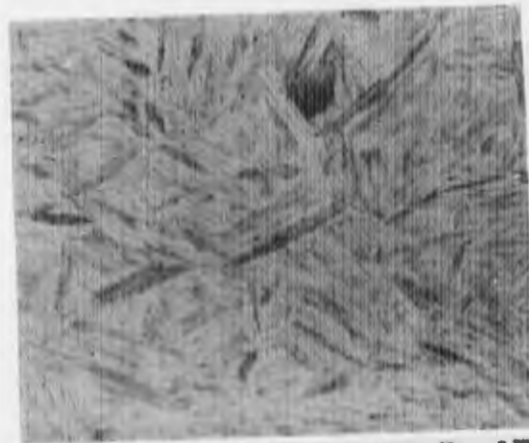
All specimens water quenched
Picral etch X1000



Heat No. 1. Specimen No. LX5
Austenitized 4 hours at 1550°F. Few
undissolved carbides.



Heat No. 1. Specimen No. LX6
Austenitized 4 hours at 1575°F. Very
few undissolved carbides.



Heat No. 1. Specimen No. LX7
Austenitized 4 hours at 1600°F. No
undissolved carbides observed in the
microscope eyepiece, but the in-
creased sensitivity of the photo-
graphic emulsion reveals some very
small carbides out of solution.

FIGURE C-2

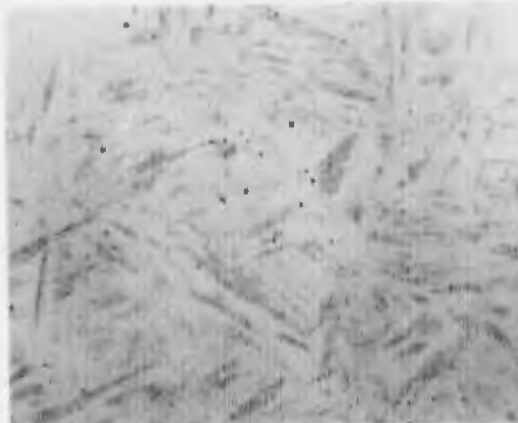
Effect of Austenitizing Temperature upon Degree of Carbide Solution in High Alloy Steel

All specimens oil quenched

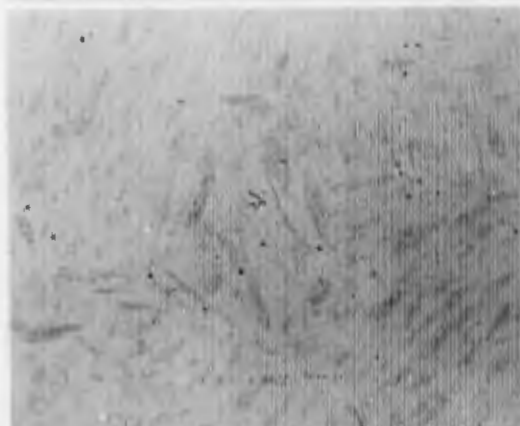
Picral etch X100C



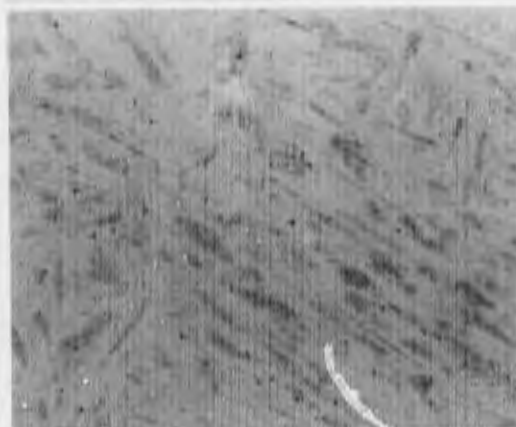
Heat No. 12. Specimen No. 12A5
Austenitized 4 hours at 1550°F. Many undissolved carbides.



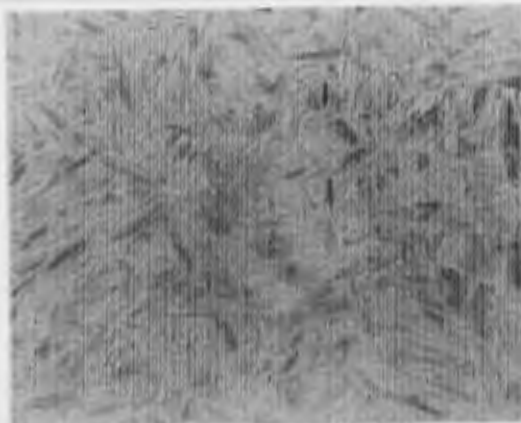
Heat No. 12. Specimen No. 12A6
Austenitized 4 hours at 1600°F. Few undissolved carbides.



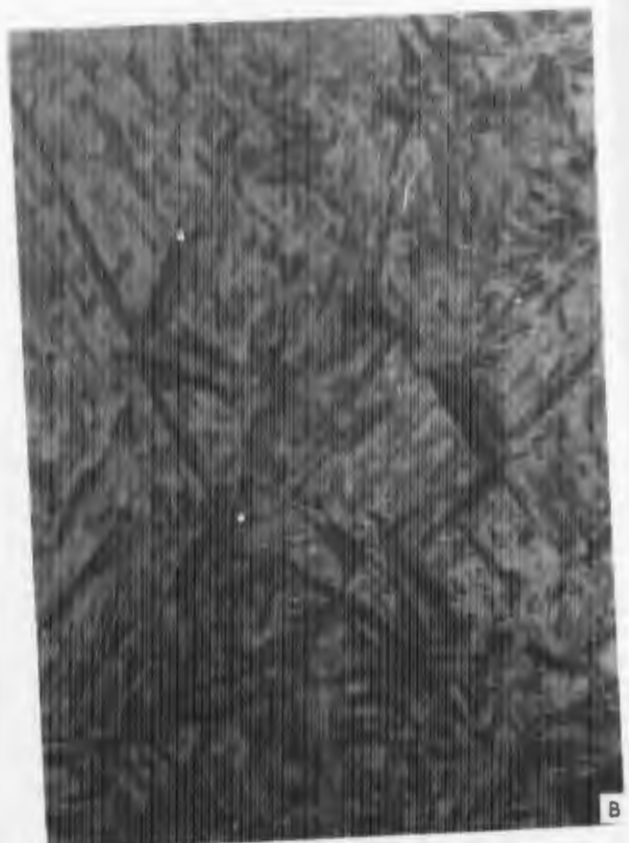
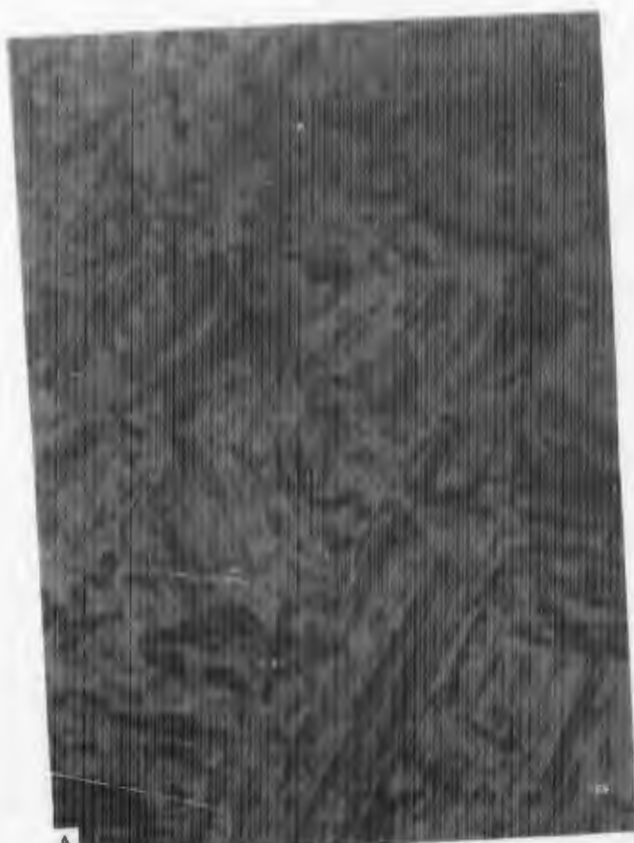
Heat No. 12. Specimen No. 12A7
Austenitized 4 hours at 1625°F. Few undissolved carbides.



Heat No. 12. Specimen No. 12A8
Austenitized 4 hours at 1650°F. Very few undissolved carbides.



Heat No. 12. Specimen No. 12A9
Austenitized 4 hours at 1675°F. No undissolved carbides visible in microscope eyepiece.



WTN.639-6790

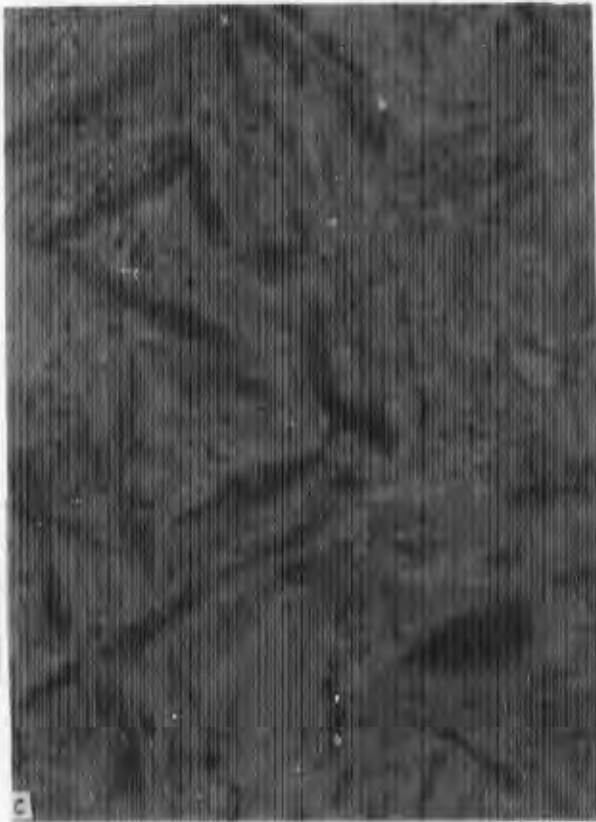
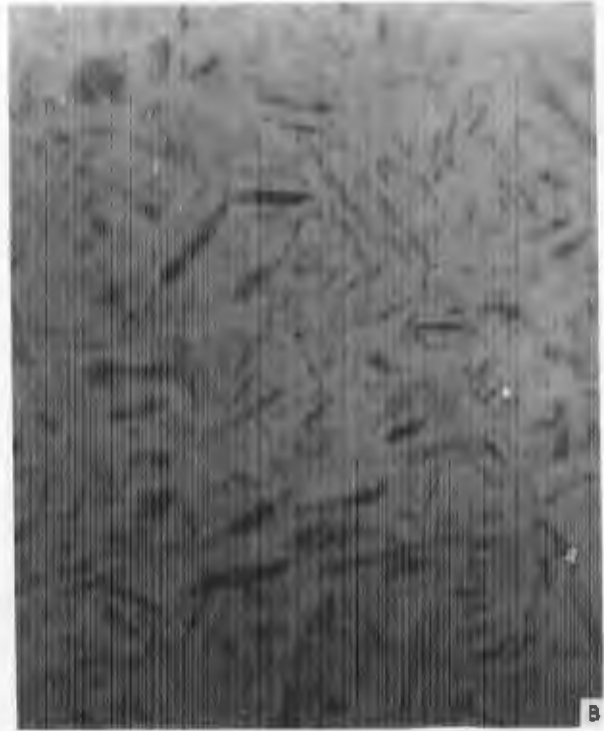
FIGURE 1-2

Microstructure of As-Quenched Joniny Bar from Heat #6

Etchant: 1% Picral

<u>Magnifi- cation</u>	<u>Loca- tion*</u>	<u>Remarks</u>
A X1000	5	100% martensite. Suggestion of tempering in darker needles. Compare Fig. 1-B, nital etch.
B X1000	9	First appearance of intermediate transformation product - the very black needles. Compare Fig. 1-D, nital etch.
C X2500	3	100% martensite. Darker needles, like those in A, suggest tempering. Compare Fig. 1-C, nital etch.
D X2500	9	Intermediate transformation product evidenced by areas having very black resolvable carbide particles. Remaining structure martensitic.
E X1000	15	Increasing amounts of intermediate transformation product. Background martensitic. Compare Fig. 1-F, nital etch.
F X2500	15	Intermediate transformation product seen as areas of black, resolvable carbide particles.
G X1000	26	Intermediate transformation product represented by very black areas. Background as in E. Compare Figure 1-J, nital etch.
H X1000	33	Same structure as in G. Compare Fig. 1-M, nital etch.
I X2500	33	Intermediate transformation product seen as areas of black, resolvable carbide particles.

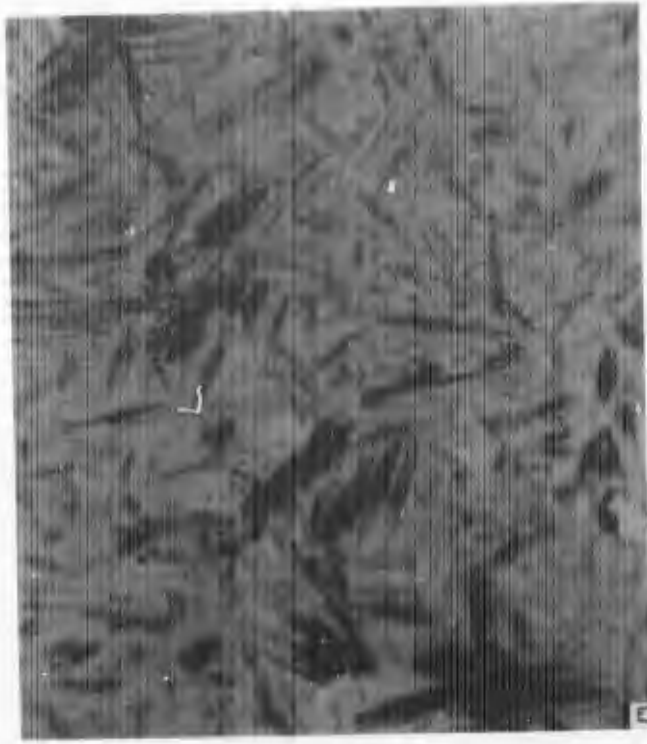
*Distance from quenched end in sixteenths of an inch.



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B



E



G



C

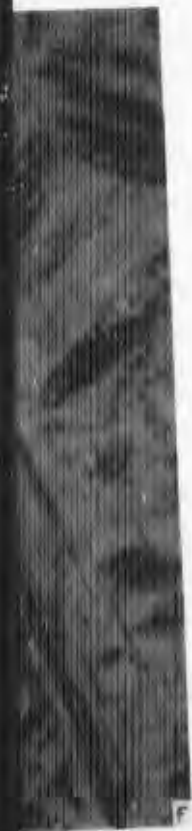


F

WTN. 639-6803



WTN. 639-6804



MTN. 630-6004

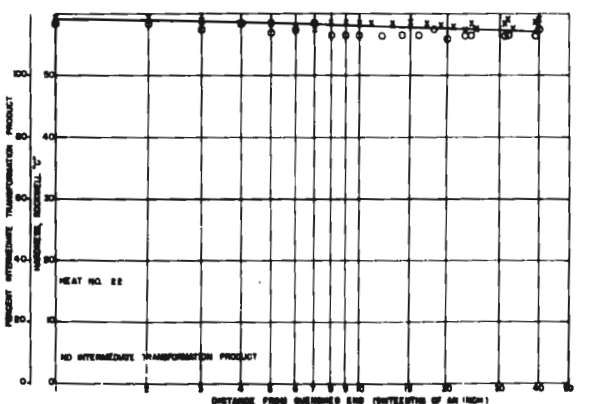
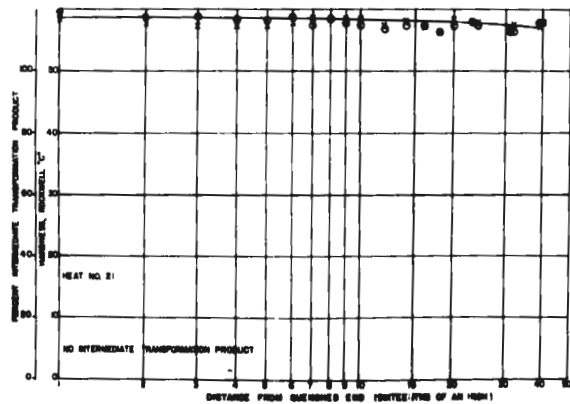
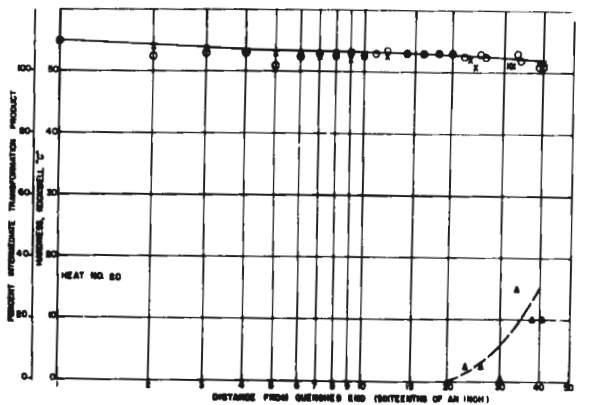
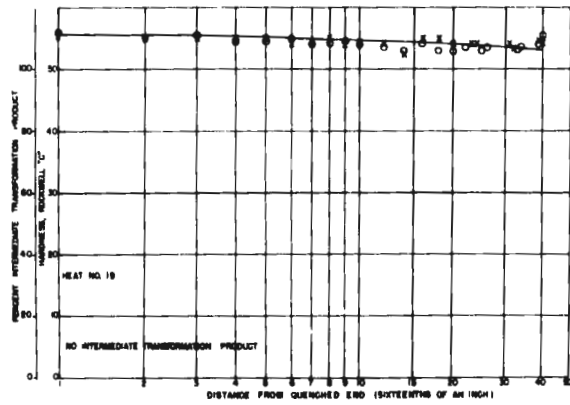
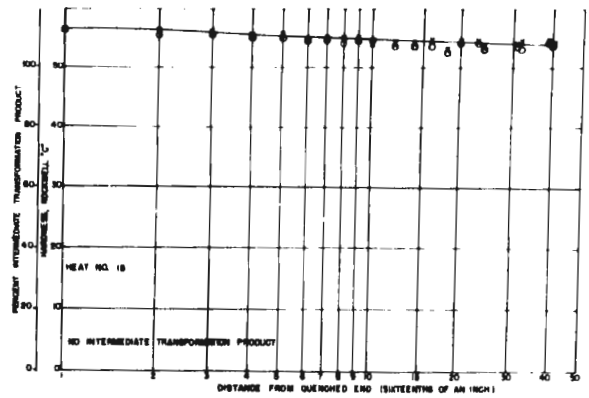
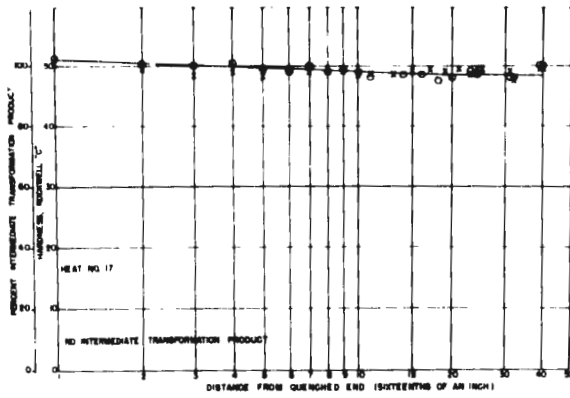


Figure E1-continued

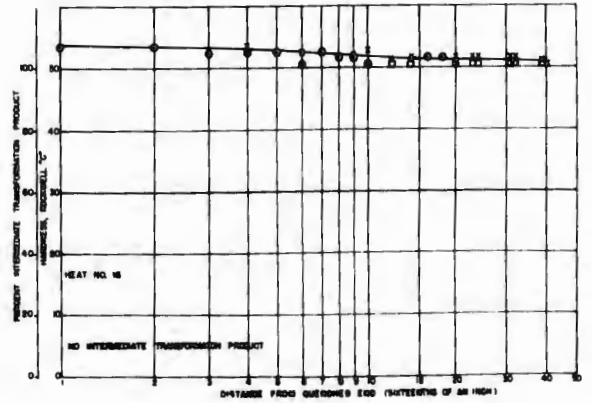
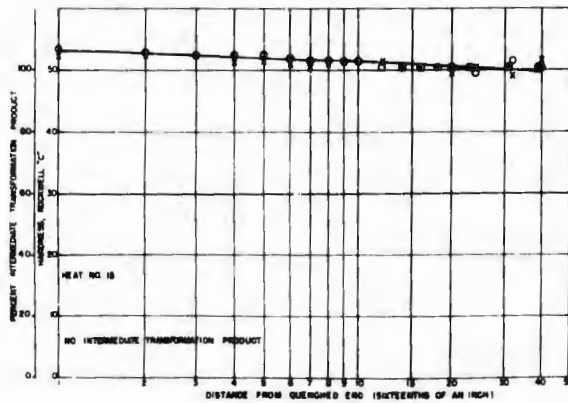
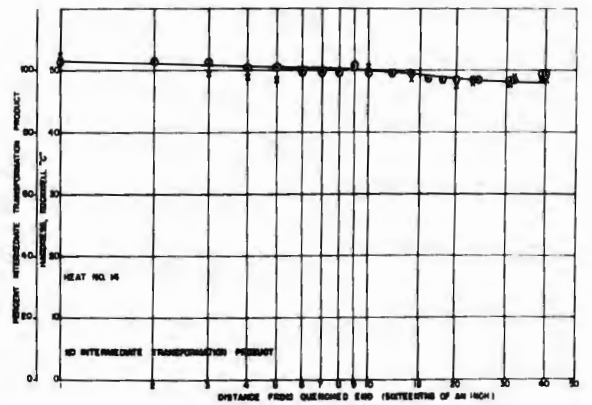
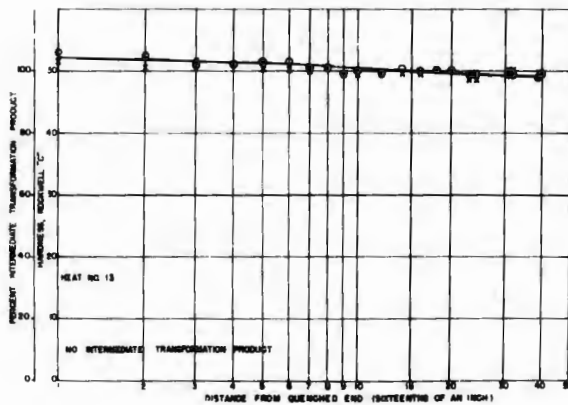
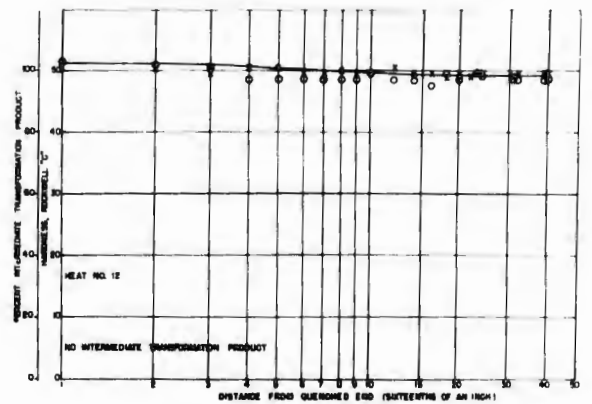
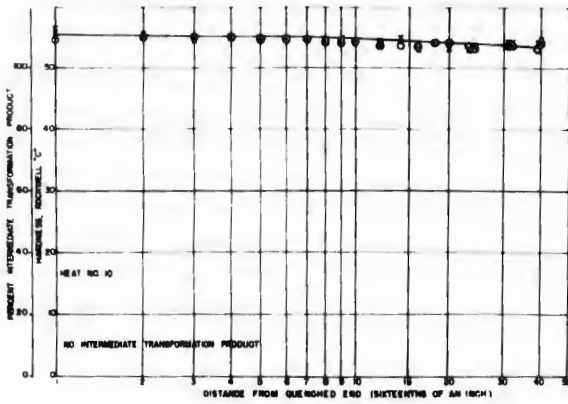


Figure E1 - continued

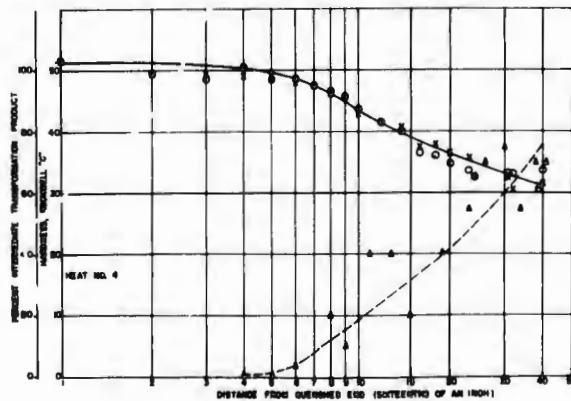
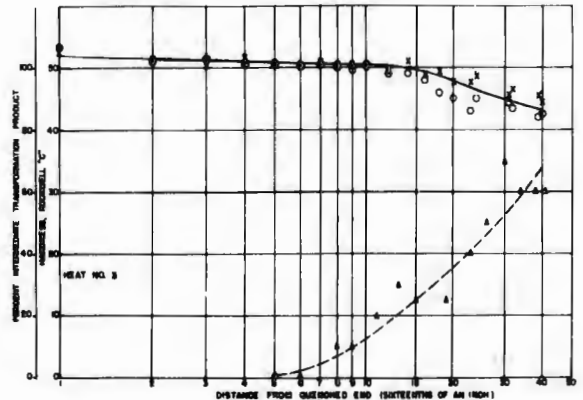
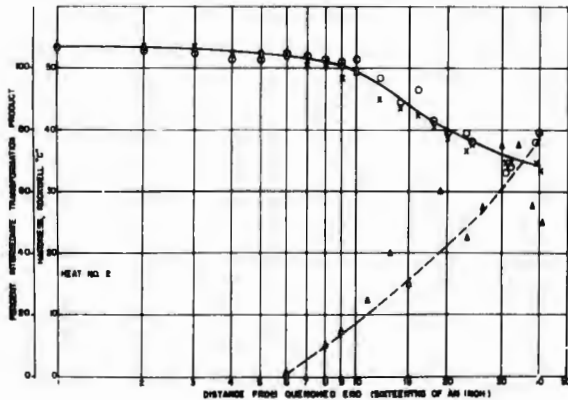
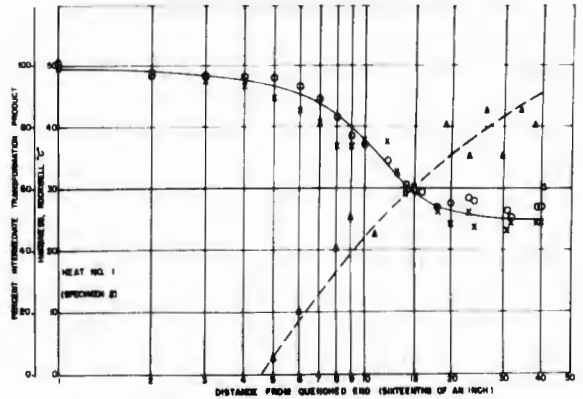
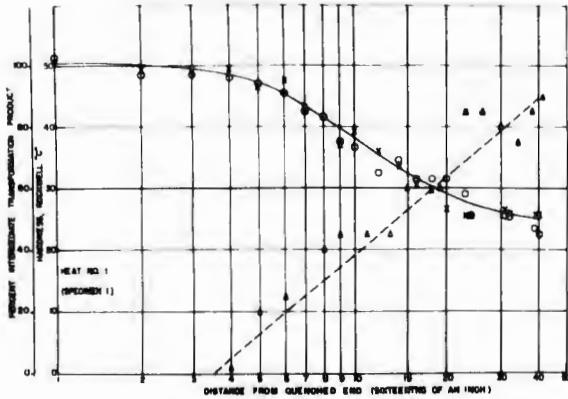


FIGURE E1

RESULTS OF HARDNESS AND MICROSTRUCTURAL SURVEYS
OF JOMINY BARS FROM THE EXPERIMENTAL HEATS

-) HARDNESS VALUES OPPOSITE
X) FACES OF SAMPLE.
- △ % INTERMEDIATE TRANSFORMATION
PRODUCT OBSERVED MICROSCOPICALLY.

FIGURE E-3

Microstructure of As-Quenched Joniny Bar from Heat #6

Etchant: 1% Nital

Magnification: X1000

	<u>Location*</u>	<u>Remarks</u>
A	1	100% martensite.
B	9	100% martensite. Suggestion of tempering effect in some needles.
C	42	Areas of intermediate transformation product. (White arrows indicate some of the areas.) Background is martensite with suggestion of tempering effect.

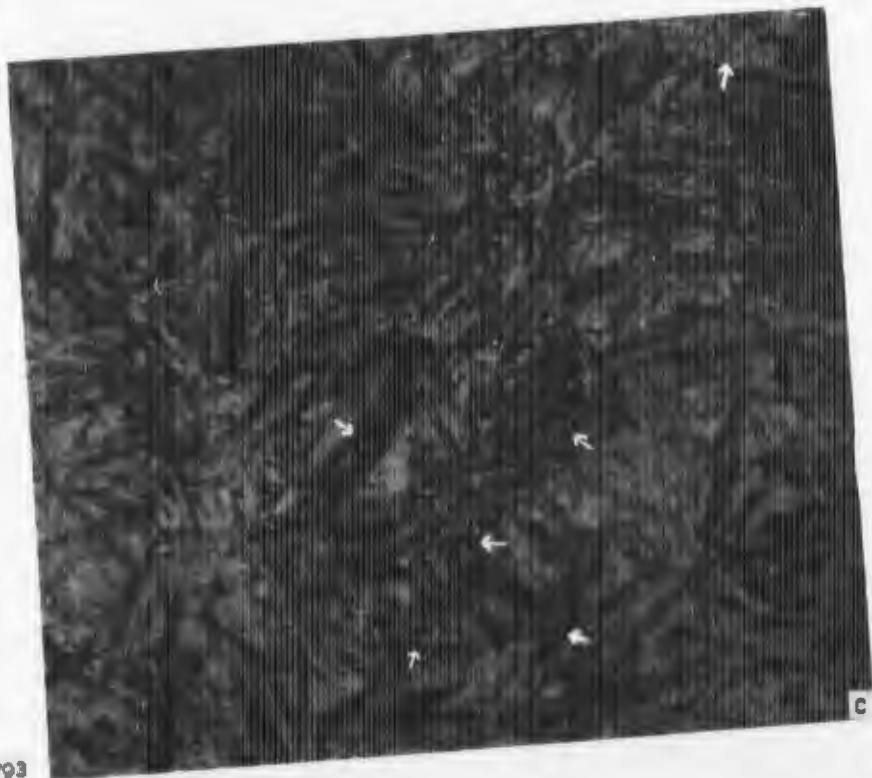
*Distance from quenched end in sixteenths of an inch.



A



B



C

WTN.639-6793

FIGURE E-4

Microstructure of As-Quenched Jominy Bar from Heat #17

Etchant: 1% Nital

Magnification: X1000

	<u>Location*</u>	<u>Remarks</u>
A	1	100% martensite.
B	22	100% martensite, with suggestion of tempering effect in some needles.
C	41	Like B.

*Distance from quenched end in sixteenths of an inch.



WTN.639-6794

FIGURE E-5

Microstructure of As-Quenched Jominy Bar from Heat #19

Etchant: 1% Nital

Magnification: X1000

	<u>Location*</u>	<u>Remarks</u>
A	1	100% martensite.
B	22	Like A.
C	39	Like ^{A.} B.

*Distance from quenched end in sixteenths of an inch.



A



B



C

WTN.639-6795

FIGURE B-6

Microstructure of As-Quenched Joniny Bar from Heat #20

Etchant: 1% Nital

Magnification: X1000

	<u>Location*</u>	<u>Remarks</u>
A	4	100% martensite.
B	18	100% martensite. Suggestion of tempering effect in dark needles.
C	34	Intermediate transformation product in background of martensite. White arrows indicate some of the transformed areas.

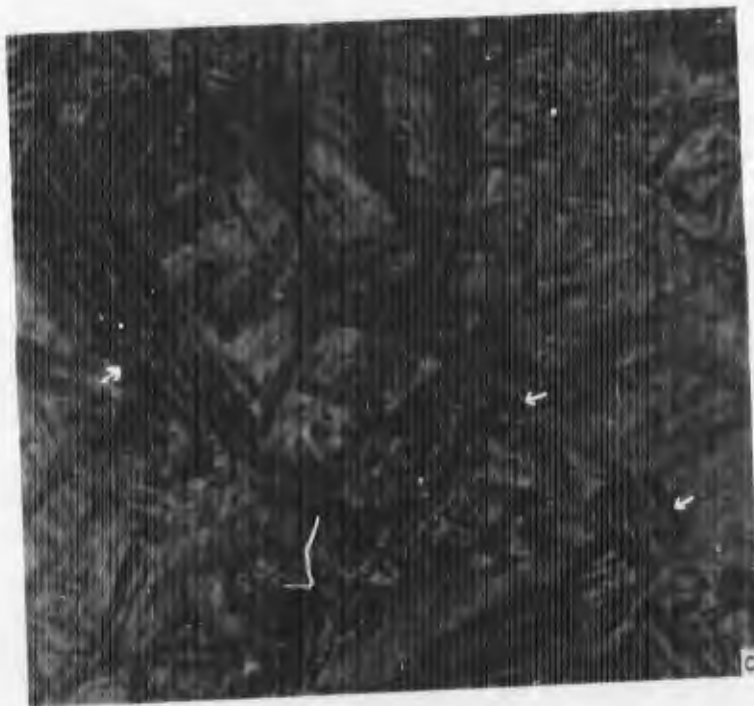
*Distance from quenched end in sixteenths of an inch.



A



B



C

WTN.639-6791

FIGURE B-7

Microstructure of As-Quenched Joniny Bar from Heat #22

Etchant: 1% Nital

Magnification: X1000

	<u>Location*</u>	<u>Remarks</u>
A	6	100% martensite.
B	19	Like A.
C	42	Like A but with greater amount of light etching back- ground.

*Distance from quenched end in sixteenths of an inch.

FIGURE B-8

Microstructure of Joniny Bar from Heat #22

Tempered $\frac{1}{2}$ Hour at 500°F.

Etchant: 1% Nital

Magnification: X1000

	<u>Location*</u>	<u>Remarks</u>
A	5	Precipitated carbides too fine to be resolved.
B	19	clearly at this magnification. Note presence of such particles in
C	40	martensite-like needles.

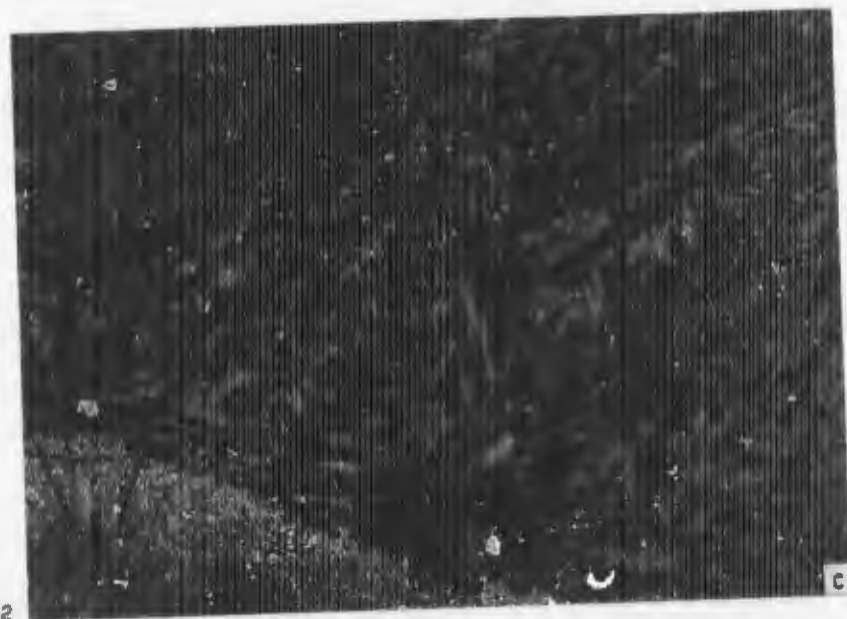
*Distance from quenched end in sixteenths of an inch.



A



B



C

WT 639-6792

FIGURE 1-9

Microstructure of Jominy Bar from Heat #6

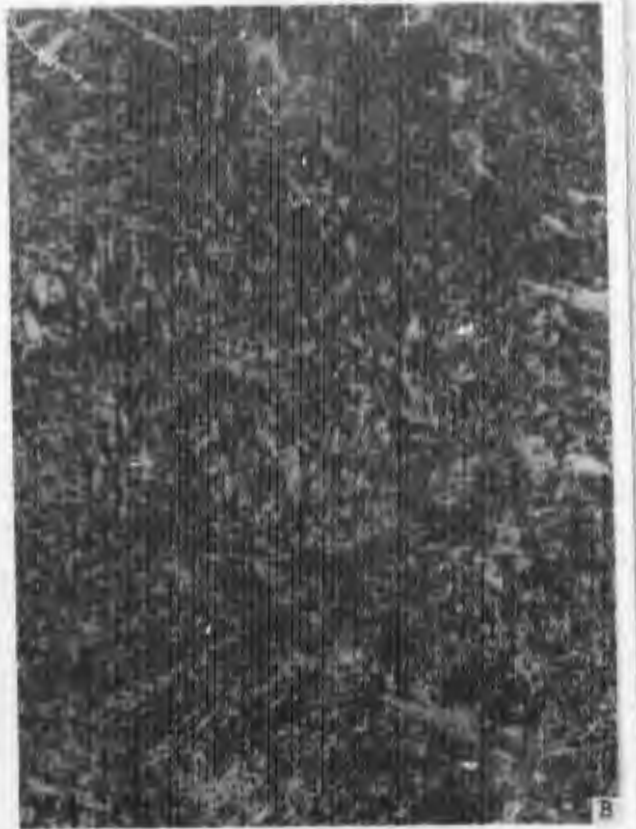
Tempered 4 Hours at 1210°F.

Etchant: 1% Nital

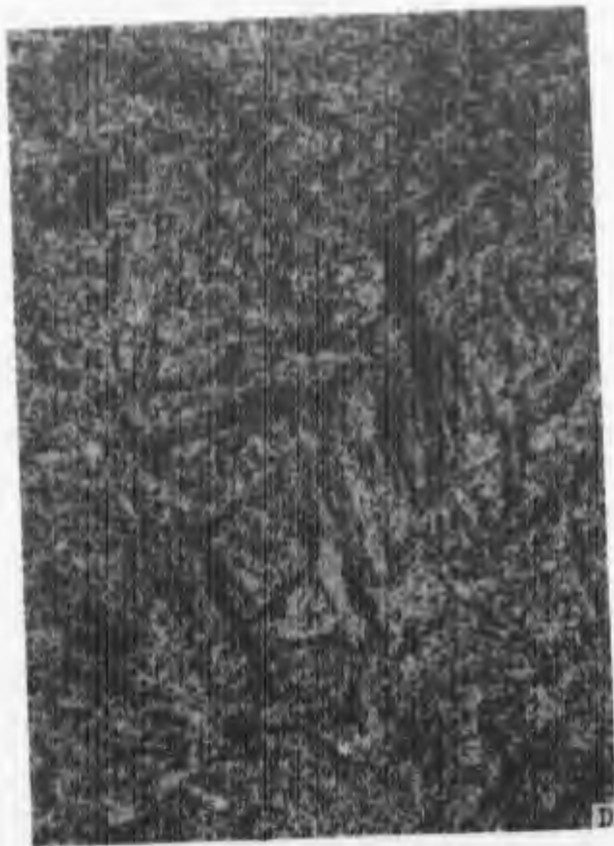
Magnification: X1000

	<u>Location*</u>	<u>Remarks</u>
A	5	Precipitated carbide particles just resolvable at this magnification.
B	9	Areas of tempered intermediate transformation product not readily distinguishable from areas of tempered martensite.
C	15	
D	26	
E	33	

*Distance from quenched end in sixteenths of an inch.



WTN.639-6917



WTN.639-6918

APPENDIX F

Martensite Transformations

APPENDIX F

Martensite Transformations

As a guide in the heat-treatment of the various steels, it was desired to determine the temperature of the beginning and end of the austenite-martensite transformation (M_s and M_f points). The thermal arrest method appeared to be the least laborious and most straight-forward. Preliminary work indicated, however, that while the M_s point could be measured satisfactorily by the thermal arrest method, the M_f could not. Even though a temperature differential technique (outlined below) was used, no abrupt change in cooling rate could be found at the end of the transformation. Recourse was had to the dilatometric method, which did give a reasonably sharp indication of the apparent end of the transformation. Simultaneous thermal arrest and dilatometric measurements were, therefore made.

A Chevenard^{1,2} type dilatometer was available for the dilatometric measurements. This dilatometer is designed so that the change of length of a steel specimen is recorded photographically as a function of the change in length of a standard specimen by means of optical lever arrangements. (Figures F1 and F2 show typical dilatometer records.) The change in length of the metal standard, similar dimensionally to the specimen, but of such composition that it undergoes no phase changes within the temperature range under consideration, serves as a measure of the temperature of the steel specimen.

When, as in the cases for which the dilatometer was designed, cooling or heating is slow, the temperature indicated on the film (that of the standard) will be the same as that of the specimen. More rapid cooling (in air) is, however, needed, when it is desired to obtain transformation of austenite to martensite in steels of moderate hardenability without interference by the pearlite or bainite reactions. In such cases, the temperature of the sample may differ from that of the standard during the cooling, even though the standard is made of a material (nickel) having about the same thermal conductivity, specific heat, and density, as the steel specimen.

To determine this temperature difference and for use in the thermal analysis measurements, thermocouples were welded to both the nickel and steel specimens and connected to two high-speed recording galvanometers similar to that used by Greninger.³ The galvanometers record, simultaneously on the same film, the steel temperature and the difference between the steel and the nickel temperatures, as functions of time. (A typical galvanometer record is shown as Figure F3.) By the use of these data, the steel temperature corresponding to any nickel temperature could be calculated. The beginning and end of the martensitic "break" were, therefore, read from the dilatometer film (see Figure 1) in terms of the length of the nickel standards, converted to nickel

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1. P. Chevenard; "Dilatometre Differential Enregistreur". *Revue de Metallurgie (Memoires)*, 14, 610-640 (1917).
 2. F. Bellenrauth; "Ein neues optisches Dilatometer". *Z. Metallkunde*, 7, 163-165 (1933).
 3. A. B. Greninger; "The Martensite Thermal Arrest in Iron-Carbon Alloys and Plain Carbon Steels". *Trans. ASM*, 10, 1-26 (1942).

temperature by a calibration chart prepared for the nickel standards, and finally obtained in terms of steel temperature by subtracting the difference (obtained from the galvanometer curve) between nickel and steel temperatures.

A determination of the M_s point could be obtained from the thermal data of the galvanometer record alone. A change in slope of the temperature-versus-time curve occurs when the martensite transformation begins. This thermal arrest is more easily noted on the temperature difference curve, which, because of its lesser range, can be obtained with about four times the sensitivity of the temperature curve. Since the steel temperature and the temperature difference curves are synchronized, the arrest can be located on the difference curve and readily transferred to the steel temperature curve. Calibration lines are recorded with the temperature curve on each film, so the steel temperature corresponding to the arrest is readily found. As can be seen in Figure F3, no sharp change occurs in either the steel temperature or the difference curve at the end of the martensite transformation, so, as mentioned above, the M_f could not be determined without the use of the dilatometer. Details of the operating techniques and the necessary calculations appear elsewhere.¹

Some difficulties were encountered because the thin specimens used (.077-inch diameter x 2 inches long) tended to decarburize during the austenitizing treatment, despite the use of a .002-inch nickel electroplate and the passage of purified nitrogen gas through the furnace. The decarburization was thought to be due to air leaking in through the furnace opening which admitted the dilatometer assembly. This opening could not be sealed, and it was, therefore, decided to reduce the decarburization by cutting the austenitizing time to 15 minutes and raising the temperature in an effort to obtain carbide solution and homogeneity of the austenite, equivalent to that obtained in 4 hours at the lower, standard, austenitizing temperature. On the basis of meager data available in the literature^{2,3} it was estimated that an increase in temperature of 45°F. should compensate for the shorter austenitizing time, and the temperatures were accordingly raised approximately 45°F. above those given in Appendix B.

The procedure adopted was to austenitize one specimen from each heat for 15 minutes in the dilatometer furnace, then withdraw it and cool in a current of air supplied by a small electric fan. This gave a cooling rate of approximately 80°F. per second at 1300°F. If it was thought that the M_f might be below 75°F., the specimen and nickel standard, after reaching room temperature, were further cooled to -310°F. The run was then repeated on the same specimen using another 15 minutes austenitizing time.

If an accident (such as the breaking of a thermocouple) occurred during either run, two more runs were made, using a new specimen. The same procedure was followed if the M_s temperature obtained in the second run was more than 20°F. higher than that of the first run, indicating that possibly decarburization had occurred. If the M_s of the second run was more than 20°F. lower than

1. L. D. Jaffe and P. Terris; "Technique of Martensite Temperature Determination". Watertown Arsenal Report. In Preparation.
2. G. A. Roberts and R. F. Mehl; "Effect of Inhomogeneity in Austenite on the Rate of the Austenite-Pearlite Reaction in Plain Carbon Steels". Trans. A.I.M.E., 154, 318-334 (1943).
3. G. T. Williams; "Hardenability Variations in Alloy Steels—Some Investigations with the End-Quench Test". Trans. ASM, 22, 157-185 (1940).

that of the first, indicative of increasing carbide solution or homogenization, the additional runs were made at a higher austenitizing temperature.

As a check of the technique used, dilatometer specimens from heats 4, 15, and 21 (Specimens 4W2-2, 15A4-1, and 21A4-1) were examined microscopically after being used for the martensite determinations. No definite undissolved carbides were observed, and the austenitic grain size was measured as ASTM 5-6. It was found, however, that the heat 4 specimen contained approximately 10 per cent of intermediate transformation product, such as that shown in Figure 1. This unexpected transformation was probably due to the manganese content of this heat being lower than desired, resulting in correspondingly low hardenability. It was decided to rerun the low-alloy heats 1, 2, 4 and 5, employing a higher cooling rate. This was achieved by using specimens having a diameter of .060 inch instead of .077 inch (with a correspondingly smaller nickel standard) and quenching in a stream of commercial tank helium, rather than in an air current. Cooling rates of 150° to 200° F. per second at 1300° F. were obtained in this way, but the galvanometer curves were not as satisfactory as those made with air-cooling. The M_s temperatures found in heats 4 and 5 were slightly lower than had been found at the slower cooling rate of 80° F. per second, but the difference may not have been significant. The specimens quenched in helium were examined microscopically after being run twice. The heat 1 sample contained over 20 per cent bainite despite the higher quenching rate. Heats 2, 4, and 5 showed between 1 and 5 per cent bainite, but almost all of this was at the decarburized surface. Thus, it appears that only in the case of heat 1 is it likely that the formation of bainite introduced serious error in the determination of martensite transformation temperatures,

The results obtained in all usable runs are tabulated in Table FI, summarized in Table FII. The M_s temperatures measured by the thermal arrest are in good agreement with the predictions made before the start of the experimental work (Appendix A). The deviations which occur may be accounted for on the basis of the deviations of the carbon contents found in the check analyses from the .30 per cent upon which the estimates were based. An increase of .01 per cent carbon lowers the M_s approximately 7° F. in the range under consideration.¹ The precision of the M_s temperature determinations for the lower alloy steels is perhaps $\pm 20^\circ$ F., and is limited by the precision with which the film record is measured and by the reproducibility of the runs, which is limited in turn by segregation in the castings. In the high-alloy steels, the galvanometer indication of the M_s arrest is not sharp but gradual, and it becomes very difficult to determine just when the transformation begins. (Compare Figure F4, for a high-alloy heat, with Figure F3, for a low-alloy.) It has not yet been determined whether this effect is due to greater segregation in the high-alloy heats, to greater decarburization at the high austenitizing temperatures used, or to the effect of high-alloy content or of high austenitizing temperatures upon the amount of martensite formed per degree lowering of the temperature just below the M_s point. In any case, because of the uncertainty as to the selection of the "break" on the galvanometer readings, the temperatures given for M_s as determined by thermal arrest for the higher alloy heats may be an error by as much as $\pm 50^\circ$ F.

The temperatures found for M_s by the dilatometric method are in all cases

1. A. B. Greninger, op. cit.

higher than those found by thermal analysis, averaging approximately 100° F. higher. Part of this difference is accounted for by the fact that check measurements indicated that the ends of the 2-inch long specimens used were as much as 45° F. hotter than the midlength at the M_s point. Thus, the transformation would begin at the midlength and would be indicated on the dilatometer record, at a time when the temperature averaged over the length and indicated on the record was somewhat higher. Moreover, with the dilatometer end pieces available, it was necessary to leave a shoulder .010 inches thick and .150 inches in diameter at each end of the specimens, which was in contact with the quartz end pieces and would cool much more slowly than the rest of the sample. This might increase the temperature averaged over the specimen by perhaps 25° F. It is, therefore, clear that the indication of M_s temperature by the dilatometer would be higher and less reliable than by the thermal arrest measurements. Only the latter are, therefore, given in Table FII. The M_s and M_f points on the dilatometer record tended to be less sharp for high-alloy (Figure F2) than for low-alloy (Figure F1) steels, but this effect was not as pronounced as in the galvanometer curves.

The M_f temperatures had perforce to be obtained from the dilatometric measurements. The dilatometer indications were less sharp for the end than for the beginning of the reaction, and the precision of the M_f values was limited by the uncertainty inherent in the choice of the end of the reaction on the dilatometer record. This precision was perhaps ± 30 F. for the lower-alloy heats and $\pm 50^{\circ}$ F. for the higher alloy.

The specimen shoulders are somewhat hotter than the rest of the specimen at the M_f , thus giving a reading somewhat higher than the true M_f value, while the nonuniformity of temperature over the gauge length is small at the M_f . Moreover, it should be noted that dilatometer and galvanometer curves do not indicate the very beginning and end of the martensite transformation, but only the points at which the expansion or heat evolution accompanying it become negligible as compared with the normal thermal contraction or cooling. Since the martensite transformation on continuous cooling starts abruptly but ends gradually,¹ this introduces little error in the M_s determination, but the value obtained for the end of the transformation is probably higher than the true M_f . In addition, since it appears likely that the M_f is lower, the lower the cooling rate^{2,3} it will be lower for the center of a $\frac{1}{2}$ -inch or heavier plate, even if

*At least, the per cent of austenite retained at room temperature is greater, the lower the cooling rate.

1. A. Gulyaev: "Transformation of Retained Austenite at Sub-Zero Temperatures, with High-Alloy Steels". (In Russian). Metallurg, 14, (Number 3), 64-71 (1939).
2. J. A. Mathews: "Austenite and Austenitic Steels", Trans. A.I.M.E., 71, 568-596(1925).
3. S. S. Steinberg and V. I. Zyusin: "Transformation of Austenite in Plain Carbon Steels and Some Special Steels at Low Temperatures". (In Russian). Metallurg, 11, (Number 8), 3-15(1936).

continuously water-quenched, than it is for a dilatometer specimen cooled at the relatively rapid rate used. Thus, the value obtained for M_f in dilatometer measurements is almost certainly higher than the M_f which will occur in full-sized plates. The original estimates of the M_f temperature, while considerably lower than the measured temperatures, may not be a great deal lower than the temperatures at which the reaction will end in $1\frac{1}{2}$ to 6-inch thick plates.

It might also be mentioned that even if the austenite-martensite reaction in a particular steel ends above room temperature, it is not certain that no austenite will be retained at room temperature. There is evidence that, in some steels at least, the reaction ceases while considerable quantities of austenite remain undecomposed.

1. A. Gulysev, op. cit.

TABLE FI
Martensite Temperature Determinations

Heat No.	Specimen No.	Time Run	Aust. Temp. °F.	Ms		Mf		Dilatometer		Thermal Arrest		Remarks
				°F.	OF.	°F.	OF.	Arrest	Arrest	°F.	Arrest	
1	1W2-1	1	1700	763	428	Sharp		Sharp		Very Sharp		
1	1W2-1	2	1700	783	453	Sharp		Sharp		Sharp		
1	1XD-1	1	1700	693	336	Poor		Poor		Very Poor		Helium quench
1	1XD-1	2	1700	729	387	Very Poor		Very Poor		Very Poor		Helium quench
1	Selected Values			770	430					690		
2	2M4-1	1	1700	775	439	Sharp		Sharp		Sharp		
2	2M4-1	2	1700	766	450	Sharp		Sharp		Sharp, Double		
2	2MD-1	1	1700	675	271	Good		Good		Very Poor		Helium quench
2	2MD-1	2	1700	801	381	Good		Good		Very Poor		Helium quench. Axis poor
2	Selected Values			770	440					660		
3	3M2-4	1	1700	-	-	Sharp		Sharp		Difference couple shorted.		Atmosphere poor
3	3M2-4	2	1700	736	412	Sharp		Sharp		Sharp		Atmosphere poor
3	3M3	1	1700	797	451	Sharp		Sharp		Fair		
3	3M3	2	1700	736	376	Sharp		Sharp		Fair		
3	Selected Values			740	390					651		

TABLE FI (Continued)

Heat No.	Specimen No.	Time Run	Aust. Temp. °F.	Dilatometer		Thermal Arrest		Remarks
				M _f °F.	Arrest	M _a °F.	Arrest	
4	4W2-1	1	1700	469	Sharp	685	Sharp	
4	4W2-1	2	1700	401	Sharp	684	Good	
4	4W2-2	1	1725	-	Sharp	685	Fair	Specimen lifted from dilatometer.
4	4W2-2	2	1725	392	Sharp	714	Fair	
4	4XD-1	1	1700	412	Good	667	Fair	Helium quench
4	4XD-1	2	1700	343	Fair	662	Poor	Helium quench
4	Selected Values			730 400		680		
5	5W4-1	1	1700	424	Sharp	721	Good	
5	5W4-1	2	1700	-	Off Scale	741	Good	
5	5S3D-1	1	1700	390	Slipping	619	Fair	
5	5S3D-1	2	1700	435	Good	628	Poor	
5	5MD-1	1	1680	466	Good	685	Good	Helium quench
5	5MD-1	2	1680	451	Good	696	Good	Helium quench
5	Selected Values			790 440		690		
6	6N3-1	1	1700	363	Sharp	615	Sharp	Atmosphere poor
6	6N3-1	2	1700	356	Sharp	622	Sharp	Difference curve irreg. Atmosphere poor.
6	6N3	1	1700	-	Sharp	-	-	Thermocouples Shorted
6	6N3	2	1700	396	Sharp	617	Fair	
6	Selected Values			710 360		620		

TABLE VI (Continued)

Heat No.	Specimen No.	Time Run	Inst. Temp.		Dilatometer		Thermal Arrest		Remarks
			Mg	°F.	Mg	°F.	Mg	°F.	
7	7M4-2	1	1740	781	Sharp	Sharp	610	Sharp	
7	7M4-2	2	1740	766	Sharp	Sharp	610	Poor	
7	Selected Values			770			610		
8	8M4-2	1	1740	714	Sharp	Sharp	619	Skipped	
8	8M4-2	2	1740	756	Sharp	Sharp	594	Fair	
8	8M4-1	1	1770	-	Sharp	Sharp	-	-	
8	8M4-1	2	1770	691	Sharp	Sharp	601	Very Poor	Thermocouples Shorted
8	8M4-3	1	1770	626	Sharp	Sharp	615	Very Poor	Thermal Arrest Doubtful
8	8M4-3	2	1770	671	Sharp	Sharp	612	Very Poor	Thermal Arrest Doubtful
8	Selected Values			680			610		Thermal Arrest Doubtful - A.C. Pickup
9	9M4-2	1	1770	585	Good	Good	552	Sharp	
9	9M4-2	2	1770	576	Sharp	Sharp	563	Very Poor	Thermal Arrest Doubtful
9	Selected Values			580			550		
10	10B6-2	1	1725	664	Sharp	Sharp	601	Fair	Atmosphere Poor
10	10B6-2	2	1725	675	Good	Good	622	Poor	Atmosphere Poor
10	10G3	1	1725	612	Sharp	Sharp	538	Fair	Thermal Arrest Doubtful
10	10G3	2	1725	622	Sharp	Sharp	538	Poor	
10	Selected Values			630			550		
12	12M4-3	1	1770	794	Sharp	Sharp	653	Poor	
12	12M4-3	2	1770	-	Pin Stuck	Pin Stuck	599	Very Poor	Vibration in Galv. Curves
12	12M4-1	1	1770	770	Fair	Fair	599	Good	Severe Vibration in Galv. Curves
12	12M4-1	2	1770	797	Sharp	Sharp	567	Fair	Thermal Arrest Doubtful
12	12M4-2	1	1795	752	Sharp	Sharp	624	Poor	Thermal Arrest Doubtful
12	12M4-2	2	1795	786	Good	Good	635	Poor	Dilatometer Axis Ragged
12	12B6D-1	1	1795	691	Poor. Slipped at Mg	Poor. Slipped at Mg	628	Very Poor	
12	12B6D-1	2	1795	680	Poor	Poor	608	Very Poor	
12	Selected Values			750			600		

TABLE VI (Continued)

Heat No.	Specimen No.	Time Run	Aust. Temp. °F.	Dilatometer			Thermal Arrest		Remarks
				M _s °F.	M _f °F.	Arrest	M _s °F.	Arrest	
13	13A4-1	1	1770	783	363	Sharp	601	Poor	Difference curve irreg. Thermal Arrest Doubtful
13	13A4-1	2	1770	792	396	Sharp	617	Very Poor	
13	13A4-2	1	1795	667	334	Sharp	621	Very Poor	Thermal Arrest Doubtful Thermal Arrest Doubtful
13	13A4-2	2	1795	730	325	Fair	649	Poor	
13	Selected Values			670	330		620		
14	12A4-1	1	1770	651	313	Good	495	Sharp	Couples Broke During Run Dilatometer Slipped at M _f
14	12A4-1	2	1770	667	320	Sharp	525	Poor	
14	12A4-2	1	1770	658	270	Sharp	606	Fair	
14	12A4-2	2	1770	680	266	Sharp	576	Fair	
14	12B6D-1	1	1770	774	423	Good	579	Sharp	
14	12B6D-1	2	1770	828	-	Good	-	-	
14	12B6D-2	1	1770	696	345	Good	563	Fair	
14	12B6D-2	2	1770	702	358	Good	585	Fair	
14	Selected Values			680	320		580		
15	15A4-1	1	1770	633	286	Sharp	520	Fair	
15	15A4-1	2	1770	626	302	Sharp	520	Fair	Dilatometer Curve Irregular at M _f
15	Selected Values			630	290		520		
16	16A4-2	1	1770	702	307	Sharp	516	Poor	Vib. or A.C. Pickup in Galv. Curves Dilat. Slipped Near M _s . Thermal Arrest Doubtful
16	16A4-2	2	1770	669	264	Sharp	502	Poor	
16	16A4-1	1	1795	640	282	Sharp	597	Very Poor	Difference Curve Irregular Difference Curve Irregular Thermal Arrest Doubtful Thermal Arrest Doubtful
16	16A4-1	2	1795	640	273	Sharp	601	Poor	
16	16B6-7	1	1795	786	313	Poor	612	Very Poor	
16	16B6-7	2	1795	752	277	Poor	597	Extremely Poor	
16	Selected Values			640	280		510		

TABLE FI (Continued)

Heat No.	Specimen No.	Time Run	Aust. Temp. °F.	Dilatometer		Thermal Arrest		Remarks
				M. of. °F.	Arrest	M. of. °F.	Arrest	
17	17A4-1	1	1770	806	Sharp	635	Fair	Dilatometer Slipped at Ms
17	17A4-1	2	1770	797	Sharp	558	Poor	
17	17A4-3	1	1795	709	Sharp	590	Poor	
17	17A4-3	2	1795	712	Fair	585	Poor	
17	Selected Values			710	330	590		Dilatometer Slipped at Ms
18	18	1	1700	-	Sharp	599	Doubtful	Difference Couple Broke. Galv. Film Fogged
18	18	2	1700	-	Good	-	-	
18	18	3	1700	730	Sharp	540	Very Poor	Thermocouple Welds Defective Note: Third Run on Specimen
18	18B6-4	1	1700	640	Unreadable	570	Poor	
18	18B6-4	2	1700	-	Good	538	Doubtful	Difference Couple Broke
18	18B6-5	1	1740	621	Poor. Irregular Ms	572	Poor. Partial Short	
18	18B6-5	2	1740	622	Sharp	565	Poor	AC Pickup. Thermal Arrest Doubtful
18	18A4-2	1	1740	-	Pin Stuck	520	Extremely Poor	
18	18A4-2	2	1740	628	Good	556	Very Poor	Thermal Arrest Doubtful
18	18A4-2	2	1740	620	Good	570	Very Poor	
19	19B6-3	1	1700	-	Off Scale	583	Poor	Anstemitizing Temp. May Be Too Low
19	19B6-3	2	1700	633	Sharp	561	Poor	
19	19B6-6	1	1740	639	Fair	572	Poor	
19	19B6-6	2	1740	664	Fair	541	Poor	
19	Selected Values			640	220	550		
20	20B6-3	1	1750	831	Sharp	646	Good	Anstemitizing Temp. May Be Too Low
20	20B6-3	2	1750	815	Good	646	Fair	
20	Selected Values			820	430	650		

TABLE VI (Continued)

Heat No.	Specimen No.	Time Run	Aust. Temp. °F.	Dilatometer			Thermal Arrest		Remarks
				M _s °F.	M _f °F.	Arrest	M _s °F.	Arrest	
21	21A4-1	1	1770	595	--	Fair	--	--	Temperature Couple Shorted M _f from Length vs. Steel Temp. Plot Standard Lifted from Dilatometer Not Coded Enough to Get M _f
21	21A4-1	2	1770	624	36	Fair	450	Very Poor	
21	21A4-2	1	1770	--	--	--	437	Extremely Poor	
21	21A4-2	2	1805	570	--	Fair	502	Extremely Poor	
21	Selected Values			570	40		460		
22	22A4-3	1	1770	603	75	Poor. Irreg. near M _s	471	Fair, Double	Therm. Arrest & M _f Doubtful. M _f from Length - Temp. Plot M _f from Length vs. Steel Temp. Plot
22	22A4-3	2	1770	694	126	Fair	464	Extremely Poor	
22	Selected Values			620	90		470		

TABLE FII

Summary of Martensite Temperatures

M_s Determined by Thermal Arrest

M_f Determined Dilatometrically

<u>Heat No.</u>	<u>M_s (°F.)</u>	<u>M_f (°F.)</u>
1	690	430
2	670	440
3	640	390
4	630	400
5	690	440
6	620	360
7	610	410
8	610	340
9	550	270
10	550	310
12	600	370
13	620	330
14	580	320
15	520	290
16	510	280
17	590	330
18	570	220
19	550	220
20	650	430
21	460	40
22	470	90

Direction of Expansion of Specimen

FIGURE 2-1
HEAT TREATING RECORD
HEAT 4, RUN 6-5
TYPICAL OF LOW-ALLOY STEELS

Direction of Expansion of Specimen

Cooling Record

$M_s \downarrow$

$M_s \uparrow$

Temperature

Direction of Specimen / Increasing Temperature

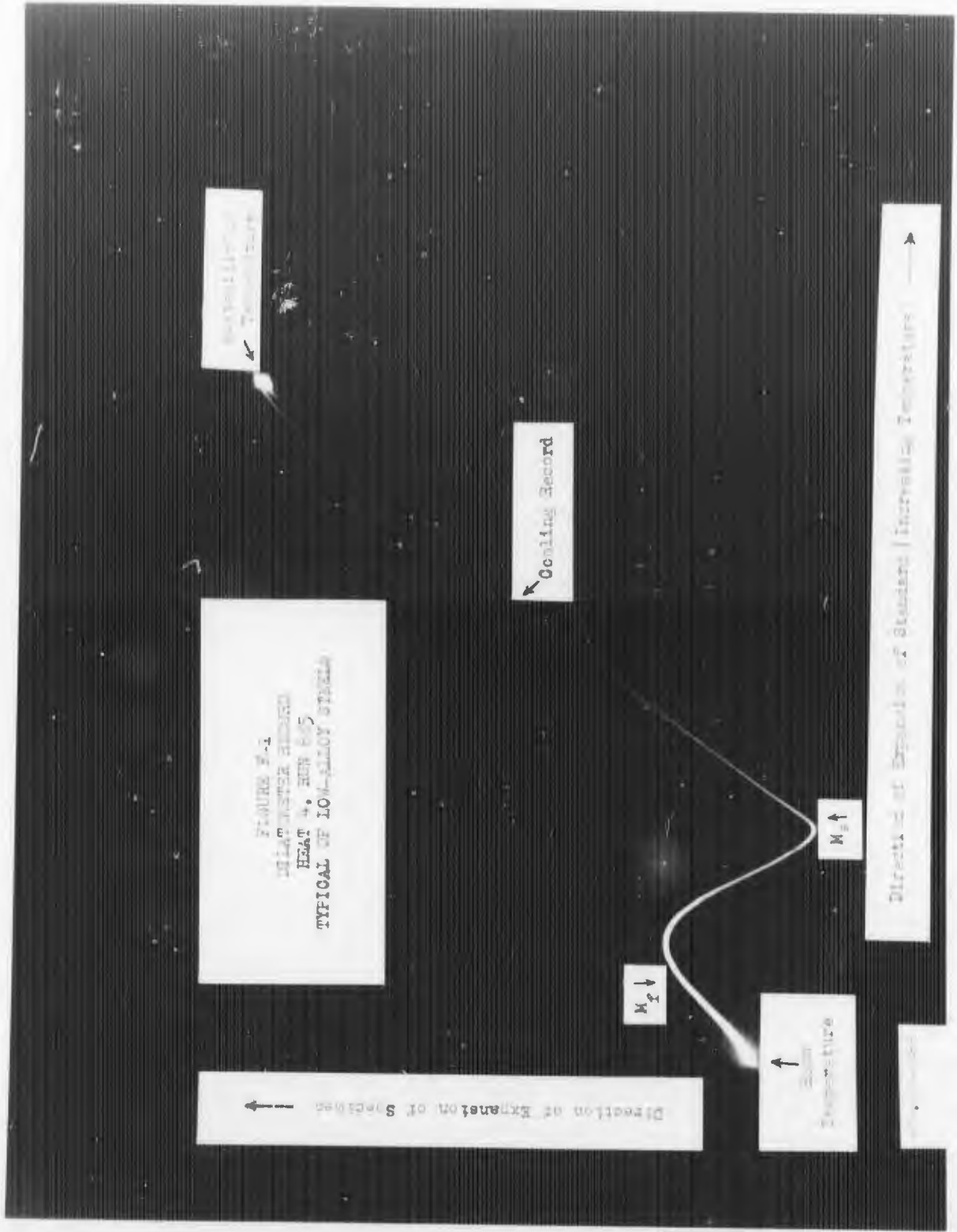


FIGURE P-2
DILATOMETER RECORD
HEAT 21, RUN 630
TYPICAL OF HIGH-ALLOY STEELS

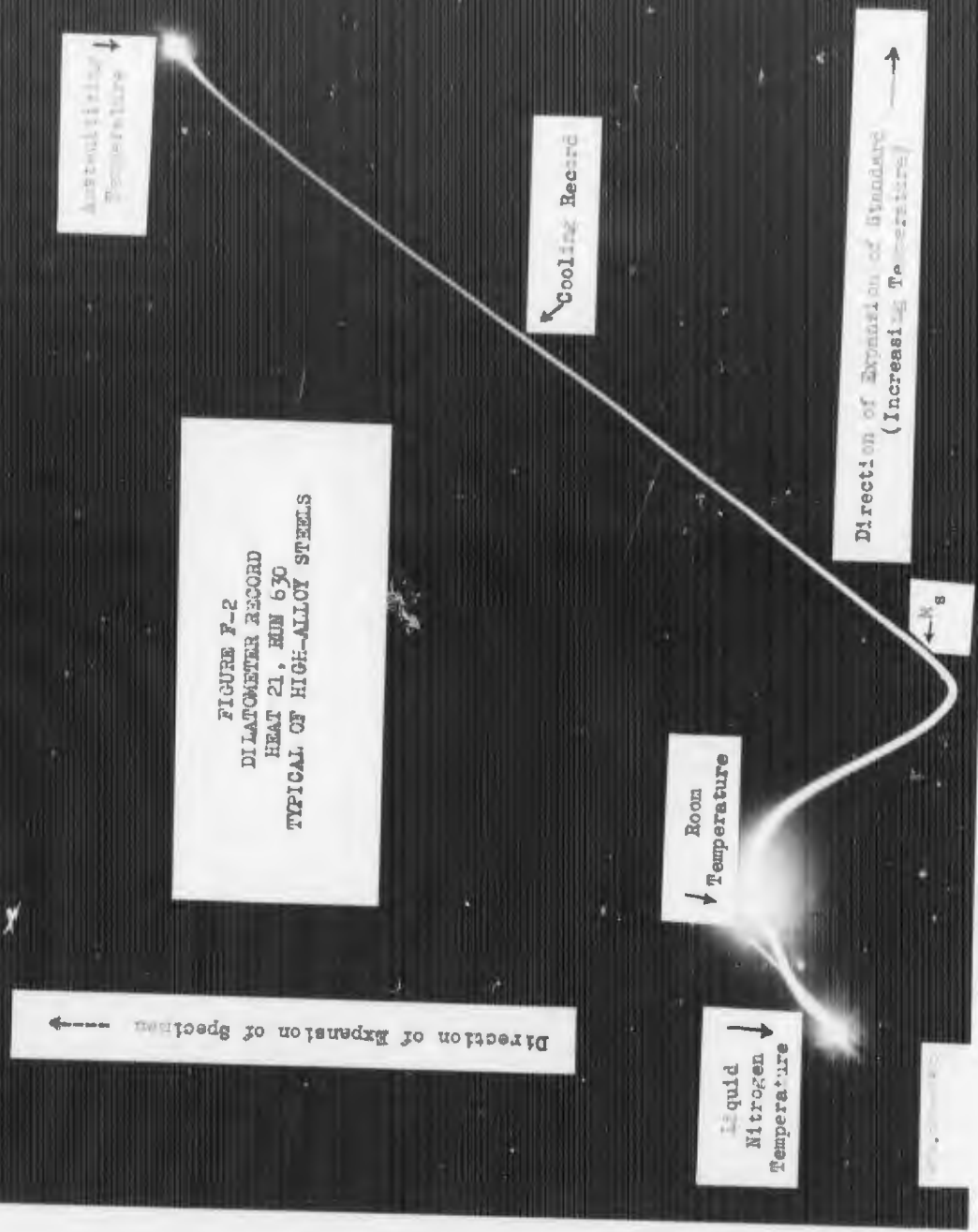


FIGURE F-7
GALVANOMETER RECORD
HEAT 4, RUN 685
TYPICAL OF LOW-ALLOY STEELS

Austenitizing
Temperature

Temperature
Curve

Differential
Calibration
Line

M_s

Differential
Curve

Differential
Zero Line

Room Temperature Line

Direction of Increasing Time

Direction of Increasing Temperature and Temperature Difference

WTN.639-6957

Direction of Increasing Temperature and Temperature Difference ←

Austenitizing Temperature ↘

Differential Calibration Line →

Differential Zero Line ↓

Differential Curve (Cooling from austenitizing to room temperature) ↘

Temperature Curve (Cooling from room to liquid nitrogen temperature) ↘

FIGURE 1-4
CALCULATED AREA
HEAT 21, RUN 670
TYPICAL OF HIGH-ALLOY STEELS

Direction of Increasing Time →

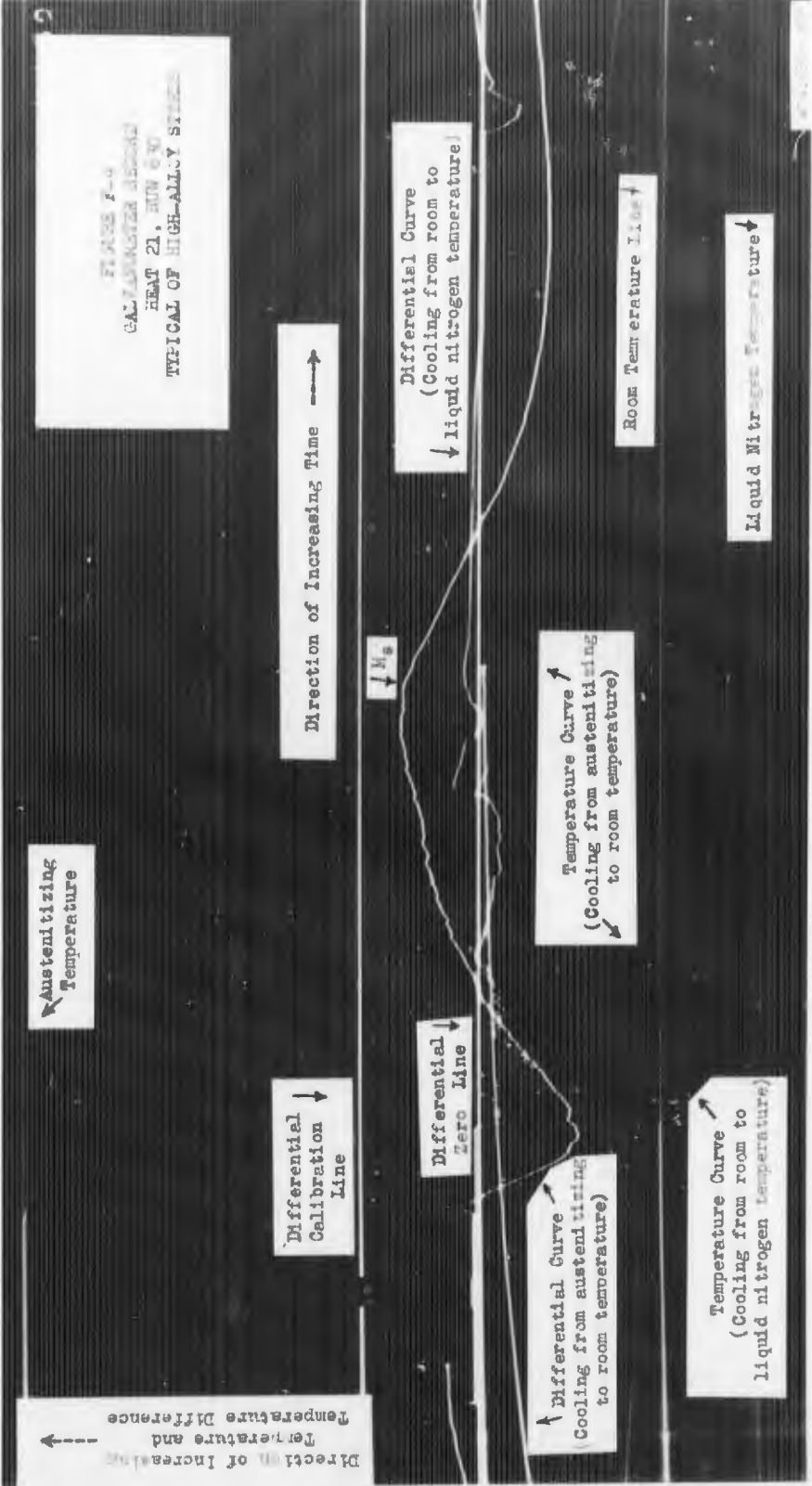
M_s ↓

Differential Curve (Cooling from room to liquid nitrogen temperature) ↓

Temperature Curve (Cooling from austenitizing to room temperature) ↘

Room Temperature Line ↓

Liquid Nitrogen Temperature ↓



APPENDIX G

Small Section Results

APPENDIX G

Small Section Results

As has been explained in the body of this report, it was desired to determine the properties obtained with the various heats in small sections.

Two 11/16-inch diameter, 5-inch long, impact blanks from each heat were given what was considered the optimum treatment. This consisted of austenitizing for four hours at the temperature selected as described in Appendix C, quenching, cooling to a temperature considered to be certainly below the M_f , tempering for four hours at approximately the temperature selected as explained in Appendix D, and quenching from the tempering temperature. The impact blanks were placed in previously heated furnaces and allowed one-half hour to one hour to reach temperature. Water was used for quenching, both from the austenitizing and from the tempering temperature, for heats 1, 2, 4, and 5, which had low hardenability and were not considered likely to quench-crack, and oil was used for the other heats, which it was thought were likely to crack. These quenches, it was believed, would entirely prevent the formation of ferrite, pearlite and bainite.

After heats 1 through 6 were quenched from the austenitizing temperature, they were given no cold treatment; heats 7 through 10, 17, 18, and 20 were cooled to approximately -100°F . in dry ice and alcohol, while heats 12 through 16, 19, and 21 through 25 were cooled to about -320°F . in liquid nitrogen.

In order to find out whether retained austenite was likely to be a problem, one or two impact blanks from heats 7 through 22 were given the optimum treatment outlined above, except that the cold-treatment was omitted. To determine whether the heats under study are susceptible to temper-embrittlement, one or two blanks from each heat were given the optimum treatment, including sub-zero cooling where specified, but were furnace-cooled instead of quenched from the tempering temperature.

It is difficult to match the air-cooling of a heavy plate with a small specimen, so no delayed-quenches were made on the impact blanks. As a substitute, quenches stepped at 1000°F . were used. Two impact blanks from heat 6, a 3-inch plate, and from each of heats 10, 12 and 17 (6-inch plates) were quenched into molten salt at 1000°F . and then into oil at room temperature. The time at 1000°F . was chosen as somewhat more than the estimated time for a full-sized plate to cool from the austenitizing temperature to 1000°F ., being 45 minutes for heat 6 and 90 minutes for heats 10, 12, and 17. The sub-zero cooling, the tempering and the cooling from the temper were the same as those used in the optimum treatment.

After heat-treatment, two standard .394 inch square Charpy bars, having a V-notch with .010 inch base radius, were machined from each impact blank. Where two impact blanks from a heat had received identical heat-treatments, the Charpy bars from one were broken at -40°F . and those from the other at room temperature. Where a heat-treatment was represented by a single impact blank, the Charpy bars cut from it were tested at -40°F .

The results obtained are given in detail in Tables GI, GII, and GIII and summarized in the body of this report. The system used for rating fractures is given in Table GIV.

It will be noted that the blanks from heats 3, 6, 10, 18, 19, and 20 were retreated before test. This was necessary because the original tempering temperature was based upon the results obtained with temper bars that were not ground sufficiently to remove all decarburized surface before their hardnesses were measured. (See Appendix D.) As a result, the impact blanks were too hard after the original heat-treatment. When the trouble was detected, new temper bars were run and the impact blanks requenched and tempered at the tempering temperatures found with these new bars.

Heat 19 was the first heat in which difficulty was encountered in softening the quenched steel to Rockwell C 26. The impact blanks were requenched and retempered twice in an effort to obtain minimum hardness without exceeding the A_{c1} temperature on the draw.

Heat 9 was requenched and retempered because the furnace was accidentally turned off during the original tempering cycle.

On heats 7 and 8, there was some confusion, contradictory results being obtained on repetition of the temper bar runs. It is possible that a group of these bars was not properly quenched. As a result, the impact blanks were first thought to be too hard and were retreated, but after machining were then found too soft, so a new set of blanks were obtained and treated. On heat 9, the Charpy specimens were also found too soft, perhaps for the same reason, and a second set was taken from this heat also.

The Charpy values found on heat 23, even with the optimum treatment, were abnormally low. The A_{c1} temperature might have been exceeded in tempering the specimens of this heat. A new set of blanks was, therefore, obtained and treated, using a tempering temperature 5°F. lower. The energy absorption obtained with the optimum treatment improved but was still low. The poor impact property values found are probably associated with the conchoidal fractures^{1,2,3} that occurred with varying severity in almost all Charpy bars from heat 23. Most of the Charpy bars tested were slightly (perhaps .002 inch) out of square, but it is not believed that this affected the results.

A nominal variation of $\pm 5^{\circ}\text{F.}$ from the predicted temperatures of Appendix D was allowed to facilitate scheduling of the heat treatment. However, fluctuations and errors of temperature control in the various furnaces that had to be used for tempering were undoubtedly greater.

1. G. W. Austin; "Burnt Alloy Steels". Iron and Steel Institute, Alloy Steels Research Council, First Report, 189-211 (1936).
2. A. Hurlich; "Effects of the Conchoidal Fracture upon the Physical and Metallurgical Characteristics of Cast Armor". Watertown Arsenal Laboratory Report, WAL 710/413. 1943.
3. C. Lorig, G. K. Manning, A. R. Elsea, and P. S. Rosenthal; "Final Report on Improvement of Low-Alloy Armor Steels. Part VII - Causes of Intergranular Fracture in Cast Armor Plate". National Defense Research Committee, Report M-286. Watertown Arsenal Report 710/446-13. 1944.

TABLE GII

IMPACT RESULTS OF SPECIMENS AIR COOLED FROM TEMPER IN 1" ROUNDS

OIL QUENCHED AND COOLED TO INDICATED TEMPERATURE. AIR COOLED FROM TEMPER IN 1" ROUNDS.

HEAT NO.	TESTED AT ROOM TEMPERATURE			TESTED AT -40°F			TEMP. OF COOLING
	FOOT POUNDS	FRAC-TURE	RC HARDNESS	FOOT POUNDS	FRAC-TURE	RC HARDNESS	
12				18.1	Cdf	25.5 25.5 25.0	-320°F
AVE. VALUES				25.2	Cdf	26.5 23.5 25.5	
				21.8	Cdf	25.2	
13				26.8	Fc	23.5 23.5 23.5	-320°F
AVE. VALUES				22.2	Fc	25.0 24.5 23.5	
				24.5	Fc	23.9	
15				20.8	Fc	30.5 31.0 30.0	-320°F
AVE. VALUES				21.5	Fc	30.5 31.5 31.0	
				21.2		30.8	
16				27.3	Fc	30.5 29.5 29.5	-320°F
AVE. VALUES				26.5	Fc	31.5 31.0 29.5	
				27.0	Fc	30.3	
19 ^{aa}	43.7	Fc	28.5 28.0 29.0	35.8	Fc	27.5 27.5 27.5	-320°F
AVE. VALUES	40.4	Fc	27.5 28.5 27.5	39.1	Fc	28.5 27.5 28.0	
	42.1	Fc	28.0	37.5	Fc	28.0	
20 ^a				61.9	F	23.5 24.5 24.5	-100°F
AVE. VALUES				60.9	F	23.5 24.0 24.5	
				61.4	F	24.1	
21	25.6		30.5 31.5 31.5	15.3	Fc	32.0 31.5 30.5	-320°F
AVE. VALUES	24.6		30.5 31.5 31.5	18.9	Fc	29.5 31.5 30.5	
	25.1		31.1	17.1	Fc		
22	22.2	Fc	29.5 30.5 28.5	22.0	Fc	29.5 29.5 30.0	-320°F
AVE. VALUES	26.4	Fc	30.0 29.5 29.5	18.5	Fc	29.0 29.5 29.0	
	24.3	Fc	29.6	20.3	Fc	29.6	
23	20.2	Cbf	26.5 27.5 26.5	8.5	Cb	26.5 27.5 28.0	-320°F
AVE. VALUES	19.4	Cbf	26.5 27.5 28.5	7.7	Cb	27.0 28.5 28.0	
				8.1			
23 ^b	20.5	Fc	25.0 26.5 25.5	10.1	Fc	23.5 23.5 23.0	-320°F
AVE. VALUES	17.4	Fc	24.5 25.5 25.0	8.9	Fc	23.0 24.5 22.5	
	19.0	Fc	24.3	9.5	Fc	24.3	
24	26.4	Obf	26.0 26.0 26.0	15.5	Cb	27.5 28.0 28.5	-320°F
AVE. VALUES	25.3	Cbf	27.0 26.5 27.0	17.4	Cbf	28.0 28.0 27.0	
	25.8	Cbf	27.1	16.4	Cbf	27.1	
25	29.2	Fc	27.5 27.5 28.0	17.4	Cb	29.5 29.5 28.5	-320°F
AVE. VALUES	26.8	Fc	27.5 28.5 28.5	16.8	Cb	29.0 29.5 29.5	
	28.0	Fc	28.6	17.1	Cb	28.6	

x - SEVERE SHRINKAGE
 xx - DENDRITE
 xxx - CONCHOIDAL
 a - 2ND HEAT TREATMENT
 aa - 3RD HEAT TREATMENT
 b - ADDITIONAL BARBS MADE AND HEAT TREATED

TABLE GIII
IMPACT RESULTS OF STEPPED QUENCHED SPECIMENS

STEPPED QUENCHED AND COOLED TO INDICATED
 TEMPERATURES, OIL QUENCHED FROM TEMPER.

HEAT NO.	TESTED AT ROOM TEMPERATURE			TESTED AT -40°F.			TEMP. OF COOLING
	FOOT POUNDS	FRAC-TURE	RC HARDNESS	FOOT POUNDS	FRAC-TURE	RC HARDNESS	
6 _a	45.3	F	27.5 27.5	40.2	F	26.5 26.0 27.0	ROOM TEMP
	45.8	F	28.0 27.5	40.4	F	26.0 26.5 27.5	
AVE. VALUES	45.6	F	27.0	40.3		27.0	
10 _a	47.5	F	27.5 27.5	44.1	F	26.5 26.5 25.5	-100°F.
	45.4	F	27.5 27.5	44.2	F	24.0 26.5 27.5	
AVE. VALUES	46.5	F	26.7	44.2	F	26.7	
12	54.7	F	27.0 26.0 26.0	34.5	Gdf	26.0 26.5 25.5	-320°F
	52.8	F	26.0 26.5 26.5	36.6	Gdf	26.0 26.5 26.0	
AVE. VALUES	53.8	F	26.2	35.6	Gdf	26.2	
17	58.2	F	23.0 23.0 23.0	55.5	F	22.5 25.0 25.5	-100°F
	58.4	F	23.5 24.0 23.5	60.2	F	25.5 26.5 26.0	
AVE. VALUES	58.3	F	24.3	57.9	F	24.3	

XX - DENDRITIC
 a - END HEAT TREATMENT

TABLE GIV

Standard Types of Notched Bar Impact Fractures

<u>SYMBOL</u>	<u>DESCRIPTION</u>
F	Fibrous
S	Silky (generally encountered with steels of high hardness)
Fc	Fibrous matrix with spots of crystallinity
Odf	Dull crystalline patch surrounded by fibrous border
Obf	Bright crystalline patch surrounded by fibrous border
Od	Dull crystalline (complete)
O _b	Bright crystalline (complete)

Note 1: Additional terms such as: dendritic, conchoidal, etc., used to describe the fractures, should be written out in full following the fracture type symbol.

Note 2: If it is desired to estimate the relative amounts of fibrous and crystalline surface areas, a fraction will be placed following the fracture symbol. This fraction will refer to the estimated surface area which is crystalline.

APPENDIX H

Large Section Results

APPENDIX H

Large Section Results

I. Preparation of Plates for Heat Treatment

Three 1.9 inch diameter cylindrical sections were welded into 2.0 inch diameter holes drilled in the 3 inch and 6 inch thick plates and one 0.95 inch diameter round was welded into a 1.0 inch diameter hole drilled in the 6 inch plates. The purpose of the 1.9 inch diameter inserts was to reduce the number of heat treatments to one third that would otherwise be required. After the quenching of the plate and the removal of the inserts, each insert was tempered differently: one was cooled to a predetermined subatmospheric temperature for the purpose of transforming any retained austenite which might be present to martensite, one was step-tempered at 600° F. for the purpose of transforming retained austenite to low-temperature bainite, and the third was tempered directly to obtain a hardness of Rockwell C 26. The other two insert bars were also tempered to approximately this hardness after the preliminary treatment.

The 0.95 inch diameter insert was used to determine the nature of the austenite decomposition products and the hardnesses produced by the cooling rates prevalent in 6 inch thick sections. This insert was not given any tempering or cold treatment.

The problem arose of designing a method of sealing the inserts in the 3-and-6-inch plates, so that no leakage of water could occur upon quenching, it being necessary to confine the heat extraction to the ends of the inserts. Shallow penetration welds using both ferritic and 18 Cr-8-Ni welding electrodes were found inadequate for the purpose. The method finally selected is illustrated in Figure H I, which shows the details of the welding sequence, dimensions, and the gap between the inserts and the plates. The air gap or discontinuity in metal between the insert and the plate effectively reduces the heat transfer from the insert parallel to the plate so that the cooling rates of the inserts approximate those of infinite plates. A 45° countersink was made to a depth of 1/2 inch at each end of the holes into which the inserts are welded. All plates were preheated to some temperature in the range of 500-700° F., by means of a propane torch and the inserts welded into position by multiple-bead deposits of 25 Cr-20 Ni weld rod. Leakage did occur, however, in many instances upon quenching of the 6-inch thick plates. The consequences of such leakage will be discussed later. Inserts around which no leakage occurred were used for the subatmospheric cooling treatment in order to establish the optimum hardenability characteristics of the various heats.

II. Schedule of Heat Treatments

The 23 plates, representing the 21 heats numbered 1 through 22 with the omission of heat 11, were directly quenched into water from the austenitizing temperatures. The plates were removed from the water when the ambient temperature was reached, and then subjected to the treatments listed in Table XII, Part A, which is a part of Section III of the body of the report.

After the completion of the above treatments, some of the plates were heat treated by delayed and interrupted quenches after new inserts had been welded into them. These treatments are outlined in Table XII, Part B. Other

plates were quenched and tempered with the inserts in position to determine if the cooling rates obtained by water quenching 6 inch thick sections are sufficiently rapid to avoid temper embrittlement.

Because plate Number 10 quench-cracked severely upon being directly quenched from the austenitizing temperature, plate Number 11 was used for the heat-treatment of the additional inserts from plate Number 10. Plate Number 11 differed only slightly in chemical analysis from plate Number 10, consequently the substitution should have no appreciable effect upon the results.

The inserts from plates Numbers 7, 8, and 9 were heat treated in plate Number 12 in an attempt to find the lower limit of the alloy content necessary for obtaining the same properties in a 6-inch section that were obtained in small sections, because all of the 6-inch plates made for the experimental program were found to be capable of accomplishing this end. Details of the quenching and tempering treatments given each plate and insert are contained in Table H-I.

III. Heat Treating Equipment

The plates were heated to the hardening temperatures in a gas-fired hearth furnace. The plates were charged into the cold furnace and came up to temperature with the furnace in approximately 3 hours. After being held at temperature for 4 to 6 hours, the plates were removed and quenched in the vertical position. The quenching tank consisted of a cylindrical unit 12 feet deep and 5 feet in diameter, having a capacity of 1700 gallons. A flow of approximately 450 gallons/minute was maintained during every quench conducted, the water entering at the bottom and rising in a spiral stream to overflow into the outlet at the top of the tank. The water temperature remained in the range of 55° F. to 65° F. during the entire time that the heat-treatments were being conducted. The plates were quenched individually and immersed to a depth of approximately 6 feet below the surface.

The plates were not removed from the quenching tank until they were cold to the touch. The length of time required to cool the plates from their austenitizing temperatures to the ambient temperatures were as follows:

<u>Plate Thickness</u> <u>Inches</u>	<u>Time to Cool to</u> <u>Water Temperature,</u> <u>Minutes</u>
1-1/2	6
3	10-14
6	40

After being quenched, the 1-1/2 inch thick plates were tempered in a gas-fired hearth furnace. The inserts welded into the 3-inch and 6 inch thick plates were removed by being pushed out under a 400 ton, steam-powered press. Between 100 and 150 tons pressure was required to cause shear failure of the welds. The inserts which were cooled to -75° C. (-100° F.) were immersed in a mixture of solid carbon dioxide and acetone, whereas those cooled to -190° C. (-310° F.) were immersed in liquid nitrogen. The inserts were maintained at temperature for a minimum time of 10 minutes. The inserts were generally

cooled to below room temperature within two hours after being quenched. The effect of aging at room temperature prior to subatmospheric cooling upon the transformation characteristics of austenite in the alloy steels under consideration is uncertain. Cohen and Gordon¹ have found that, in high speed steel, aging at room temperature, although lowering the temperature at which austenite transformation begins, does not depress the temperature of completion of the transformation. If the same phenomenon holds for lower-alloy steels, then the aging at room temperature prior to subatmospheric cooling should not affect the results, because the subatmospheric temperatures were, in all cases, lower than the M_s temperatures.

The inserts which were step-tempered at 600° F. were placed in a 6KW Lindberg Cyclone tempering furnace and then given the finish temper in a 12 KW Lindberg Cyclone tempering furnace, if the tempering temperature was below 1225° F., or in a 24 KW Lindberg box-type furnace, if the tempering was 1225° F. or higher. The inserts were tempered for 4 hours at temperature, and generally required 1 hour to reach the tempering temperatures.

IV. Impact Tests

Four V-notch Charpy impact bars were machined from the midsection of each of the 1-1/2 inch plates, and from the middle of each 1.90 inch diameter insert bar in the 3 inch and 6 inch thick plates and were notched so that the bases of the notches corresponded to the midsection of the plates and inserts. Two were tested at room temperature and two at -40° F. The fractured surfaces of the impact bars were rated in accordance with the standard nomenclature listed in Table G II, Appendix G. Three Rockwell C hardness readings were made on each Charpy bar after it had been broken. The individual values of the Charpy impact results, hardness readings and fracture ratings are contained in Tables H II and H III.

The effect of leakage of water into the spaces between the holes and the inserts was of grave concern since it could not be readily determined what effect the leakage had upon the cooling rate and the transformation during quenching. No difficulties were experienced in the case of the 3 inch thick plates; all inserts upon removal had clean bright surfaces indicating completely air-and-water-tight closures during and after quenching. All the weld-cracking difficulties were confined to the 6 inch plates. However, at least one, and in many cases two of the inserts in the 6 inch plates showed no evidence of leakage, and consequently the transformation characteristics could be determined from the results obtained on the inserts which did not leak. It was determined subsequently that the leakage did not materially affect the results, because the impact values obtained on the inserts which did show signs of leakage were exactly in line with the expectations based upon logical considerations and upon the results obtained when no leakage occurred. The leakage apparently occurred late in the quenching operation, at which time any change in the cooling rate occasioned by leakage could not affect the austenite decomposition to bainite. It is quite possible, however,

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1. P. Gordon and M. Cohen:
"The Transformation of Retained Austenite In High-Speed Steel at Subatmospheric Temperatures." Trans. A. S. M., 30, (Number 3), 569-587 (September, 1942).

that the degree of completion of the austenite decomposition to martensite was affected by the leakage. The discrepancy between the retained austenite effect observed in the small sections and the relatively negligible effect observed in the full sized section results may be, in many cases, traced to the effects of the leakage, which may have caused a more complete transformation to martensite than would otherwise have occurred. In addition, the much lower heating rates of the 1.90 inch diameter inserts during tempering as compared to those of 1 1/16 inch diameter rounds may have aided in the transformation of austenite to the lower temperature bainites which have satisfactory impact properties.

V. Microscopic Surveys of Inserts

The 0.95 inch inserts which were quenched in the 6 inch plates were ground and polished and subjected to microscopic examination in accordance with the technique described in Appendix E. Rockwell C hardness surveys were also made along ground flats to determine the variation in hardness through the cross section of the 6 inch plates produced by quenching. In essence, the 0.95 inch inserts provided data which is an extension of the data obtainable from the standard Jominy hardenability test to slower cooling rates than are obtained in the air cooled end of the Jominy test specimen.

No hardenability inserts were necessary in the 3 inch plates because the cooling rate in the center of a water-quenched 3 inch plate corresponds to that occurring at approximately 1-1/2 inches from the water quenched end of the Jominy bar, hence the amount of transformation products other than martensite present in the middle of a 3 inch plate can be predicted from an examination of the Jominy bar. The center cooling rate of a 1-1/2 inch thick plate upon water quenching is equivalent to that at 1/2 inch from the water quenched end of the Jominy bar.

Hardness traverses of the 0.95 inch inserts are contained in Table H IV. Examination of these results indicates that in no cases did the hardness decrease through the cross section.

The results of the microscopic examination of the 0.95 inch inserts are summarized in Table H V. Intermediate temperature transformation products were found only in the inserts from heats 9, 10, and 20. Structures which have been identified as tempered martensite (see appendix E) were observed in all inserts except those from heats 21 and 22.

VI. Quench-Cracking

No quench-cracking was experienced in the direct quenching of either the 1-1/2 inch or the 3 inch plates. Quench-cracking did occur in several of the 6 inch plates. Figure H2 contains drawings of all plates which quench-cracked, and shows the locations of all cracks. It will be noted that, except in the cases of plates numbered 10, 18, 21 and 22, the cracking is confined to the projecting shrink head and to the side of the plate, immediately under the projecting shrink head. An extensive amount of shrinkage porosity was evident at the re-entrant angle between the plate and the projection, and it was this extensive network of porosity which was obviously responsible for the quench-cracking occurring in this region. Plates numbered 21 and 22 quench-cracked severely upon being quenched cold, but these plates contain 0.39 per cent and 0.375 per cent carbon respectively, in addition to being very high in both nickel and chromium. Plate Number 18 contains 0.34 per cent carbon and plate Number 10, 0.32 per cent carbon. Quench-cracking is thus confined to the higher carbon heats.

TABLE HI

Heat Treatments of Plates and Inserts

<u>Plate No.</u>	<u>Thick-ness Inches</u>	<u>Austenitizing Temp. °F.</u>	<u>Length of Time at Temp. Hrs.</u>	<u>Length of Time in Water to Quench Cold Minutes</u>	<u>Tempering Temperature °F.</u>	<u>Tempering Cycle Hrs. Rise Hrs. Hold</u>	<u>Coolant</u>
*1	1½	1650	4	6	1165	2 4	Water
2	1½	1650	4	6	1165	2 4	Water
4	1½	1650	4	6	1165	2 4	Water
5	1½	1650	4	6	1165	2 4	Water

*These four plates were austenitized and tempered together, but were quenched individually. The entire plates were quenched and tempered and the Charpy impact bars machined from the midsection of the plates.

TABLE HI (Continued)

Insert No.	Plate Hole No.	Aust. Temp. °F. & Length of Hold	Time in Water Minutes	Condition of Insert When Removed from Plate	Elapsed Time between Quench and Sub-cooling	Sub-cooling Temp. °C.	Step Temp. °F.	Time in Furnace for Step Temp.	Tempering Temp. °F.	Length of Time in Tempering Furnace Hours	Cool from Temper	Remarks
Plate No. 2 (3" Thick)												
2B2	A	1650 5 hrs.	10	dry	-	-	-	-	1155	5	water	3/8" countersink
2B1	B	"	"	dry	-	-	-	-	1155	5	air	25-20 Cr-Ni
2B2	C	"	"	dry	-	-	-	-	1155	5	furnace	electrodes
Plate No. 3												
3P1	A	1650 4 hrs.	10	dry	-	-	-	-	1205	5	water	18-8 Cr-Ni
3P2	B	"	"	dry	-	-	-	-	1205	5	air	electrodes
3P1	C	"	"	dry	-	-	-	-	1205	5	furnace	1/4" countersink
Plate No. 5 (3" Thick)												
5B1	A	1650 5 hrs.	10	dry	-	-	-	-	1155	5	water	3/8" countersink
5B2	B	"	"	dry	-	-	-	-	1155	5	air	25-20 welds
5B2	C	"	"	dry	-	-	-	-	1155	5	furnace	
Plate No. 6 (Direct Quench)												
6P1	A	1650 4 hrs.	10	dry	-	-	-	-	1205	5	water	18-8 Cr-Ni
6P2	B	"	"	dry	-	-	-	-	1205	5	air	electrodes
6B1	C	"	"	dry	-	-	-	-	1205	5	furnace	1/4" countersink

TABLE HI (Continued)

Insert Hole No.	Plate No.	Anst. Temp. °F. & Length of Hold	Time in Water Minutes	Condition of Insert When Removed from Plate	Elapsed Time between Quench and Sub-cooling	Sub-cooling Temp. °C.	Step Temp. °F.	Time in Furnace for Step Temp.	Tempering Temp. °F.	Length of Time in Tempering Furnace Hours	Cool from Temper	Remarks
<u>Plate No. 6 (Delayed Quench)</u>												
6R2	A	1650 5 hrs.	20 min.	dry	-	-	-	-	1210	5	water	3/8" countersink 25-20 Cr-Ni electrodes
6X1	B	"	10 min.	dry	-	-	-	-	1210	5	air	Plate cooled in air from 1650°F. to 950-1000°F.
6Y1	C	"	"	dry	-	-	-	-	1210	5	furnace	on surface in 20 minutes, then water quenched cold.
<u>Plate No. 7 (Direct Quench)</u>												
7P1	A	1700 4 hrs.	12	dry	40 min.	-75	-	-	1220	5	water	18-8 Cr-Ni electrodes
7P2	B	"	"	dry	-	-	600	4	1220	4	water	
7R1	C	"	"	dry	-	-	-	-	1220	5	water	1/4" countersink
<u>Plate No. 7 (Delayed and Interrupted Quench)</u>												
7R2	A	1700 4 1/2 hrs.	45 min.	dry	-	-75	-	-	1220	5	water	25-20 Cr-Ni electrodes 3/8" countersink
7Q1	B	"	-	dry	-	-	600	3	1220	4	water	Plate air cooled from 1700° to 1000° on surface in 15 min., water quenched for 3 min., held in air for 2 min., water quenched 10 min.
7O2	C	"	-	dry	-	-	-	-	1220	5	water	

TABLE HI (Continued)

Insert Hole No.	Plate No.	Aust. Temp. °F.	Length of Hold	Time in Water Minutes	Condition of Insert When Removed from Plate	Elapsed Time between Quench and Sub-cooling	Sub-cooling Temp. °C.	Step Temp. °F.	Time in Furnace for Step Temp.	Temper-ing. °F.	Length of Time in Tempering Furnace Hours	Cool from Temper	Remarks
<u>Plate No. 8 (Direct Quench)</u>													
8F1	A	1700	4 hrs.	12	dry	23 min.	-75	-	-	1220	5	water	18-8 Cr-Ni
8F2	B	"	"	"	dry	-	-	600	4	1220	4	water	electrodes
8F3	C	"	"	"	dry	-	-	-	-	1220	5	water	
<u>Plate No. 8 (Interrupted Quench)</u>													
8F2	A	1700	5 hrs.		dry	45 min.	-75	-	-	1220	5		25-20 Cr-Ni electrodes
8F1	B	"	"		dry	-	-	600	3	1220	4		Plate, water quenched for 4½ min., held in air for 2 min., water quenched 12 min.
8F2	C	"	"		dry	-	-	-	-	1220	5		
<u>Plate No. 9</u>													
9F1	A	1725	5 hrs.	14	dry	2 hrs.	-75	-	-	1205	5	water	18-8 Cr-Ni electrodes
9F2	B	"	"	"	dry	-	-	600	3	1205	5	water	3/8" countersink
9F1	C	"	"	"	dry	-	-	-	-	1205	5	water	
<u>Plate No. 10 (Direct Quench)</u>													
10F1	A	1675	4 hrs.	35	wet	-	-	600	3	1225	4½	oil	18-8 Cr-Ni welds
10F1	B	"	"	"	dry	15 min.	-75	-	-	1225	5	oil	1/4" countersink plate quench
10F1	C	"	"	"	wet	-	-	-	-	1225	5	oil	cracked severely

TABLE HI (CONTINUED)

Insert No.	Plate No.	Ans. Temp. of Length of Hold	Time in Water Minutes	Condition of Insert When Removed from Plate	Elapsed Time between Quench and Sub-cooling	Sub-cooling Temp. °C.	Step Temper. °F.	Time in Furnace for Step Temper.	Temper. °F.	Length of Time in Tempering Furnace Hours	Cool from Temper	Remarks
<u>Plate No. 12 (Inserts from Heats 7, 8, 9, Heat-treated in 6" Thick Plate)</u>												
721	A	175 4 hrs.	40	wet	3/4 hrs.	-75	-	-	1215	5	water	25-20 Cr-Ni electrodes Heat treatment performed to determine lower alloy content limit necessary for hardening 6" sections.
821	B	"	"	wet	"	-75	-	-	1215	5	water	6" long inserts were machined from remaining section of heats 7, 8, 9.
921	C	"	"	wet	"	-75	-	-	1215	5	water	
922	D	"	"	wet	-	-	-	-	-	-	-	
<u>Plate No. 11 (Delayed Quench)</u>												
1002	A	1700 6 hrs.		dry	1 hr.	-75	-	-	1225	5	water	25-20 Cr-Ni Welds 1/2" countersink Plate air cooled from 1700° to 1000°F on surface in 30 min., water quenched for 40 min.
1001	B	"		dry	-	-	600	3 1/2	1225	4	water	
1002	C	"		dry	-	-	-	-	1225	5	water	
1001	D	"		dry	-	-	-	-	-	-	-	
<u>Plate No. 11 (Inserts Tempered in Plate)</u>												
1021	A	1675 5 hrs.	40	dry								Entire plate tempered: Step temper - 600°F. - 2 hrs. rise - 3 hrs. hold. Final temper - 1225°F. - 2 hrs. rise - 4 hrs. hold. Plate quenched in water after final temper.
1022	B	"	"	dry								25-20 Cr-Ni Welds 1/2" countersink
1023	C	"	"	wet								

*Plate No. 11 substituted for plate No. 10 because of severe cracking of No. 10. Inserts from heat No. 10 were welded into Plate No. 11.

TABLE III (Continued)

Insert No.	Plate No.	Insert Hole No.	Aust. Temp. °F. & Length of Hold	Time in Water Minutes	Condition of Insert When Removed from Plate	Elapsed Time between Quench and Sub-cooling	Sub-cooling Temp. °C.	Step Temper. °F.	Time in Furnace for Step Temper. °F.	Tempering in Furnace Hours	Cool from Temper	Remarks
<u>Plate No. 14</u>												
14M	A		175 1/2 hrs.	40	dry	1 1/2 hrs.	-190	-	1200	5	water	
14E2	B		"	"	Slightly wet	-	-	600	3	4	water	18-8 Cr-Ni Welds
14O1	C		"	"	Slightly wet	-	-	-	1200	5	water	1/2" countersink
14J1	D		"	"	Slightly wet	-	-	-	-	-	-	-
<u>Plate No. 15 (Direct Quench)</u>												
15M	A		175 1/4 hrs.	40	dry	2 hrs.	-190	-	1230	5	water	25-20 Cr-Ni Welds
15E1	B		"	"	dry	-	-	600	3	4 1/2	water	
15O1	C		"	"	Slightly wet	-	-	-	1230	5	water	1/2" countersink
15J1	D		"	"	dry	-	-	-	-	-	-	-
<u>Plate No. 15 (Inserts Tempered in Plate)</u>												
10O1	A		175 5 hrs.	40	Slightly wet	-	-	-	-	-	-	-
15E2	B		"	"	dry	-	-	-	-	-	-	-
17O2	C		"	"	dry	-	-	-	-	-	-	-
17J1-2	D		"	"	-	-	-	-	-	-	-	-

Entire plate tempered:
 Step temper - 600°F., 2 hrs. rise - 3 hrs. hold.
 Final temper - 1225°F., 2 hrs. rise - 4 hrs. hold.
 Plate water quenched after temper.

25-20 Cr-Ni Welds

TABLE III
FULL SECTION RESULTS

QUENCHED TO ROOM TEMPERATURE

Heat No.	QUENCHED TO ROOM TEMPERATURE						HEAT TREATED - AIR COOLED FROM TEMPER						HEAT TREATED - FURNACE COOLED FROM TEMPER								
	Tested at -100° C.			Tested at -50° C.			Tested at -10° C.			Tested at 10° C.			Tested at 50° C.			Tested at 100° C.					
	Spec. No.	Fracture	Hardness Rc	Spec. No.	Fracture	Hardness Rc	Spec. No.	Fracture	Hardness Rc	Spec. No.	Fracture	Hardness Rc	Spec. No.	Fracture	Hardness Rc	Spec. No.	Fracture	Hardness Rc			
1.	1A-1	Chf	14.8	21.5	21.5	19.5	Chf														
	1A-2	Chf	17.5	18.5	19.5	Chf															
	Average		36.9	21.0	21.0	21.0															
	2B-1	Chf	55.5	21.0	21.0	22.0	Chf	2B-1	Chf	61.9	17.0	20.0	20.0	F	2B-1	Chf	21.5	20.0	21.5	Chf	
	Average		56.1	21.6	21.6	21.6	Chf	21.6	21.6	21.6	21.6	21.6	21.6	F	21.6	21.6	21.6	21.6	21.6	Chf	
2.	2A-1	Chf	30.7	23.5	26.5	27.0	Chf														
	2A-2	Chf	46.7	22.5	26.0	21.5	Chf														
	Average		47.7	23.4	23.4	23.4	Chf														
	3A-1	F	56.7	23.5	24.5	24.5	F	3A-1	F	51.9	24.5	23.5	23.5	F	3A-1	F	50.9	24.5	24.0	23.5	F
	Average		52.8	24.5	24.5	24.5	F	24.5	24.5	24.5	24.5	24.5	24.5	F	24.5	24.5	24.5	24.5	24.5	24.5	F
3.	3A-1	F	54.8	24.5	24.5	24.5	F	3A-1	F	49.2	24.5	24.5	24.5	F	3A-1	F	49.2	24.5	24.5	24.0	F
	3A-2	F	54.8	24.5	24.5	24.5	F	3A-2	F	49.2	24.5	24.5	24.5	F	3A-2	F	49.2	24.5	24.5	24.0	F
	Average		54.8	24.7	24.7	24.7	F	24.7	24.7	24.7	24.7	24.7	F	24.7	24.7	24.7	24.7	24.7	24.7	F	
	4A-1	F	54.5	24.5	24.5	24.5	F	4A-1	F	51.5	24.5	23.5	23.5	F	4A-1	F	50.9	24.5	24.0	23.5	F
	Average		52.7	25.9	25.9	25.9	F	25.9	25.9	25.9	25.9	25.9	F	25.9	25.9	25.9	25.9	25.9	25.9	25.9	F
4.	4A-1	F	54.5	24.5	24.5	24.5	F	4A-1	F	51.5	24.5	23.5	23.5	F	4A-1	F	50.9	24.5	24.0	23.5	F
	4A-2	F	54.5	24.5	24.5	24.5	F	4A-2	F	51.5	24.5	23.5	23.5	F	4A-2	F	50.9	24.5	24.0	23.5	F
	Average		52.7	25.9	25.9	25.9	F	25.9	25.9	25.9	25.9	25.9	F	25.9	25.9	25.9	25.9	25.9	25.9	25.9	F
	5A-1	F	54.5	24.5	24.5	24.5	F	5A-1	F	51.5	24.5	23.5	23.5	F	5A-1	F	50.9	24.5	24.0	23.5	F
	Average		52.7	25.9	25.9	25.9	F	25.9	25.9	25.9	25.9	25.9	F	25.9	25.9	25.9	25.9	25.9	25.9	25.9	F
5.	5A-1	F	54.5	24.5	24.5	24.5	F	5A-1	F	51.5	24.5	23.5	23.5	F	5A-1	F	50.9	24.5	24.0	23.5	F
	5A-2	F	54.5	24.5	24.5	24.5	F	5A-2	F	51.5	24.5	23.5	23.5	F	5A-2	F	50.9	24.5	24.0	23.5	F
	Average		52.7	25.9	25.9	25.9	F	25.9	25.9	25.9	25.9	25.9	F	25.9	25.9	25.9	25.9	25.9	25.9	25.9	F
	6A-1	F	54.5	24.5	24.5	24.5	F	6A-1	F	51.5	24.5	23.5	23.5	F	6A-1	F	50.9	24.5	24.0	23.5	F
	Average		52.7	25.9	25.9	25.9	F	25.9	25.9	25.9	25.9	25.9	F	25.9	25.9	25.9	25.9	25.9	25.9	25.9	25.9
6.	6A-1	F	54.5	24.5	24.5	24.5	F	6A-1	F	51.5	24.5	23.5	23.5	F	6A-1	F	50.9	24.5	24.0	23.5	F
	6A-2	F	54.5	24.5	24.5	24.5	F	6A-2	F	51.5	24.5	23.5	23.5	F	6A-2	F	50.9	24.5	24.0	23.5	F
	Average		52.7	25.9	25.9	25.9	F	25.9	25.9	25.9	25.9	25.9	F	25.9	25.9	25.9	25.9	25.9	25.9	25.9	F
	7A-1	F	54.5	24.5	24.5	24.5	F	7A-1	F	51.5	24.5	23.5	23.5	F	7A-1	F	50.9	24.5	24.0	23.5	F
	Average		52.7	25.9	25.9	25.9	F	25.9	25.9	25.9	25.9	25.9	F	25.9	25.9	25.9	25.9	25.9	25.9	25.9	25.9

TABLE III
CONTINUED
FULL SECTION RESULTS

Spec. No.	QUERENCED TO ROOM TEMPERATURE										QUERENCED TO BELOW ROOM TEMPERATURE									
	TESTED FROM TOP					TESTED FROM BOTTOM					TESTED FROM TOP					TESTED FROM BOTTOM				
	Spec. No.	Fracture	Spec. No.	Fracture	Average	Spec. No.	Fracture	Spec. No.	Fracture	Average	Spec. No.	Fracture	Spec. No.	Fracture	Average	Spec. No.	Fracture	Spec. No.	Fracture	Average
7.	701-1	51.8	21.5	25.5	25.5	702-1	51.8	21.5	25.5	25.5	701-2	51.8	21.5	25.5	25.5	702-2	51.8	21.5	25.5	25.5
8.	801-1	51.8	21.5	25.5	25.5	802-1	51.8	21.5	25.5	25.5	801-2	51.8	21.5	25.5	25.5	802-2	51.8	21.5	25.5	25.5
9.	901-1	51.8	21.5	25.5	25.5	902-1	51.8	21.5	25.5	25.5	901-2	51.8	21.5	25.5	25.5	902-2	51.8	21.5	25.5	25.5
10.	1001-1	51.8	21.5	25.5	25.5	1002-1	51.8	21.5	25.5	25.5	1001-2	51.8	21.5	25.5	25.5	1002-2	51.8	21.5	25.5	25.5
11.	1101-1	51.8	21.5	25.5	25.5	1102-1	51.8	21.5	25.5	25.5	1101-2	51.8	21.5	25.5	25.5	1102-2	51.8	21.5	25.5	25.5
12.	1201-1	51.8	21.5	25.5	25.5	1202-1	51.8	21.5	25.5	25.5	1201-2	51.8	21.5	25.5	25.5	1202-2	51.8	21.5	25.5	25.5
13.	1301-1	51.8	21.5	25.5	25.5	1302-1	51.8	21.5	25.5	25.5	1301-2	51.8	21.5	25.5	25.5	1302-2	51.8	21.5	25.5	25.5
14.	1401-1	51.8	21.5	25.5	25.5	1402-1	51.8	21.5	25.5	25.5	1401-2	51.8	21.5	25.5	25.5	1402-2	51.8	21.5	25.5	25.5
15.	1501-1	51.8	21.5	25.5	25.5	1502-1	51.8	21.5	25.5	25.5	1501-2	51.8	21.5	25.5	25.5	1502-2	51.8	21.5	25.5	25.5
16.	1601-1	51.8	21.5	25.5	25.5	1602-1	51.8	21.5	25.5	25.5	1601-2	51.8	21.5	25.5	25.5	1602-2	51.8	21.5	25.5	25.5
17.	1701-1	51.8	21.5	25.5	25.5	1702-1	51.8	21.5	25.5	25.5	1701-2	51.8	21.5	25.5	25.5	1702-2	51.8	21.5	25.5	25.5
18.	1801-1	51.8	21.5	25.5	25.5	1802-1	51.8	21.5	25.5	25.5	1801-2	51.8	21.5	25.5	25.5	1802-2	51.8	21.5	25.5	25.5
19.	1901-1	51.8	21.5	25.5	25.5	1902-1	51.8	21.5	25.5	25.5	1901-2	51.8	21.5	25.5	25.5	1902-2	51.8	21.5	25.5	25.5
20.	2001-1	51.8	21.5	25.5	25.5	2002-1	51.8	21.5	25.5	25.5	2001-2	51.8	21.5	25.5	25.5	2002-2	51.8	21.5	25.5	25.5
21.	2101-1	51.8	21.5	25.5	25.5	2102-1	51.8	21.5	25.5	25.5	2101-2	51.8	21.5	25.5	25.5	2102-2	51.8	21.5	25.5	25.5
22.	2201-1	51.8	21.5	25.5	25.5	2202-1	51.8	21.5	25.5	25.5	2201-2	51.8	21.5	25.5	25.5	2202-2	51.8	21.5	25.5	25.5

TABLE III (Continued)

Asterisks attached to Fracture Ratings have following meaning:

* - Severe shrinkage.

** - Dendritic fracture.

TABLE VIII
ADDITIONAL HEAT TREATMENTS OF FULL SECTIONS

Heat Treatment	TEMPERED AT ROOM TEMPERATURE				TEMPERED AT 400° C.				TEMPERED AT ROOM TEMPERATURE				TEMPERED AT 400° C.				TEMPERED TO TEMPERATURE BELLS BEEN TREATED							
	Spec. No.	Fracture	Spec. No.	Fracture	Spec. No.	Fracture	Spec. No.	Fracture	Spec. No.	Fracture	Spec. No.	Fracture	Spec. No.	Fracture	Spec. No.	Fracture	Spec. No.	Fracture	Spec. No.	Fracture				
6. Oil-quenched, cooled in air 10 minutes, water quenched.	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8
7. Oil-quenched and interrupted quench. Air cooled 15 minutes, water quenched 2 minutes, water quenched 10 min.	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8
8. Interrupted quench. Inertly quenched 10 minutes, held in air 10 minutes, water quenched 10 minutes.	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8
9. Inertly heat treated in 6° plate #2	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8
10. Inertly heat treated in 6° plate #2	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8
11. Inertly heat treated in 6° plate #2	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8
12. Oil-quenched, then treated in plate #1. Cooled in air 30 minutes prior to tempering.	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8
13. Interrupted quench. Inertly quenched 9 minutes, held in air 5 minutes, water quenched 30 min.	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8
14. Oil-quenched and interrupted quench. Cooled in air 10 minutes, held in air 5 minutes, water quenched 30 min.	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8
15. Heat treated in plate #1. Same as above.	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8
16. Heat treated in plate #1. Same as above.	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8
17. Heat treated in plate #1. Same as above.	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8	100-1	51.8	100-2	51.8	100-3	51.8	100-4	51.8

* - Percentage porosity visible on fracture
** - Ductile

TABLE VIII (Continued)

Additional Heat Treatments on Full Sections

Heat No.	Special Heat Treatment	Quenched to Temperature Below Room Temperature						Temp. of Cooling °F.					
		Tested at Room Temp.			Tested at -40°F.								
		Spec. No.	Ft.-Lbs.	Hardness Rc	Fracture	Spec. No.	Ft.-Lbs.	Hardness Rc	Fracture				
7	Insert Heat Treated in 6" Plate #11	723-3	49.6	26.0	25.5	27.0	723-1	31.8	24.0	23.5	24.5	CbF	
		723-4	40.7	25.5	25.5	26.5	723-2	26.9	25.0	23.5	25.5		CbF
		Average	45.2	25.2	25.2		Average	29.4	25.2	25.2			CbF
8	Insert Heat Treated in 6" Plate #11	823-3	37.8	25.0	26.5	27.5	823-1	32.6	25.0	25.5	25.0	Fc	
		823-4	37.4	26.5	26.5	26.0	823-2	29.1	26.5	25.5	26.5	Fc	
		Average	37.6	26.0	26.0		Average	30.9	26.0	26.0		Fc	
9	Insert Heat Treated in 6" Plate #11	923-3	38.6	24.5	26.5	25.5	923-1	42.4	26.5	26.5	26.0	F	
		923-4	35.8	26.5	25.5	26.0	923-2	42.8	24.5	26.5	26.5	F	
		Average	37.7	25.9	25.9		Average	42.6	25.9	25.9		F	

* Severe shrinkage porosity visible on fractured surface.

** Cracks and severe shrinkage visible on fractured surface.

Plate #11 heated 4 hours at 1725°F., water quenched cold in 40 minutes, inserts removed within 1 hour after quenching. Insert #7 slightly wet, inserts nos. 8 and 9 dry. Inserts cooled to -100°F. then tempered at 1180°F. for 4 hours at temperature, water quenched.

TABLE H IV
HARDNESS RESULTS ON MICRO-INSERT BARS

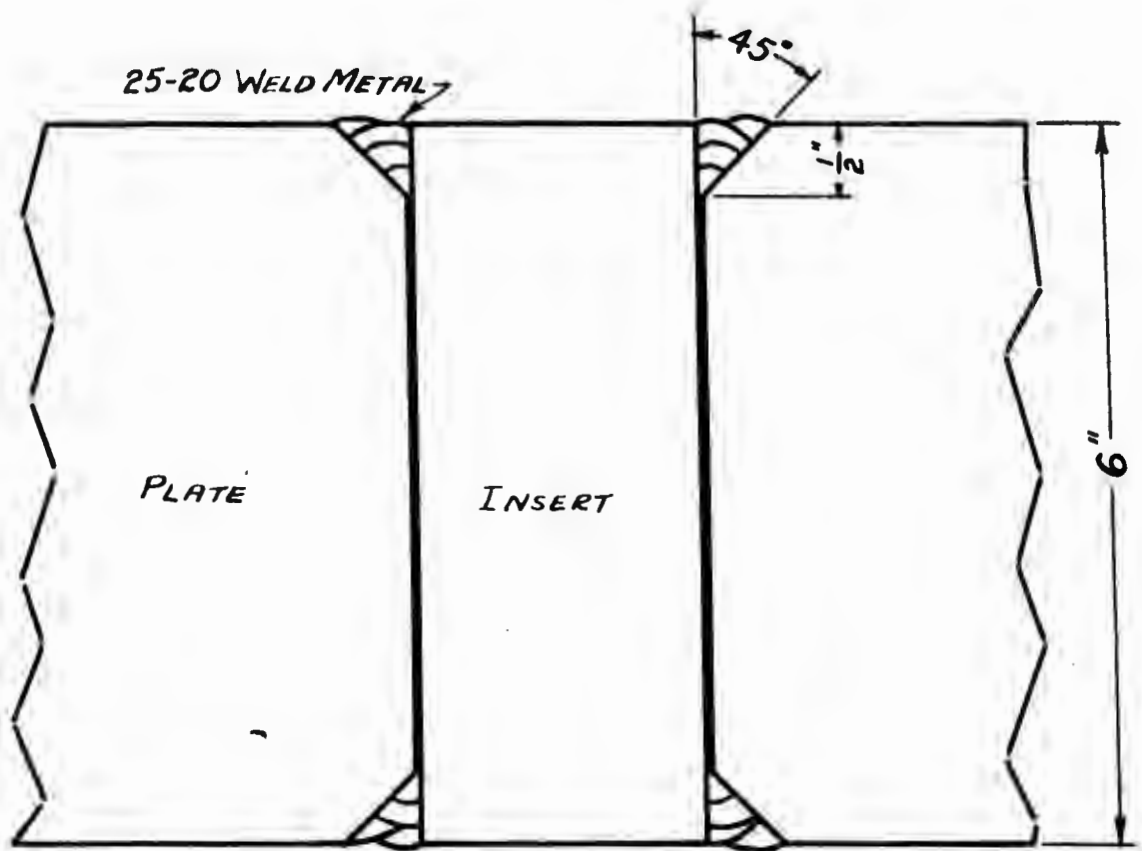
Heat	Quench	Distance from Center (Inches)													
		2½	2	1½	1	1/2	1/4	0	0	1/4	1/2	1	1½	2	2½
9	Direct	45½	44½	43½	44½	44½	45½	45	45½	45½	45½	45½	46	47	48
		48½	49	48½	48	49	49	48½	48½	48½	49	49	49	49	49
10	Delayed	53½	52½	52½	51½	52½	53	52½	53½	53½	52½	52½	53½	52½	53½
		54	53	53½	52½	53½	53½	54	53½	53	53½	53	54	53½	53
12	Direct	49½	49½	48	49½	52½	48½	49½	48½	47½	48½	49	50	49½	49½
		49½	49½	50½	51½	51½	50½	52½	52½	50½	51½	50½	50½	50½	50½
13	Direct	48½	49½	48	47½	47	46½	47½	46½	46½	47	47½	46½	48	47½
		49½	47½	47½	46	46	43½	42½	43½	43½	42½	46½	47½	47½	48½
13	Inter- rupted	46	47	46	46½	46½	46½	46½	47½	46½	46½	46½	47½	47	47½
		47	47½	47	47½	47	47	45½	46½	46½	46½	45	46	47	46½
14	Direct	48½	47½	48	48½	47½	47½	48½	48½	46½	47½	47½	48½	48	48½
		49½	48½	48½	47½	48½	47½	46½	47	47½	47	46	47½	46½	47½
15	Direct	48½	48½	48½	45½	48½	49½	48½	49½	48	49	49	50	51½	51½
		50½	50½	49½	48½	49½	49½	49	49½	48½	48½	49½	50½	50½	50½
16	Direct	49½	49	47½	45½	46½	45½	45½	45½	44½	45½	44½	45½	46½	47½
		50½	49½	48½	47½	46½	45½	45½	46½	45½	46½	45½	47½	50	50½
16	Delayed & Inter- rupted	50	48½	49½	50½	49½	48	48½	48½	49	49	48½	50	55	49½
		49½	50	51	49½	48½	49	49½	50½	50½	49½	50	49	49	49½
17	Direct	48½	48	48	47	46½	46½	46½	47	47	47	46½	47½	45½	45½
		46	48½	48½	48½	47½	47½	47	47½	47½	47	48½	48½	48½	50
18	Direct	54½	54½	54	54	53½	--	54½	54½	--	54	53½	53½	54½	54½
		54½	53½	54½	54½	54½	54½	54½	55½	54½	55	54½	54½	53½	54½
19	Direct	54½	54½	54½	55½	55½	--	55½	55½	--	55½	54½	54½	53½	54½
		54½	54½	54½	54½	54½	54½	54½	55½	54½	54½	55	54½	54½	54½
20	Direct	47	50	50½	49½	47	46	50	48	46½	46½	48½	50	47½	47
		49	50	50½	51½	51	51	52½	50½	51	50	51	51½	52	51½
21	Direct	55½	55½	54½	55½	53½	54½	54½	53½	54½	55	55	56½	56	55½
		56½	56½	55½	56½	56	55½	54½	56½	55½	55	56½	56½	55½	56½
22	Direct	56½	58	57½	55½	57	57½	57½	56½	57	57½	56½	57	56½	56½
		57½	57½	56½	57½	57½	57½	59	58	58	57½	58	57½	56½	57½

TABLE IV

MICROSTRUCTURAL SURVEY OF INSERT BARS
CONTAINING INTERMEDIATE TRANSFORMATION PRODUCT

Heat * Number	Survey Number	Per Cent Intermediate Transformation Product at Indicated Distances in Sixteenths of an Inch from Center of Full Sections.										
		19	15	11	8	4	0	4	8	11	15	19
9	1	-	15	5	-	-	5	-	-	5	-	5
	2	-	-	5	-	-	-	-	-	5	10	-
	3	-	-	-	-	5	5	-	-	-	-	-
	Average	-	5	3	-	2	3	2	8	3	3	2
10	1	-	-	-	-	-	-	-	-	-	-	-
	2	-	-	-	-	-	-	-	-	-	-	-
	3	-	-	-	-	5	-	-	-	-	-	-
	Average	-	-	-	-	2	-	-	-	-	-	-
20	1	10	15	15	15	20	5	5	-	5	5	5
	2	5	10	5	10	10	1	5	10	10	-	10
	3	25	15	20	10	5	1	10	10	-	15	25
	Average	15	15	15	10	10	2	5	5	5	5	15

* No other 6 inch heats contain intermediate transformation product. Structure of these steels, however, shows tempering effect except 21-22.

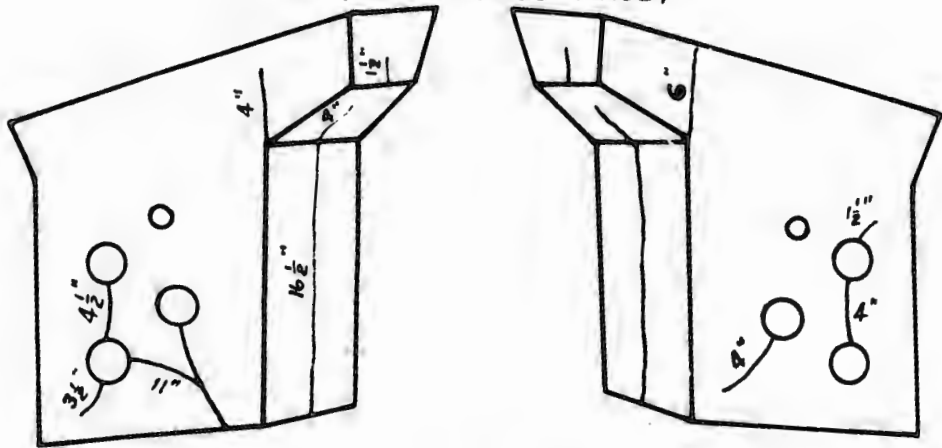


DIAM. OF HOLE - $2 \begin{smallmatrix} -0.00 \\ +0.01 \end{smallmatrix}$ "

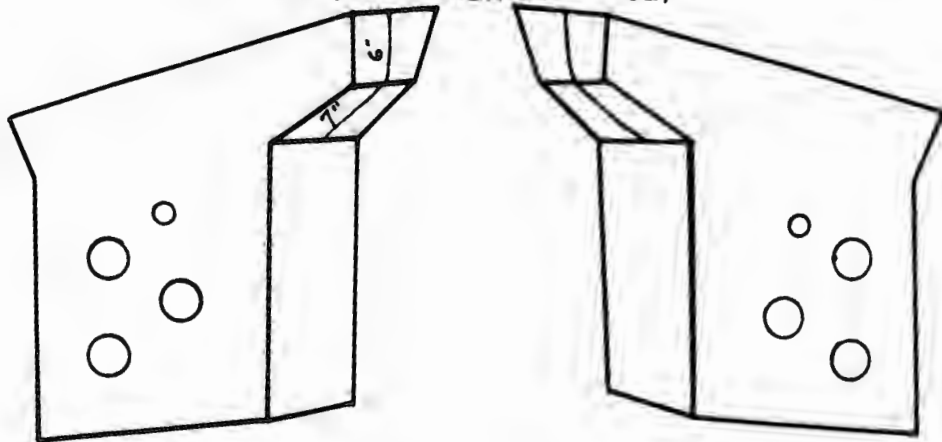
DIAM. OF INSERT - $1.90 \begin{smallmatrix} -0.01 \\ +0.00 \end{smallmatrix}$ "

DETAILS OF WELDING OF INSERTS
IN 6" THICK PLATES

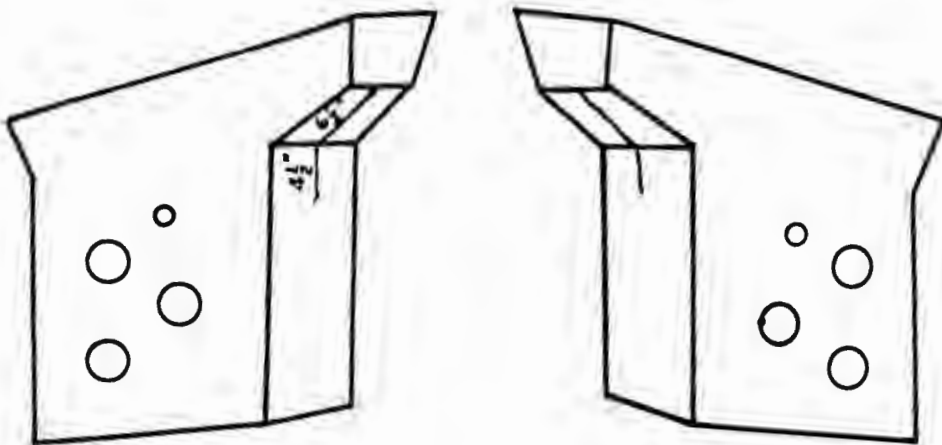
HEAT 10 (HEAT TREATED TWICE)



HEAT 13 (HEAT TREATED TWICE)

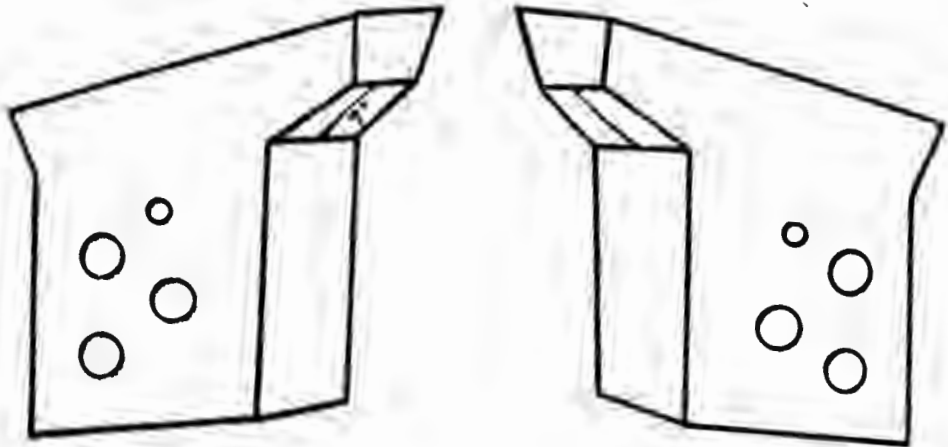


HEAT 14

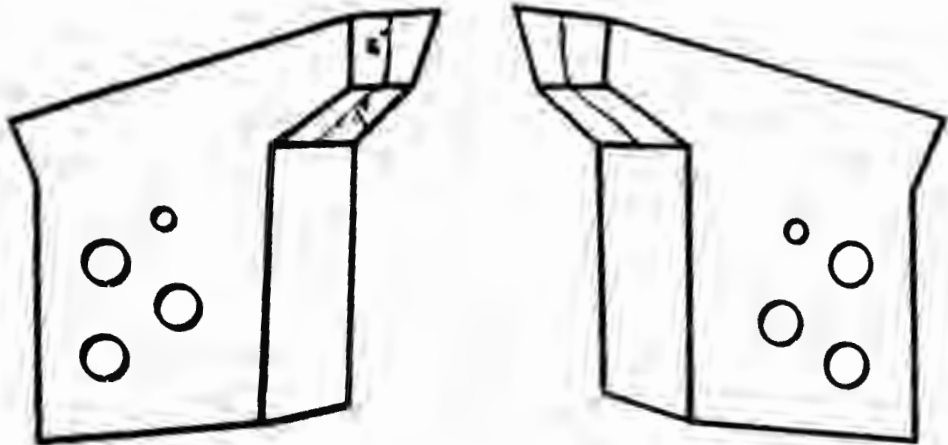


QUENCH CRACKING DEVELOPED UPON
HEAT TREATMENT OF 6" THICK PLATES

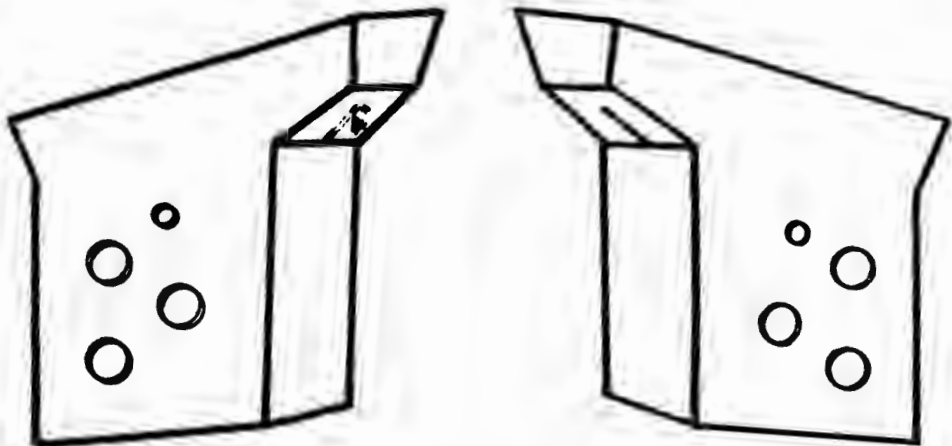
HEAT 15 (HEAT TREATED TWICE)



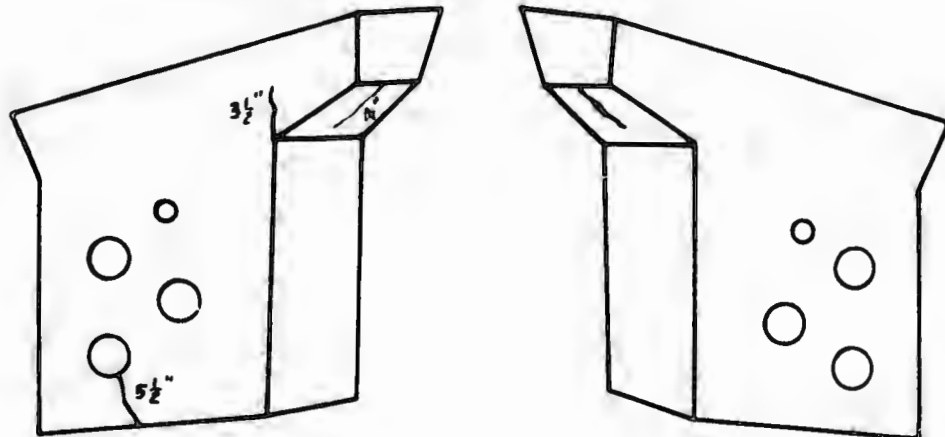
HEAT 16 (HEAT TREATED TWICE)



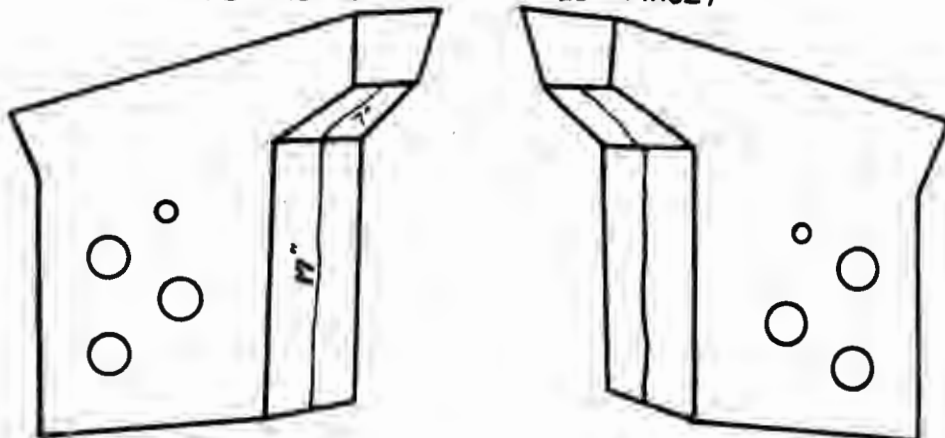
HEAT 17



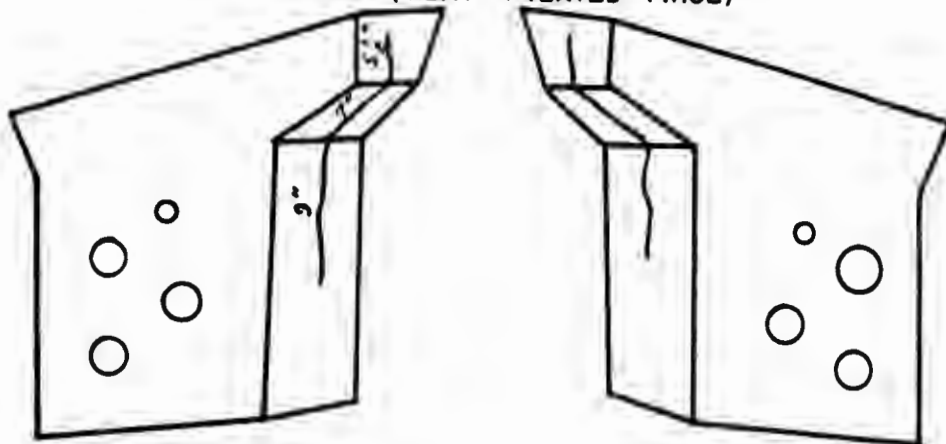
HEAT 18 (HEAT TREATED TWICE)



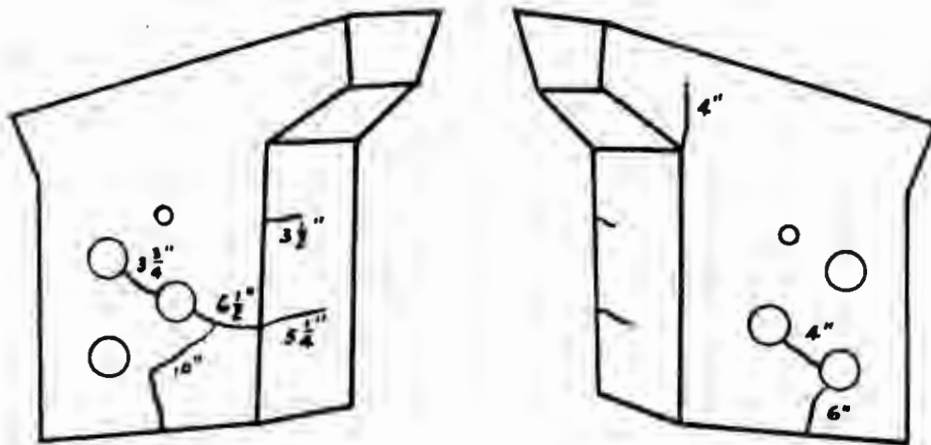
HEAT 19 (HEAT TREATED TWICE)



HEAT 20 (HEAT TREATED TWICE)



HEAT 21



HEAT 22

