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THE EFFECT OF METALLURGICAL VARIABLES IN SHIP-PLATE STEELS ON THE TRANSITION TEMPERATURES IN THE DROP-WEIGHT AND CHARPY V-NOTCH TESTS

SSC-145

BY

F. W. BOULGER AND W. R. HANSEN

SHIP STRUCTURE COMMITTEE

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SECRETARY
SHIP STRUCTURE COMMITTEE
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WASHINGTON 25, D. C.

December 3, 1962

Dear Sir:

The Ship Structure Committee has sponsored, at the Battelle Memorial Institute, a research project entitled "Metallurgical Variables and Drop-Weight Test." The purpose of this project, which was recently completed was to study the effect of metallurgical variables on the performance of ship steels in the drop weight test.

Herewith is a copy of the report, The Effect of Metallurgical Variables in Ship-Plate Steels on the Transition Temperatures in the Drop-Weight and Charpy V-Notch Tests, by F. W. Boulger and W. R. Hansen, containing the data and conclusions obtained from this study.

The project was conducted under the advisory guidance of the Committee on Ship Steel of the National Academy of Sciences - National Research Council.

Please address comments to the Secretary, Ship Structure Committee.

Yours sincerely,

J Fabik

J. J. Fabik
Rear Admiral, U.S. Coast Guard
Chairman, Ship Structure Committee

Serial No. SSC-145

Report on

Project SR-151

to the

SHIP STRUCTURE COMMITTEE

on

THE EFFECT OF METALLURGICAL VARIABLES IN SHIP-PLATE STEELS ON THE TRANSITION TEMPERATURES IN THE DROP-WEIGHT AND CHARPY V-NOTCH TESTS

by

F. W. Boulger and W. R. Hansen
Battelle Memorial Institute

under

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under

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Washington, D. C.
U. S. Department of Commerce, Office of Technical Services

December 3, 1962

ABSTRACT

Twenty-nine heats were produced and processed in the laboratory in order to study the effects of composition and ferrite grain size on drop-weight transition temperatures. To provide an internal check and to permit comparisons with other investigations, parallel studies were made on V-Notch Charpy specimens. The experimental steels covered the following ranges in composition: 0.10/0.32 % carbon, 0.30/1.31 % manganese, 0.02/0.43 % silicon, and nil/0.136 % acid soluble aluminum. These ranges were intentionally wider than the limits permitted for ship plate. Although most of the data were obtained on hot-rolled samples, some plates were heat-treated in order to cover a wider range in ferrite grain size.

The experimental data were used for a multiple correlation analysis conducted with the aid of an electronic computer. The study showed that carbon raises and manganese, silicon, aluminum and finer ferrite grain sizes lower both drop-weight and Charpy transition temperatures. Quantitatively, variations in composition and grain size have a more marked effect on V_{15} Charpy transition temperatures than on the drop-weight transition temperature.

Useful correlations were found between transition temperatures in drop-weight tests and those defined by seven different criteria for Charpy tests.

Evidence was accumulated that conditions ordinarily used for drop-weight tests are more severe for 1-1/4-in. thick plate than for 5/8-to 1-in. thick plate.

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INTRODUCTION

Project SR-151, to study quantitatively the effects of metallurgical variables on performance in the drop-weight test, was established by the Ship Structure Committee late in 1958 on recommendation of the Committee on Ship Steel of the National Academy of Sciences-National Research Council. This project was initiated as a result of the increasing use of the drop-weight (nil-ductility) test in predicting the ductile to brittle behavior of steel. Qualitative data indicated the drop-weight test was not as sensitive to metallurgical variables as the Charpy V-notch test. Furthermore, the available information indicated that the drop-weight test did not show the superiority of killed steels over semikilled steels reflected by Charpy tests. This difference in sensitivity to brittle fracture is considered important because the drop-weight transition temperature had been reported[1] as correlating better with service failures than the V-notch test did at a constant energy level. Therefore, this project was concerned with establishing quantitatively the effects of metallurgical variables in the drop-weight test. For comparison, Charpy V-notch data were obtained for the steels investigated.

This report summarizes the results of the investigation. Most of the steels used for the study were made and processed in the laboratory. However, some tests were also made on commercial ABS-Class C ship steels. During the course of the investigation, data were obtained on the effects of C, Si, Mn, and Al on transition temperatures of drop-weight and Charpy specimens. In addition, the effects of heat treatment which changed the ferrite grain size and the transition temperatures were also investigated. Finally a few exploratory studies were made on commercial Class C ship plates to evaluate the effects of plate thickness, grain size, and heat treatment on the performance of drop-weight specimens.

EXPERIMENTAL PROCEDURES

Preparation of Materials

A total of twenty-nine, 500-lb induction-furnace heats were made and processed in the laboratory for the investigation. C, Mn, Si, and Al contents were systematically varied beyond their normal ranges for commercial ship plate. The success of the investigation depended to a large extent on controlling the melting and rolling practices closely so that the laboratory steels would have properties comparable to those of commercial steels with similar compositions. Since the techniques developed in a previous project[2] had proved satisfactory they were used as a guide for the current investigation.

Briefly, the melting procedure was as follows: The 500-lb heats were made from a charge of low-metalloid iron in magnesia crucibles under a blanket of argon. After the charge was melted and the desired temperature reached, the melts were partially deoxidized by adding about nine lbs of silicomanganese per ton of charge. This addition insured consistent recoveries of subsequent additions of ferromanganese and ferrosilicon. Carbon, in the form of graphite, was added about 45 sec before tapping to produce the desired compositions. In some heats, aluminum shot was added with the graphite. The steels were poured into two 6 in. x 6 in. big-end-up molds and the ingots were capped with a steel plate when necessary.

Subsequently, the ingots were heated to 2250 F and pressed to slabs 4-1/2 in. thick and 5-1/2 in. wide. After reheating to 2250 F, they were rolled to 1-3/4-in.-thick slabs using a reduction of approximately 1/4 in. per pass. The slabs were then cut into three pieces, to facilitate handling, and reheated to 2250 F. They were then rolled to about 0.725-in. thick plates using a reduction of approximately 0.170 in. per pass. After equalizing at 1850 F for 20 min the final reduction to 0.625 (5/8) in.-thick plate was made in one pass while at that temperature. After the final pass the 5-in. wide by 60-in. long plates were placed on edge on a brick platform, with a brick separating each plate, and allowed to cool in still air.

TABLE 1. CHEMICAL ANALYSES OF EXPERIMENTAL LABORATORY STEELS

Heat Number		Mn/C	Chemical Composition,** per cent						
Assigned	Battelle	Ratios	C	Mn	Si	P	S	Al (Soluble)	Al (Total)
			Carbon-Manganese Series						
			Killed Steels						
1	B 6353	1.50	0.20	0.30	0.21	0.016	0.022	0.039	0.041
2	B 6327	3.84	0.19	0.73	0.24	0.014	0.018	0.039	0.042
2-2	B 6932	4.32	0.19	0.84	0.26	0.016	0.029	0.039	--*
3	B 6366	6.55	0.20	1.31	0.26	0.016	0.024	0.038	--
5	B 6360	1.37	0.32	0.44	0.24	0.016	0.030	0.036	--
17	B 6879	2.92	0.24	0.70	0.23	0.016	0.029	0.045	--
6	B 6368	4.00	0.30	1.20	0.22	0.015	0.026	0.066	--
7	B 6359	3.50	0.12	0.42	0.22	0.016	0.029	0.019	--
15	B 6903	5.33	0.15	0.80	0.24	0.018	0.031	0.050	--
4	B 6367	10.90	0.11	1.20	0.22	0.015	0.026	0.093	--
			Semikilled Steels						
8	B 6406	2.00	0.22	0.44	0.08	0.015	0.025	--	--
9	B 6409	3.95	0.20	0.79	0.05	0.015	0.025	--	--
9-2	B 7064	3.68	0.22	0.81	0.02	0.016	0.020	--	--
10	B 6464	5.95	0.21	1.25	0.04	0.015	0.027	--	--
12	B 6405	1.39	0.28	0.39	0.05	0.012	0.025	--	--
18	B 6904	2.68	0.29	0.75	0.03	0.015	0.031	--	--
13	B 6427	3.80	0.30	1.14	0.03	0.015	0.027	--	--
14	B 6361	3.50	0.12	0.42	0.10	0.015	0.030	--	--
16	B 6880	5.23	0.13	0.68	0.03	0.016	0.022	--	--
11	B 6410	13.00	0.10	1.30	0.05	0.015	0.027	--	--
			Silicon-Aluminum Series						
19	B 6930	3.62	0.21	0.76	0.40	0.018	0.024	Nil	--
20	B 6931	3.52	0.21	0.74	0.03	0.013	0.024	0.017	--
21	B 6914	4.00	0.21	0.83	0.42	0.019	0.027	0.043	--
22	B 6933	3.82	0.22	0.83	0.06	0.016	0.024	0.114	--
23	B 6913	3.95	0.20	0.79	0.24	0.018	0.025	0.136	--
24	B 6929	3.26	0.23	0.75	0.23	0.018	0.026	Nil	--
25	B 7191	3.04	0.23	0.70	0.13	0.013	0.029	0.034	--
26	B 7192	3.54	0.24	0.85	0.43	0.015	0.023	0.120	--
27	B 7193	9.77	0.13	1.27	0.16	0.014	0.026	0.039	--

*Dashes indicate analyses not made.

**Nitrogen contents of Heats 1 through 5 ranged from 0.005 to 0.006%. Heats 8 through 12 had nitrogen contents ranging from 0.004 to 0.005%.

Composition

The compositions of the 29 laboratory heats made for this project are given in Table 1. The steels can be classified into three groups. The first group consisted of 10 aluminum-killed steels similar in composition to Class C ship-plate steel. The second group consisted of 10 semikilled or Class B type steels. In both of these groups the C and Mn contents were intentionally varied over a wider range than that permitted by the American Bureau of Shipping specifications. This wide range in composition was helpful in obtaining quantitative data from a limited number of steels. The primary purpose of these two groups of steels was to determine the effects of C, Mn, and deoxidation practice. In addition, one steel in each group (Steels 2-2 and 9-2) were made about one year after the start of the program in order to check consistency of melting practice.

The third group of nine steels listed in Table 1 was intended for studies on the effects of Si and Al as alloying agents, not deoxidizers. In eight of these steels C and Mn were held relatively constant at levels of about 0.2 and 0.8 %, respectively, while Si and Al were varied. The last steel in this group was designed to provide information on the effects of Si and Al at another C and Mn level.

The Si, P, and Su contents of all of the laboratory steels fall within ABS specifications unless intentionally varied as in the case of Si for the silicon-aluminum series of steels.

TESTING PROCEDURES

Tensile Tests

In most cases, longitudinal tensile tests were made on flat, full-plate-thickness specimens having an 8 in. gage length. Because of a shortage of wrought material, specimens with 4 in. gage lengths were used for testing Steels 25, 26, and 27. The loading rates for the yield and tensile strengths were 0.02 in. per min, and 0.2 in. per min, respectively. Tests were made on a 200,000-lb capacity Baldwin-Southwark universal testing machine. An averaging extensometer (microformer type) was used to record stress-strain curves.

Charpy Tests

The V-notch Charpy specimens were notched with a fly-cutter. Periodic checks at a magnification of 50X showed the notch dimensions were being held within the tolerances permitted by ASTM specifications. The Charpy specimens were broken on a Riehle pendulum-type 220 ft-lb capacity machine with a striking velocity of 18.1 fps. Ordinarily 25 to 30 Charpy specimens were broken in order to establish curves for transition-temperature determinations. Samples were tested at intervals of 20 F on the upper and lower plateaus and at 10 F intervals in the transition zone. The Charpy bars were taken parallel to the major rolling direction and notched through the plate thickness. The performance of the experimental steels in the Charpy test was evaluated by several criteria.

Energy-temperature curves were drawn through average values for specimens tested at various temperatures. Values for the following Charpy V-notch transition-temperature (CV TT) criteria were then obtained from the curve:

CV15 TT = 15 ft-lbs
CV25 TT = 25 ft-lbs
CV50% TT = 50% of the maximum energy value recorded for the highest testing temperature.

Generally, the highest testing temperature was chosen so that the energy corresponded to the upper plateau of the Charpy curve.

The percentage of fracture area exhibiting a fibrous appearance was also determined on all Charpy specimens to establish transition temperatures based on fracture-texture criteria. These data were obtained by visual examination and measurement with a pair of dividers and a scale. Larger percentages of fibrous texture are considered indications of greater absence of brittle fracture under the conditions of testing.

The seventh criterion used to establish transition temperatures from the Charpy data was the amount of lateral expansion opposite the notch. To obtain these data, the width of both halves of broken specimens was measured with flat-end micrometers at the compression side opposite the notch. From these values the temperature corresponding to a lateral expansion of 0.015 in. was determined.

Determination of Grain Size and Pearlite Content

Early in the program the ferrite grain sizes and pearlite contents of the laboratory steels were determined by a point counting technique with the aid of photomicrographs. Later, in determining the effect of normalizing on the ferrite grain size this method did not appear to have the required sensitivity. Although data obtained by this method were not used in evaluating the results obtained in this study, the data are given in Appendix C.

The method subsequently used to evaluate the effect of ferrite grain size and pearlite content made use of the Hurlbut counter. This technique consisted of moving the polished and etched metallographic specimen at a constant speed under a microscope equipped with a cross hair at a magnification of 1000X. The number of ferrite grains crossed and the distance covered in the lineal traverse through the ferrite and pearlite phases was recorded. The ferrite grain size was calculated from the number of ferrite grains crossed and the lineal distance occupied by the ferrite phase. This value was then converted to the ASTM scale by the relationship of $S_V = 2N_L$ where S_V is the grain boundary surface area and N_L is the number of grain boundaries or grains (for a large number of grains) intersected by a random line across the microstructure. S_V is related to the ASTM number as indicated on p. 405 of the *Metals Handbook*, 1948 edition. In this method the actual ferrite grain size is determined. Variations in pearlite content do not affect its value. The percentage of pearlite was computed from the total distance covered and that covered for the pearlite phase. The information on pearlite contents of the various samples is given in Appendix C.

Drop-Weight Tests

The drop-weight test evaluates the behavior of a steel in the presence of an ultra-sharp crack, originated during testing from a hard weld bead previously deposited and notched, on the surface of the specimen. The specimen configurations, welding techniques, and testing procedures were developed and described by Pellini and co-workers.[3,4] The transition temperature in the drop-weight test, sometimes called the nil-ductility temperature (NDT) is the highest temperature at which the specimen breaks with limited plastic deformation. The sample is broken as a simple beam in a device containing a stop which limits the deflection and the plastic deformation.

In preparing and testing the drop-weight specimens for this investigation, the precautions described in the published literature[1,3-6] were followed. The weld beads were made with "Hardex-N" hard-surfacing electrodes with 200 amp, 22 v and a feed of 6 in. per min. The drop-weight samples of the laboratory steels were 2 in. x 5 in. x 5/8 in.; the commercial Class C steels were evaluated on specimens 3-1/2 in. x 14 in. x 1-1/4 in. Based on advice received during a visit to the Naval Research Laboratory, the conditions used to deposit the weld bead were the same for both sizes of specimens. However, the smaller specimens were submerged in a bath of flowing water during welding. This technique was recommended by Puzak as a precaution to minimize the heat-affected zone.

The stops controlling the amount of bending in the drop-weight tests were set at 0.075 in. and at 0.30 in. for the 5/8 in. and 1-1/4 in. plates, respectively. The span between supports was 4.0 in. and 12.0 in., respectively. A number of check measurements were made, as described by Puzak,[4] to be certain that the desired crack openings were obtained. In addition, numerous hardness measurements were made on the weld beads and in the heat-affected zones.

In this study, the drop-weight or nil-ductility transition temperature (NDT) was defined as the highest temperature at which the tensile surface of at least one specimen fractured completely to one edge. Usually, three or four specimens were tested at 10 F above the NDT.

TABLE 2. TENSILE PROPERTIES OF HOT-ROLLED LABORATORY STEELS

Steel	Composition C, %	 Mn, %	Yield Strength 0.2% Offset, psi	Tensile Strength, psi	Elongation in 8 in., %
			Carbon-Manganese Series		
			Killed Steels		
1	0.20	0.30	33250	59950	29.4
2	0.19	0.73	36200	64150	28.4
2-2	0.19	0.84	40050	67450	30.0
3	0.20	1.31	42700	71600	24.7
5	0.32	0.44	39350	69700	23.2
17	0.24	0.70	42850	72600	26.8
6	0.30	1.20	49300	82400	20.0
7	0.12	0.42	32150	53800	29.4
15	0.15	0.80	38950	62350	31.5
4	0.11	1.20	36150	58750	26.4
			Semikilled Steels		
8	0.22	0.44	35250	61450	29.2
9	0.20	0.79	36000	63050	29.1
9-2	0.22	0.81	36100	62850	30.8
10	0.21	1.25	39250	69900	27.8
12	0.28	0.39	33950	63250	25.6
18	0.29	0.75	39300	69850	28.0
13	0.30	1.14	40650	79150	24.8
14	0.12	0.42	29700	51150	30.8
16	0.13	0.68	33600	57600	31.2
11	0.10	1.30	35200	58150	30.8
			Silicon-Aluminum Series*		
	Si, %	Al, %			
19	0.40	Nil	41400	71200	26.0
20	0.03	0.017	35950	63200	25.8
21	0.42	0.043	45200	71850	27.8
22	0.06	0.114	37050	64250	30.5
23	0.24	0.136	38900	65300	26.2
24	0.23	Nil	36900	66200	28.8
25	0.13	0.034	40050	68980	43.5**
26	0.43	0.120	42800	73150	44.5**
27	0.16	0.039	39680	65850	46.0**

*With the exception of Steel 27, which contained 0.13 C and 1.27 Mn, these steels contained about 0.2% C and 0.8% Mn.

**Elongation in 2 in.

DISCUSSION OF RESULTS ON LABORATORY STEELS

Tensile Properties

The average tensile property values for duplicate samples of the hot-rolled steels made in the laboratory are listed in Table 2. Complete tensile data is given in Table A-1 of Appendix A. All of the heats met the minimum yield strength of 32,000 psi required by ABS Specifications for hull steels. Because the compositions covered a wider range than that encountered in commercial ship steels, however, some of the other properties fell outside specification limits. Five of the steels had tensile strengths falling either above or below the specification. These deviations ranged from plus 11,400 psi (Steel 6) to minus 6850 psi (Steel 14). Only one of the steels failed to meet the ductility requirements.

The experimental data show that the hot-rolled laboratory steels with compositions falling within ABS specifications have tensile properties equivalent to those of commercial ship steel. They are in good agreement with the yield and ultimate strengths and elongation values calculated from the formulas developed in a previous investigation on ship steel.[2] Furthermore, the tensile strengths agree quite well with those predicted for commercial steels using the formula developed by Quest and Washburn.[7]

Grain Size

Based on the data in Table 3, the average ASTM ferrite grain size number of the hot-rolled steels, which had been finished at 1850 F, was 8.3. The average ASTM grain size numbers of the three series of semikilled, killed and the silicon-aluminum steels were 8.2, 8.3, and 8.4, respectively. This indicates that finishing temperature and cooling rate were the principal factors controlling ferrite grain size of the hot-rolled products. Deoxidation practice and silicon content had little or no effect. Data from other studies indicate that the amount of reduction in the last several passes may also be important.

Coarser ferrite grains were associated with lower C contents. The average ASTM ferrite grain size numbers for steels containing 0.10/0.15 and

TABLE 3

FERRITE GRAIN SIZE AND TRANSITION TEMPERATURE OF HOT-ROLLED LABORATORY STEELS

	Composition, per cent				Ferrite Grain Size[A] ASTM Number	Transition Temperature[B], F								Charpy Ft-Lb at NDT Temperature[C]
										Per Cent Fibrous Texture				
Steel	C	Mn	Si	Soluble Al		NDT	V_{15}	V_{25}	$V_{50\%}$	15	30	50	LE_{15}	
						Carbon-Manganese Series								
						Killed Series								
1	0.20	0.30	0.21	0.039	7.9	0	28	41	54	16	41	74	18	7
2	0.19	0.73	0.24	0.039	8.0	-10	-18	1	28	-13	12	41	-26	21
2-2	0.19	0.84	0.26	0.039	8.2	- 5	-31	- 9	32	-38	24	44	-42	25
3	0.20	1.31	0.26	0.038	9.4	-20	-21	0	28	-23	18	69	-29	14
5	0.32	0.44	0.24	0.036	8.7	5	42	72	72	20	50	111	21	6
17	0.24	0.70	0.23	0.045	8.5	0	18	42	38	-3	26	60	9	10
6	0.30	1.20	0.22	0.066	10.1	-20	-36	-5	33	-16	8	33	-33	17
7	0.12	0.42	0.22	0.019	6.9	-20	2	13	29	-10	13	29	-10	7
15	0.15	0.80	0.24	0.050	7.4	-20	-18	-9	10	-22	2	22	-23	11
4	0.11	1.20	0.22	0.093	7.5	-40	-53	-35	9	-40	-14	12	-45	24
						Semikilled Steels								
8	0.22	0.44	0.08	--[D]	8.0	20	43	64	85	22	47	88	28	8
9	0.20	0.79	0.05	--	8.4	0	16	30	50	5	44	75	9	7
9-2	0.22	0.81	0.02	--	8.1	10	26	47	59	6	31	64	17	10
10	0.21	1.25	0.04	--	8.6	-10	-13	10	49	-15	25	55	-9	10
12	0.28	0.39	0.05	--	8.6	30	81	105	93	44	82	133	72	5
18	0.29	0.75	0.03	--	9.0	20	41	85	90	18	49	88	35	7
13	0.30	1.14	0.03	--	9.3	20	10	48	40	22	54	81	5	12
14	0.12	0.42	0.10	--	7.4	-10	20	36	59	-3	27	49	5	7
16	0.13	0.68	0.03	--	7.7	0	32	44	56	6	0	52	14	7
11	0.10	1.30	0.05	--	8.0	-20	-28	-25	-3	-25	-20	21	-29	40
						Silicon-Aluminum Series								
19	0.21	0.76	0.40	--	8.2	10	15	38	60	1	30	56	10	13
20	0.21	0.74	0.03	0.017	8.6	10	26	44	59	-14	27	53	16	9
21	0.21	0.83	0.42	0.043	8.6	-10	-24	-2	41	-40	18	46	-34	22
22	0.22	0.83	0.06	0.114	8.3	-10	1	23	40	-23	16	54	-3	12
23	0.20	0.79	0.24	0.136	8.9	-30	-17	-4	33	-32	2	40	-19	18
24	0.23	0.75	0.23	--	8.0	0	0	23	25	-4	14	35	-3	23
25	0.23	0.70	0.13	0.034	8.3	5	-19	2	40	-22	19	60	-20	30
26	0.24	0.85	0.43	0.120	8.4	-15	-3	24	34	-46	17	78	-11	16
27	0.13	1.27	0.16	0.039	8.2	-10	-72	-41	-22	-65	-19	32	-64	70

[A] ASTM number is the average of two or more determinations.

[B] The transition temperatures were defined as follows:

C_{V15} =temp. at which the average Charpy value was 15 ft-lb

C_{V25} =temp. at which the average Charpy value was 25 ft-lb

$C_{V50\%}$=temp. at which the average Charpy value was 50% of the maximum energy value recorded for the highest testing temperature

Per Cent Fibrous =temp. where the average amount of fibrous texture was 15, 30, or 50 per cent, respectively

LE_{15} =temp. where the lateral expansion was 15 mils

[C] Average for specimens broken at the NDT.

[D] Dashes indicate tests were not made.

TABLE 4

FERRITE GRAIN SIZE AND TRANSITION TEMPERATURE OF HEAT-TREATED LABORATORY STEELS

	Composition, per cent				Ferrite Grain Size[A] ASTM	Transition Temperature[B], F								Charpy Ft-Lb at NDT
										Per Cent Fibrous Texture				
Steel	C	Mn	Si	Al	Number	NDT	V_{15}	V_{25}	$V_{50\%}$	15	30	50	LE_{15}	Temperature[C]
Normalized from 1600 F														
1	0.20	0.30	0.21	0.039	9.3	10	22	38	55	-3	34	61	8	11
2	0.19	0.73	0.24	0.039	9.3	-40	-49	-33	-5	-41	-41	4	-52	9
3	0.20	1.31	0.26	0.038	10.1	-60	-81	-66	-24	-82	-50	-15	-80	28
5	0.32	0.44	0.24	0.036	9.1	-10	38	70	53	-2	50	94	26	5
6	0.30	1.20	0.22	0.066	10.8	-40	-44	-15	10	-50	-22	18	-39	17
7	0.12	0.42	0.22	0.019	8.2	-10	-10	-1	8	-29	-1	11	-19	17
4	0.11	1.20	0.22	0.093	8.1	-60	-34	-29	6	-37	-16	41	-38	6
8	0.22	0.44	0.08	--[D]	8.2	10	51	71	77	21	52	79	37	6
9	0.20	0.79	0.05	--	8.1	-10	17	38	62	2	33	63	15	5
10	0.21	1.25	0.04	--	8.9	-20	-9	2	31	-28	17	43	-18	8
12	0.28	0.39	0.05	--	8.8	30	92	110	104	44	80	122	68	2
13	0.30	1.14	0.03	--	9.7	10	-5	42	25	2	20	75	-1	15
14	0.12	0.42	0.10	--	7.8	-10	19	37	49	-40	30	58	5	6
11	0.10	1.30	0.05	--	8.6	-20	-19	-8	12	-28	3	20	-24	20
Normalized from 1900 F														
2	0.19	0.73	0.24	0.039	8.0	-20	-15	-6	16	-30	-3	22	-18	9
9	0.20	0.79	0.05	--	7.5	20	44	61	71	24	57	90	31	11
Heated One Hour at 1900 F and Furnace Cooled to 800 F														
2-2	0.19	0.84	0.26	0.039	5.5	0	28	40	43	7	35	85	19	9
5	0.32	0.44	0.24	0.036	5.1	30	94	135	118	58	105	153	74	6
6	0.30	1.20	0.22	0.066	7.1	0	55	80	82	26	63	90	53	5
7	0.12	0.42	0.22	0.019	4.5	20	42	68	88	7	50	94	23	8
4	0.11	1.20	0.22	0.093	7.2	-50	-31	-18	5	-46	-19	- 8	-40	10
9-2	0.22	0.81	0.02	--	5.5	40	54	73	77	13	66	111	53	7
12	0.28	0.39	0.05	--	5.9	70	137	176	160	69	130	188	108	4
13	0.30	1.14	0.03	--	6.9	60	64	111	81	50	100	164	58	10
14	0.12	0.42	0.10	--	4.8	40	61	89	109	17	50	101	39	8
11	0.10	1.30	0.05	--	5.8	20	39	53	65	-4	43	67	13	9

[A] ASTM number is the average of two or more determinations.

[B] The transition temperatures were defined as follows:

C_{V15} = temp. at which the average Charpy value was 15 ft-lb

C_{V25} = temp. at which the average Charpy value was 25 ft-lb

$C_{V50\%}$ = temp. at which the average energy Charpy value was 50 per cent of the maximum value recorded for the highest testing temperature

Per Cent fibrous texture = temp. where the average amountof fibrous texture was 15, 30, or 50 per cent

LE_{15} = temp. where the lateral expanison was 15 mils

[C] Average for specimens broken at the NDT temperature.

[D] Dashes indicate analysis was not made.

0.26/0.32 % C were, respectively, 7.6 and 9.1. This correlation between C and grain size would be expected to interfere with their effects on transition temperature. Higher Mn levels also resulted in finer ferrite grains. The seven steels containing 1.10/1.31 % Mn had an average ASTM ferrite grain size number of 8.8 in the hot-rolled condition. The ASTM grain size number of the seven steels containing 0.30/0.68 % Mn was 7.9. The average C contents of these high-Mn and low-Mn groups were 0.19 and 0.20 % respectively. The data in Table 3 show that higher Mn contents result in smaller grains and both characteristics are associated with greater resistance to brittle fracture. Apparently part of the beneficial influence of Mn on transition temperature results indirectly from the grain size effect.

The variations in grain size among the hot-rolled steels were too small to provide information about the influence of grain size on transition temperature. Therefore, two sets of experimental steels were heat-treated to change their grain sizes and to determine the effects on performance of drop-weight and Charpy specimens. The properties after normalizing from 1600 F and after furnace cooling from 1900 F are given in Table 4. The effects of the two treatments are summarized in Table 5. The changes in ferrite grain size resulting from normalizing the semikilled steels at 1600 F were small, less than 0.4 ASTM numbers on the average. Therefore, the data for those materials were neglected in preparing Table 5. Furnace cooling from 1900 F increased the average ferrite grain sizes of the killed and the semikilled steels as reflected by the 2.2 and 2.5 change on the ASTM scale, respectively.

Table 5 shows that lower transition temperatures are associated with finer ferrite grain sizes. For the various Charpy criteria a change in transition temperature of about 20 F correlates with a change of one ASTM number. This value agrees quite well with data previously obtained at Battelle[3] and by other investigators.

The NDT was less affected, (than CV TT,) by variations in grain size resulting from heat treatment. Nevertheless, the drop-weight transition temperatures were changed by heat treatment, a conclusion reached by other

TABLE 5

EFFECT OF HEAT TREATING HOT-ROLLED SHIP STEELS ON THE FERRITE GRAIN SIZE AND ON TRANSITION TEMPERATURES MEASURED BY DIFFERENT CRITERIA

	Normalized from 1600 F (7 Killed Steels)	Furnace Cooled from 1900 F (5 Killed, 5 semikilled Steels)
Average change in Ferrite grain size Number, ASTM scale	0.9	-2.3
	Average Change In Transition Temperature Per Change of One ASTM Number, F	
Nil-ductility temperature	-16	12
Charpy V-notch test		
15 ft-lb level	-20	22
25 ft-lb level	-22	24
50% max energy	-24	23
15% fibrous texture	-29	10
30% fibrous texture	-27	16
50% fibrous texture	-26	20
0.015 in. lateral expansion	-8	19

investigators.[8-10]

The grain size values were also included as one of the variables in a multiple-correlation analysis made on all of the experimental data. The factors indicating the independent effect of ferrite grain size on transition temperatures defined by various criteria are discussed in another section of the report.

Drop-Weight and Charpy Tests

The average NDT and (CV TT) of all hot-rolled laboratory steels are summarized in Table 3. The individual test data are listed in Tables A2 and A6 of Appendix A. Data obtained on some of the steels after specific heat treatments are listed in Table 4, (also in Tables A-3-5, 7-9 of Appendix A).

The data in the Tables 2 and 3 show that the NDT of the steels differing in composition and heat treatment ranged 130 F, from -60 to 70. This range is appreciably less than those for transition temperatures based on Charpy specimens. For example, the following comparisons are of interest:

Charpy Criterion	Transition Temperature, °F		
	Maximum	Minimum	Range
15 ft-lb level	137	-81	218
50 % maximum energy	160	-24	184
0.015 in. lateral expansion	108	-80	188
15 % fibrous texture	69	-82	151

The data indicate that the drop-weight test is less sensitive than the Charpy test in detecting the effects of the metallurgical variables investigated on this program.

Data in Tables 3 and 4 show that the amount of energy required to break a Charpy specimen at the NDT varied considerably among steels. Figure 1 shows that the Charpy values of both killed and semikilled steels were usually less than 16 ft-lb at the NDT, however, the distribution indicates that the killed steels generally absorbed slightly more energy at the NDT.

Although there were notable exceptions, the steels with lower C contents and higher Mn contents tended to have higher Charpy energy values when tested at the NDT. The two highest Charpy values of 40 and 70 ft-lb, were obtained in Steels 11 and 27 which contained about 0.11 % C and 1.29 % Mn. A tendency for steels with a low NDT to have higher Charpy values at the NDT was also noted.

Correlation Between NDT and CV TT

The Charpy test is relatively simple to perform and is used by most steel producers and many customers or fabricators. With the increasing interest in the drop-weight test it is desirable to find useful correlations between transi-

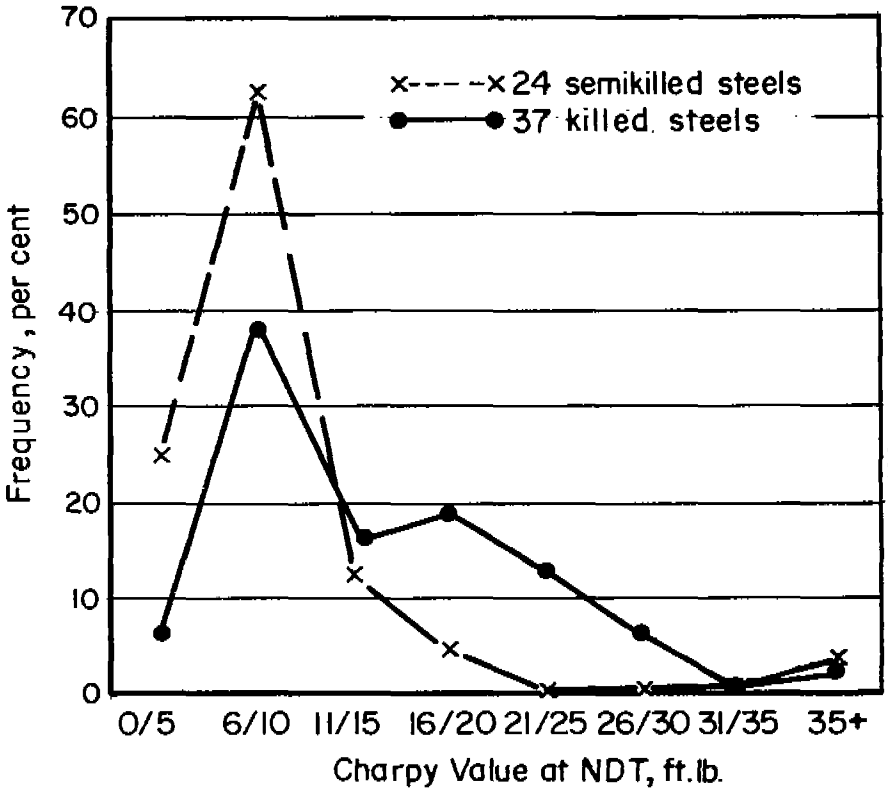

FIG. 1. FREQUENCY OF VARIOUS CHARPY VALUES IN TESTS MADE AT THE NDT ESTABLISHED BY DROP-WEIGHT TESTS.

tion temperatures determined in drop-weight tests and those defined with V-notch Charpy tests by various criteria.

Data on the correlation of the Charpy and the drop-weight test appear in the literature.[9,11-13] Gross[11] has shown that the lateral expansion transition temperature at a level of 0.015 in. has very nearly a one-to-one correlation with the NDT temperature. Other levels of expansion criteria as well as energy and fracture criteria have also been found to correlate with the NDT temperature.

Figures 2 and 3 show the correlation obtained for the Charpy criteria considered in this study. The regression lines shown in both figures were computed by standard statistical methods assuming the independent variable (in this case, the CV TT) to be correct. This method minimizes the error in the dependent variable or NDT in this case. Since similar degrees of error could be considered to exist in both tests, orthogonal-regression lines could also be computed for the data. This method does not assume either variable to be correct and minimizes the error normal to the line. For purposes of choosing a

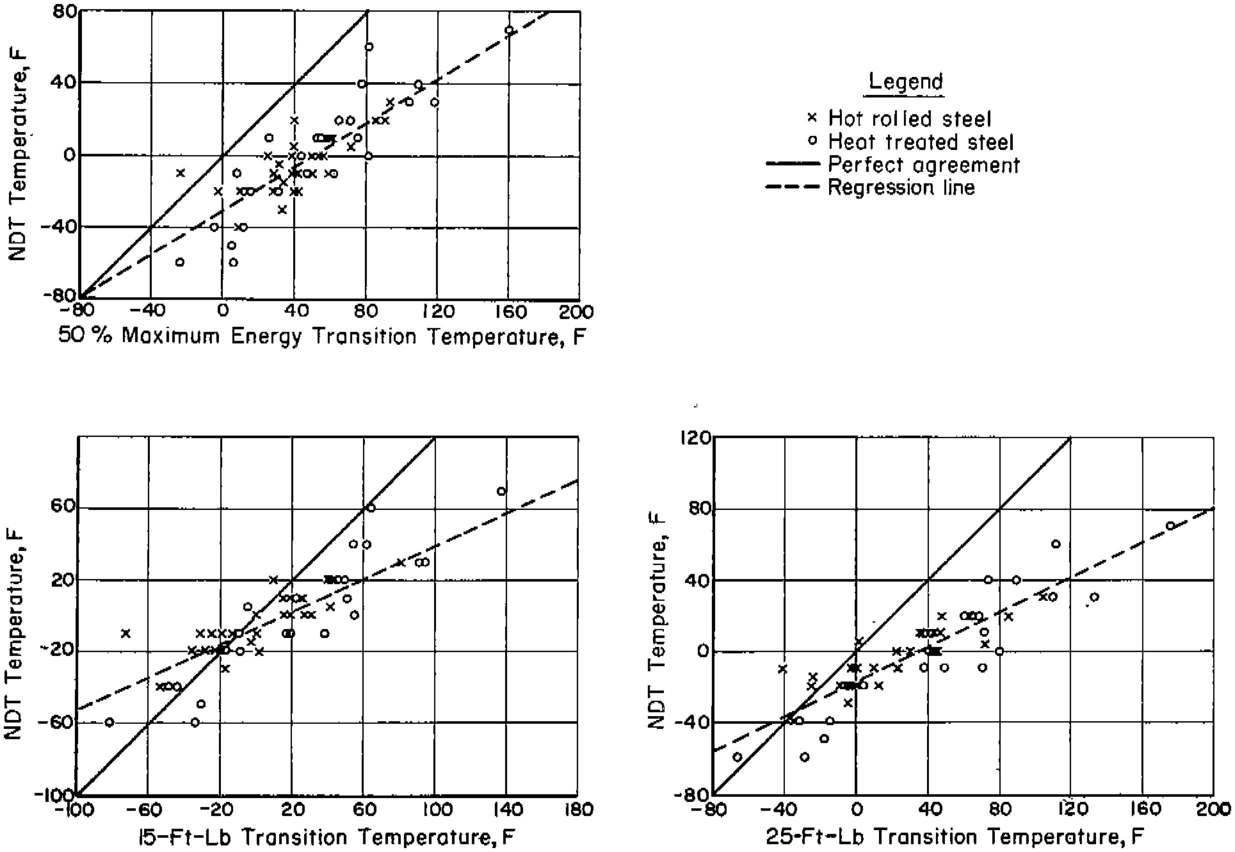

FIG. 2. RELATIONSHIP BETWEEN NIL-DUCTILITY AND CHARPY TRANSITION TEMPERATURE-ENERGY CRITERIA.

criterion for predicting the NDT temperature from Charpy data the orthogonal method of analysis is the more desirable. However, the authors do not feel that the range of steel compositions and conditions tested for this program was sufficient to warrant the calculation of the more involved orthogonal-regression lines. Furthermore, standard-regression analysis readily lends itself to the computation of the error associated with the regression line.

The regression equations, standard-deviations, and fraction of variance removed by the correlations are given in Table 6. The r^2 (fraction of variance accounted for by the correlation) values listed indicate the correlations are highly significant at the 99 % probability level. In other words, the various Charpy criteria actually do correlate closely with the NDT temperature. With the exception of the 15-ft-lb criterion which showed a significantly poorer relationship, the correlations have about the same degree of significance. The

TABLE 6

STANDARD REGRESSION EQUATIONS RELATING NIL-DUCTILITY AND VARIOUS CHARPY V-NOTCH TRANSITION TEMPERATURES

Charpy V-Notch Criterion	Regression Equation
	Energy Absorption Criteria
15 ft-lb	NDT, F = 0.46 (15 ft-lb TT, F) - 7 F S. D* = ± 17.5 F; r^{2**} = 0.563
25 ft-lb	NDT, F = 0.48 (25 ft-lb TT, F) - 18 F S. D. = ± 12.8 F; r^2 = 0.764
50% of Max. Energy	NDT, F = 0.62 (50% M.E. TT, F) - 31 F S. D. = ± 14.1 F; r^2 = 0.703
	Fracture-Appearance Criteria
15% Fibrous	NDT, F = 0.72 (15% Fibrous TT, F) + 3 F S. D. = ± 13.9 F; r^2 = 0.725
30% Fibrous	NDT, F = 0.64 (30% Fibrous TT, F) - 20 F S. D. = ± 14.6 F; r^2 = 0.696
50% Fibrous	NDT, F = 0.57 (50% Fibrous TT, F) - 38 F S. D. = ± 12.1 F; r^2 = 0.791
	Lateral Expansion Criterion
15 mil	NDT, F = 0.60 (LE_{15} TT, F) - 4 F S. D. = ± 14.0 F; r^2 = 0.721

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*S. D. = standard deviation about fitted line.

**r^2 = Fraction of the variance removed or accounted for by the correlation. Values of r^2 may range between 0 and 1. A high value of r^2 indicates a close relationship between the variables, whereas a low value indicates a poor relationship between variables.

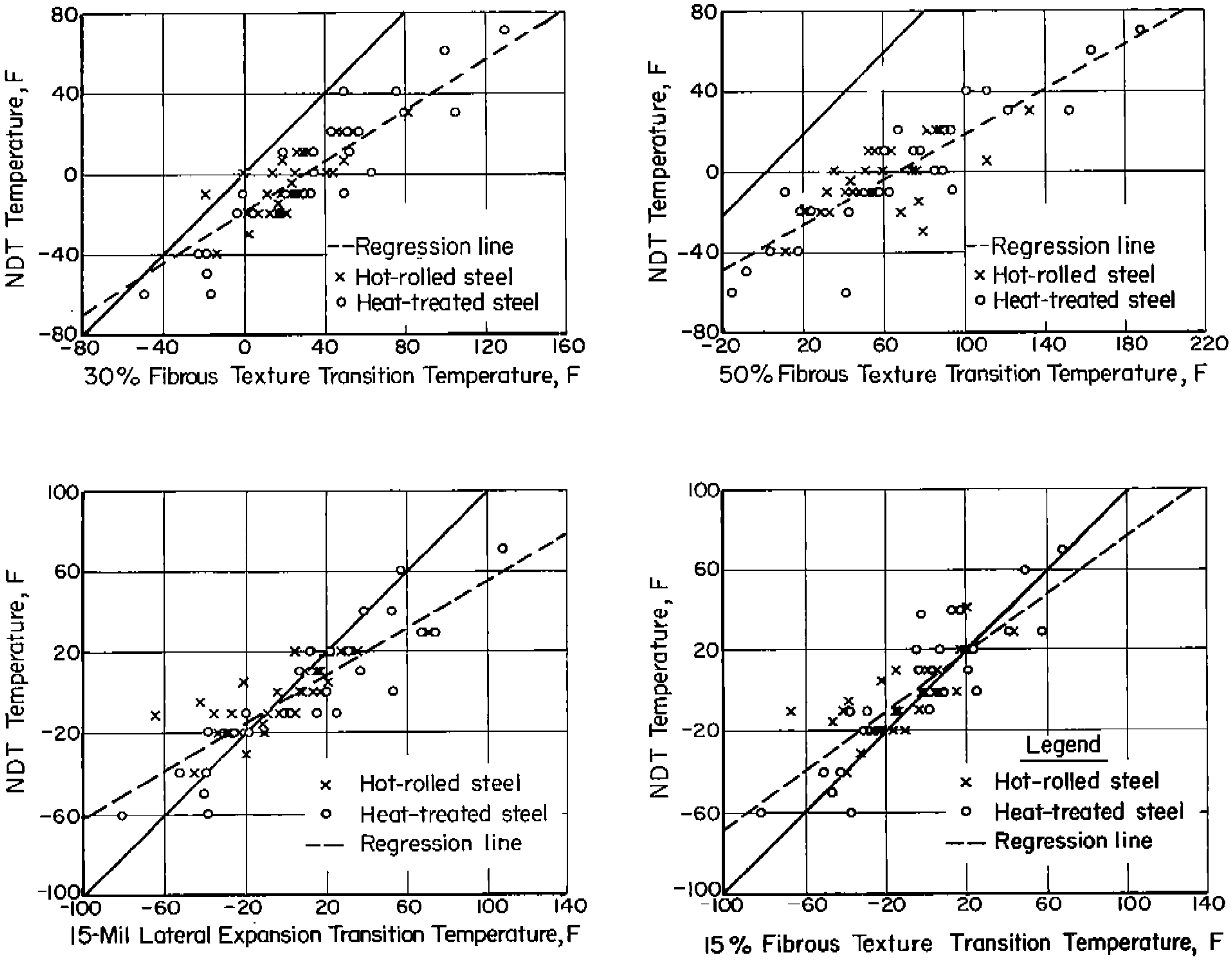


FIG. 3. RELATIONSHIP BETWEEN NIL-DUCTILITY AND CHARPY TRANSITION TEMPERATURES-- FRACTURE APPEARANCE AND LATERAL EXPANSION CRITERIA.

spread or scatter in the data as represented by the standard deviation ranged from ± 12.1 F for the 50 % fibrous criterion to ± 17.5 F for the 15 ft-lb criterion. Considering that the estimated sensitivities of the NDT and Charpy tests are 10 and 15 F, respectively, the scatter is reasonable.

Because of the low standard deviation and the fact that the slope most nearly approaches one (slope of the line of perfect agreement), the correlation of the 15 % fibrous criterion with NDT is considered the most useful one found in this study. Other criteria do not correlate as well. That low percentages of fibrous fracture might correlate well with the NDT test was suggested by Gross.[11] The existence of a reasonable correlation for this criterion would also be predicted from the fact that the regression coefficients determined for the effects of composition and grain size in a multiple correlation analysis of the data are quite similar for the two tests.

The correlations noted for this project are further evidence that appropriate Charpy transition criteria do correlate with the transition temperature determined by the drop-weight test. Based on these data and the work of other investigators, it appears that Charpy criteria such as lateral expansion and fibrous fracture show good correlations.

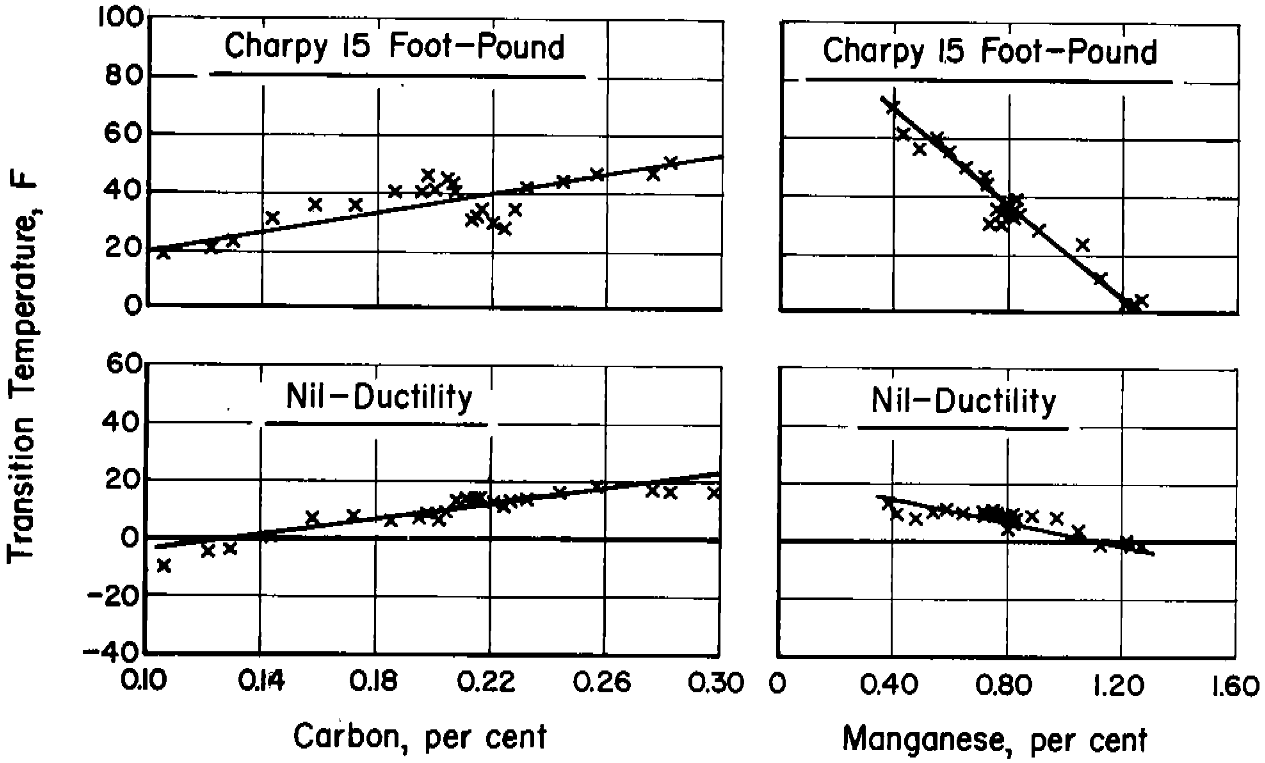
Figures 2 and 3 also show the changing relationship that these tests have with respect to temperature. A critical temperature exists for each criteria where the CV TT is higher than the NDT, and below this critical temperature the reverse situation occurs. For example, steels with a CV15 TT of 60 F would be expected to have an NDT of 20 F, or 40 degrees lower. At -20 F, however, the two transition temperatures are the same. But at a CV15 TT of -60 F, the NDT is -30 F, or 30 degrees higher.

EFFECTS OF COMPOSITION ON TRANSITION TEMPERATURES

Since the analyses of the experimental steels covered a reasonably wide range in composition, the effects of various elements on transition temperatures could be estimated with fair precision. Two different techniques were employed to estimate the effects of differences in C, Mn, Si, and Al contents on NDT and CV15 TT. The first approach was based on simple correlation analyses of transition temperatures with one variable at a time. The second technique, a multiple-correlation study with an electronic computer also showed the effects of ferrite grain size on transition temperatures. In addition it showed the independent effects of grain size and composition on several other V-notch Charpy characteristics of interest.

Simple Correlation Analyses

The simple correlation analyses were made by stepwise graphical procedures. First, the transition temperatures of steels with otherwise similar compositions were plotted against the variable of interest to get a preliminary estimate of its effect. Such plots gave useful approximations of the effects of each



(Transition temperatures adjusted to 0.20% C or 0.80% Mn, 0.05% Si, and nil Al. Points represent moving average of five measured values)

FIG. 4. EFFECT OF CARBON AND MANGANESE ON CHARPY 15 FT-LB AND NIL-DUCTILITY TRANSITION TEMPERATURES OF HOT-ROLLED STEELS WITH NO ADJUSTMENT FOR GRAIN SIZE VARIATIONS.

variable during the course of the investigation. Next, when all data were available, moving averages* for groups of five steels were computed after the data had been arranged in increasing order of the compositional variable of major interest. These averages were then corrected, on the basis of the approximate factors mentioned above, for minor variations in other compositional variables. Finally, these corrected running averages were plotted to obtain improved estimates of the effects of variations in C, Mn, Si, and Al contents. Plots obtained in this way are shown in Figs. 4 and 5.

Figures 4 and 5 indicate the following effects of compositional variations on transition temperatures:

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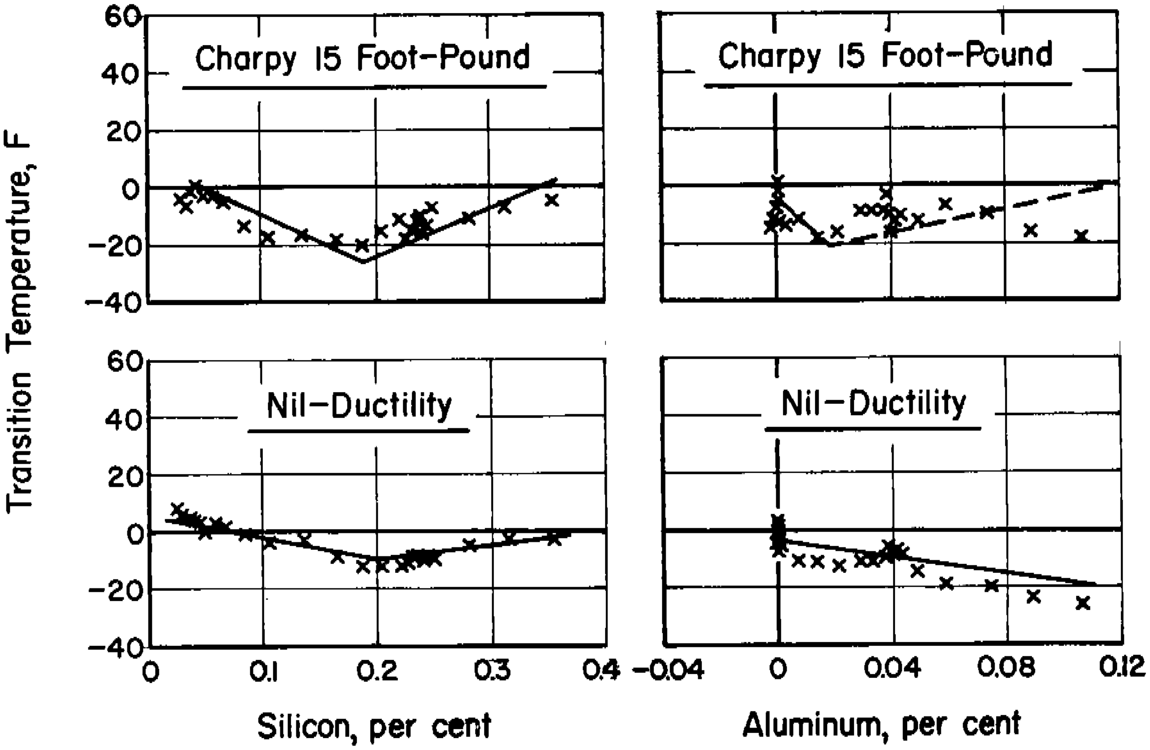
*The running or moving average, as used in Figs. 4 and 5, is a device for obtaining a series of figures which indicate the trend of data better than individual readings because fluctuations are averaged out in the calculations.

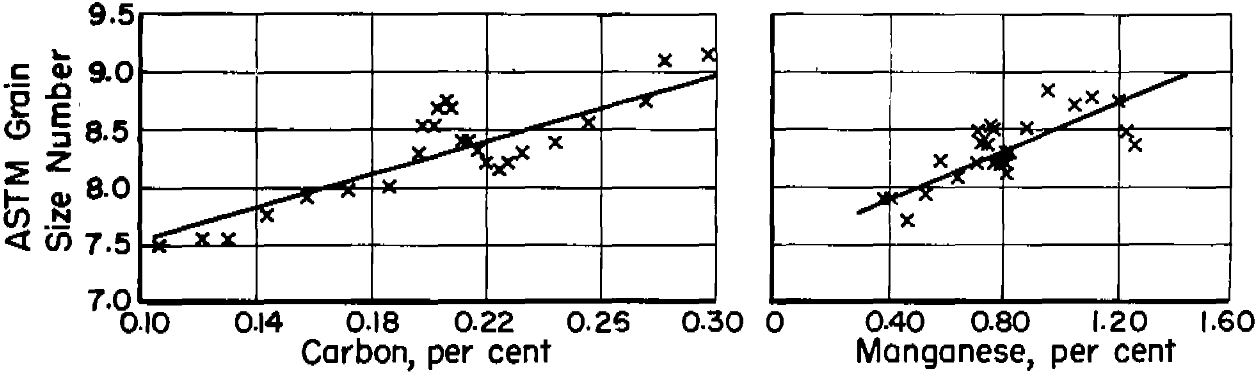


(Transition temperatures adjusted to 0.20% C, 0.80% Mn, and 0.20% Si or 0.030% Al. Points represent moving average of five measured values.)

FIG. 5. EFFECT OF SILICON AND ALUMINUM ON CHARPY 15 FT-LB AND NIL-DUCTILITY TRANSITION TEMPERATURES OF HOT-ROLLED STEELS.

Change in Composition	Range Covered, %	Change in NDT	Change in CV15
Increase of 0.01% Carbon	0.10/0.30	1.35 F	1.8 F
" of 0.01% Manganese	0.40/1.25	-0.2	-0.85
" of 0.01% Silicon	0.02/0.20	-0.6	-2.0
" of 0.01% Aluminum	0.00/0.03	-1.8	-8.0

These apparent effects of the elements on transition temperatures should not be accepted without several reservations because of the assumptions underlying the treatment of the data. For example, the treatment implies that the effect of one alloying element is not influenced by variations in the amounts of other elements present. Secondly, it is implied that the changes in transition temperatures are caused entirely by the major variable plotted and not by another



(Points represent the moving average of five measured values)

FIG. 6. EFFECT OF CARBON AND MANGANESE ON THE FERRITE GRAIN SIZE OF STEELS HOT-ROLLED IN THE LABORATORY.

strongly correlated factor. In the present case, it appears that part of the apparent effects attributed to C and Mn, in Fig. 4, may be caused by variations in ferrite grain size.

Figure 6 shows that increases in either C or Mn contents of the experimental steels were accompanied by finer ferrite grain sizes. Consequently, it appears reasonable to attribute part of the changes in transition temperatures to indirect effects of C and Mn on grain size. Figure 6 indicates that increasing the C and Mn contents by 0.01 % increases the ASTM grain size numbers by 0.075 and 0.01, respectively. Various investigators have reported that an increase of one ASTM grain size number lowers the CV15 TT approximately 20 F. Based on these estimates, it appears that the grain size variations resulting from increasing C and Mn contents by 0.01 % would account for decreases of 1.5 F and 0.2 F in CV TT, respectively. Variations in Si and Al contents did not have a significant effect on the grain size of the hot-rolled steels used for this study.

The factors indicating the effects of C, Mn, and grain size on transition temperatures of the experimental ship steels can be combined as follows:

	Change in CV15 TT for the Compositional Change Indicated	
	+0.01 % C	+0.01 % Mn
Indirect effect through grain size	-1.5 F	-0.20 F
Apparent effect from Fig. 4	1.8	-0.85
Effect for constant grain size	3.3	-0.65

The different factors listed above can be used for predicting differences in CV15 TT to be expected from changes in composition. The choice of the proper factor depends on whether the grain size of the steel is known or not. Similar calculations for the effects of C and Mn on NDT were not made because no independent estimates of the influence of grain size were available.

Multiple Correlation Analysis of Experimental Data

A multiple regression analysis of the data for compositions in Table 1 and the transition temperature and grain size-date in Tables 3 and 4 was made by computer techniques. The data obtained on both hot-rolled and on heat-treated samples were used for the correlation analysis. Multiple regression analysis is a standard statistical method for establishing the effects of a number of independent variables on a dependent variable. In this case, the dependent variable of interest was transition temperature. The object of the statistical analysis was to find an equation which best fitted all of the data points. The relationship expressed by a regression equation may be either linear or curvilinear. In this case, previous experience and preliminary study of the data indicated that Si and Al might have curvilinear effects and that Si might have interacting effects with Al and Mn. Therefore, the computer program used for the analysis allowed for these possibilities. The results of the multiple correlation analysis are summarized in Table 7. Auxiliary data, definitions of terms, and a brief discussion of the statistical techniques employed are presented in Appendix B.

The general form of the equation to determine the transition temperature for the NDT or seven Charpy criterion is as follows:

$$\begin{aligned}\text{Transition Temperature} = {} & a + b(\%C) + c(\%Mn) + d(\%Si) + e(\%Si)^2 \\ & + f(\%Si)(\%Mn) + g(\%Al) + h(\%Al)^2 + j(\%Al)(\%Si) \\ & + k(\text{ASTM No.})\end{aligned}$$

where the lower case factors a, b, c, ...etc. are obtained from Table 7.

The standard errors listed in Table 7 indicate how well the regression equation fit the experimental data. The standard error of a regression equation

TABLE 7

FACTORS[A] FOR CALCULATING THE EFFECTS OF C, Mn, Si, Al, AND FERRITE GRAIN SIZE ON THE DROP-WEIGHT AND CHARPY V-NOTCH TRANSITION TEMPERATURES[B]

Criterion	C	Mn	Si	$(Si)^2$	SiXMn	Al	$(Al)^2$	AlXSi	ASTM Ferrite Grain Size Number	Constant	Standard Error for Equation
						Drop-Weight Test					
NDT	210	-15.9	-182	377	-6.9	-159	321	-258	-11.0	77.2	11.4 F
						Charpy V-Notch Test					
15 Ft-lb	333	-66.6	-269	210	116	-512	2849	367	-18.1	168	16.9 F
25 Ft-lb	456	-61.3	-265	216	111	-583	3228	360	-20.2	178	16.8 F
50% max energy	291	-68.3	-352	332	211	-356	2601	-135	-15.5	189	15.3 F
15% shear fracture	297	-22.0	-8.6	-118	5.8	-449	2580	-128	-12.1	60.5	14.3 F
30% shear fracture	347	-27.8	-141	171	24.0	-334	1329	282	-15.3	119	14.7 F
50% shear fracture	439	-36.1	-257	246	84.6	-375	1121	975	-18.9	177	18.4 F
Lateral expansion at 15 mils	331	-52.0	-237	173	105	-458	3056	131	-16.0	129	13.7 F

[A] The factors or regression coefficients are used in the following transition temperature equation for calculating the NDT transition temperatures based on composition and ferrite grain size:

$$\text{NDT, F} = (210 \times \%\text{C}) - (15.9 \times \%\text{Mn}) - (182 \times \%\ \text{Si}) + (377 \times \%\text{Si}^2) - (6.9 \times \%\ \text{SiX\%Mn}) - (159 \times \%\text{Al}) + (321 \times \%\text{Al}^2)$$
$$-(258 \times \%\text{Al} \times \%\text{Si}) - (11.0\ \text{X ASTM ferrite grain size number}) + 77.2$$

[B] Calculations based on steels covering the following ranges: 0.10/0.32% C, 0.30/1.31% Mn, 0.02/0.43% Si, nil/0.136% acid-soluble Al.

is roughly analogous to the standard deviation used to report the scatter among experimental observations on ostensibly identical samples. Both statistics are measures of residual or unexplained variability. Table 7 shows that the standard errors of the regression equations range from 11.4 to 18 F. These values indicate the equation fits the experimental data quite well, apparently within the precision expected for transition-temperature determinations.

The statistics given in Appendix B also indicate that a high degree of confidence can be placed in the significance of the multiple correlation coefficients and regression equation. For example, the coefficients of multiple correlation indicate that the independent variables considered in the equations account for 82 to 89 per cent of the variance in transition temperatures found by testing.

The regression coefficients or factors used to calculate various types of transition temperatures from grain size and compositions, in general, have qualitatively similar effects on the NDT and each of the seven CV TT criteria. For instance, finer grain sizes are associated with lower transition temperatures defined by any criterion considered. However, the effect of a particular change in composition or grain size on transition temperatures differs quantitatively among tests.

For example, the linear effects of certain metallurgical changes* on the transition temperatures defined by various criteria are:

	NDT	Charpy, 15% Fibrous	Charpy V15
Increase of 0.01% C	2.10 F	2.97 F	3.33 F
" of 0.01% Mn	-0.16	-0.22	-0.67
" of 0.01% Si	-1.82	-0.09	-2.69
" of 0.01% Al	-1.59	-4.49	-5.12
Refining of ferrite grain size by one on ASTM scale	-11.0	-12.1	-18.1

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*These factors, or regression coefficients, are for steels containing 0.10/0.30% C, 0.40/1.25% Mn, 0.02/0.20% Si, and 0.00/0.03% Al. The factors do not take into account any of the possible curvilinear effects (e.g., Si^2) which may exist.

This tabulation indicates that the NDT is less sensitive to variations in C, Mn, Si, and Al contents, and to grain size than in the CV15 TT level. The sizes of the regression coefficients also indicate that the effects of the metallurgical variables on the Charpy 15 % fibrous texture transition temperature are intermediate between those shown by the other tests. The only exception is that the temperature associated with small amounts of fibrous texture is least affected by Si content.

In passing, it is worth mentioning that the regression coefficients showing the effects of C, Mn, Si, and ferrite grain size on the CV15 TT, shown in Table 7 are in reasonably good agreement with those reported by Harris[14] and other investigators. They also agree with the factors indicating the effects of C and Mn on the transition temperatures of steels with equal grain sizes given in the previous section of this report.

COMPARISON OF EXPERIMENTAL AND CALCULATED TRANSITION TEMPERATURES

Probably the best way to illustrate the utility of the equation derived through multiple correlation analysis is to compare calculated results with experimental transition temperatures. This was done for the drop-weight and Charpy test for steels made on this project and for commercial steels and for steels made in other laboratories.

Figure 7 compares the experimental and calculated NDT values for laboratory steels made for this study. The agreement is very good, about two-thirds of the points fall within ± 10 F of the line for perfect agreement. This is probably as good as can be expected for this test.

Figure 8 shows the correlation between calculated and experimental CV15 TT of the steels made and tested for this program. The values agree within ± 15 F which is a reasonable estimate of the reproducibility of the Charpy test. The scatter shown by Fig. 7 and Fig. 8 is within the limits expected from the standard errors of the multiple regression equations.

Figures 9 and 10 give similar comparisons between transition temperatures

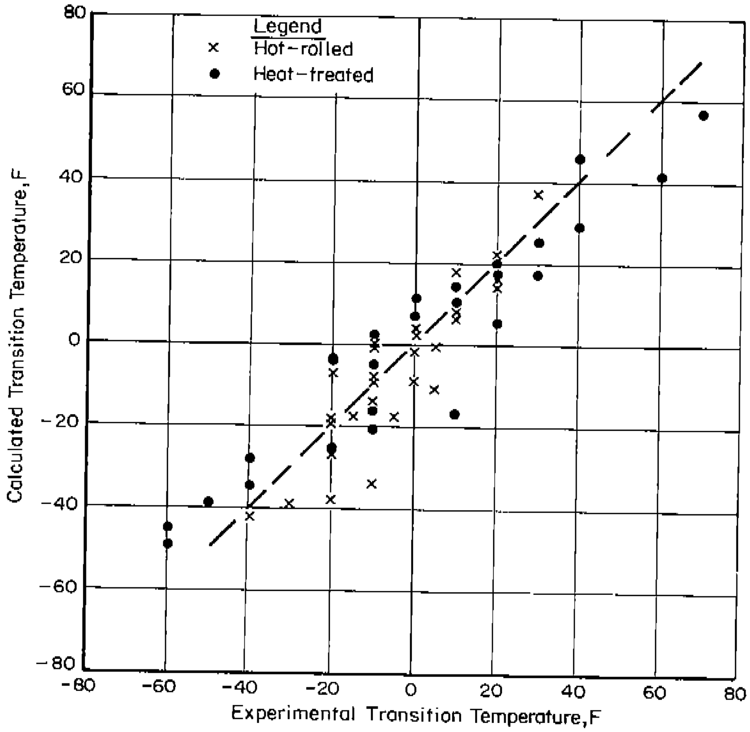

FIG. 7. CORRELATION OF EXPERIMENTAL AND CALCULATED NIL-DUCTILITY TRANSITION TEMPERATURES FOR LABORATORY STEELS.

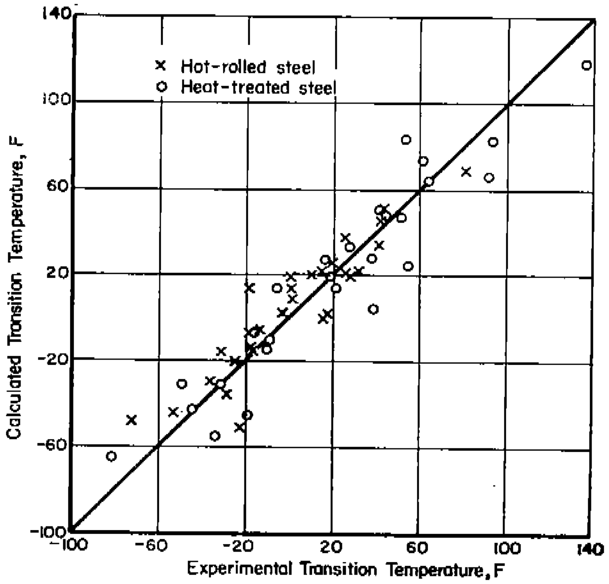

FIG. 8. COMPARISON OF EXPERIMENTAL AND CALCULATED CHARPY 15 FT-LB TRANSITION TEMPERATURE FOR LABORATORY STEELS MADE ON THIS PROJECT.

reported for hot-rolled steels by other investigators and those calculated by formulas developed on this project. The information available for the calculations and for preparing the figures is recorded in Appendix A. When the grain sizes were known, the transition temperatures were calculated by the equation obtained by multiple correlation analysis illustrated in Table 7. Unfortunately, the grain sizes had not been reported for 29 of the 62 steels. In those cases

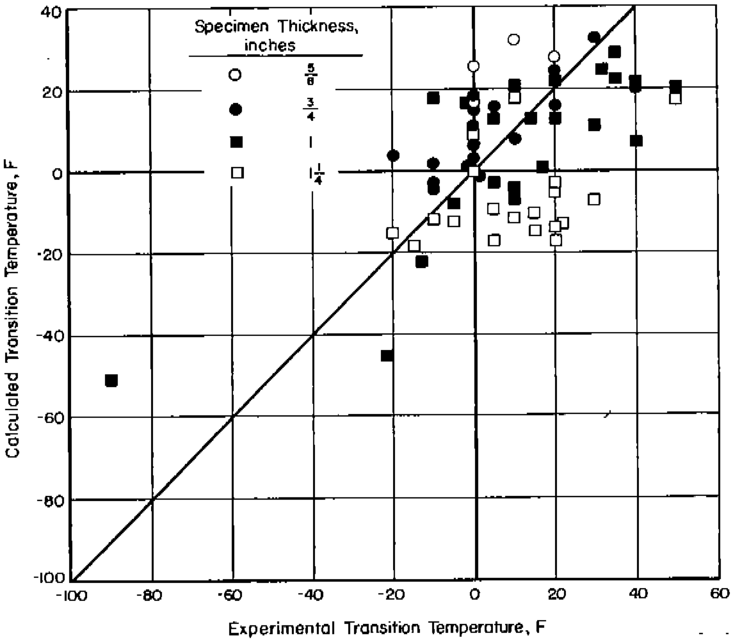

FIG. 9. COMPARISON OF EXPERIMENTAL AND CALCULATED NIL-DUCTILITY TRANSITION TEMPERATURES FOR COMMERCIAL AND LABORATORY STEELS OTHER THAN THOSE TESTED ON THIS PROJECT.

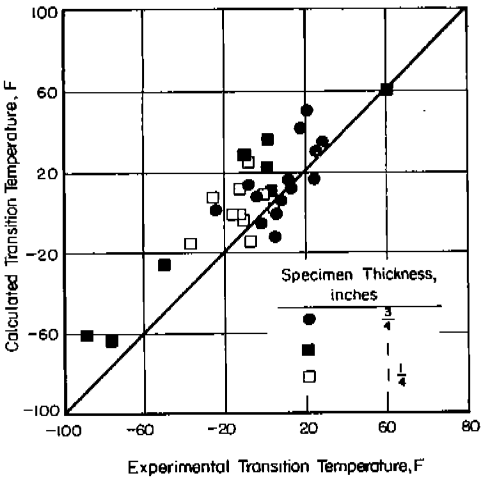

FIG. 10. COMPARISON OF EXPERIMENTAL AND CALCULATED CHARPY 15 FT-LB TRANSITION TEMPERATURE FOR COMMERCIAL AND LABORATORY STEELS OTHER THAN THOSE TESTED ON THIS PROJECT.

the transition temperatures used for the comparisons were calculated by the following equations:

$$\text{NDT, F} = 0\text{ F} + 135\,(\%\,C) - 20\,(\%\,Mn) - 60\,(\%\,Si) - 180\,(\%\,Al)$$

$$\text{V15 Charpy, F} = 80\text{ F} + 180\,(\%\,C) - 85\,(\%\,Mn) - 200\,(\%\,Si) - 800\,(\%\,Al)$$

These formulas are based on the simple (not multiple) correlation analyses of the data obtained on the 5/8-in. thick laboratory plates.

Figure 9 shows that about half of the calculated and experimentally determined NDT fall within ± 10 F of the line for perfect agreement. However, the dispersion of the points around the trend line was affected by the plate thickness at which the tests were made. Specifically, the relationships between calculated and measured NDT were as follows:

Specimen Dimensions, in.	Number of Specimens		Calculated-Measured NDT, F
	Total	Below Trend Line	
3-1/2 x 14 x 5/8	4	0	+ 18
3-1/2 x 14 x 3/4	17	4	+ 5-1/2
3-1/2 x 14 x 1	22	16	- 3
3-1/2 x 14 x 1-1/4	19	15	- 16

These comparisons indicate that the equations developed on this project from data for 2 x 5 x 5/8-in. specimens fit experimental data obtained on 3/4 or 1-in. plate by 3-1/2 x 14 in. specimens quite well. Apparently the differences in length, width, and thickness compensate so the specimens give approximately equivalent results. On the other hand, the equation predicts NDT about 16 F below those obtained experimentally with 3-1/2 x 14-in. specimens on 1-1/4 in. plate. This indicates that the conditions recommended for 1-1/4 in. plate are more severe than those recommended for 1, 3/4, and 5/8-in. plate. Conversely, Puzak's data[1,5] for the 3-1/2 x 14 x 5/8-in. specimens indicate they were tested under conditions less severe than those for 2 x 5 x 5/8-in. specimens. Similar experiences led Puzak and Babecki[4] to recommend 2 x 5-in. specimens for drop-weight tests on 5/8-in. plate.

Figure 10 illustrates the extent of the agreement between calculated CV15 TT and those determined experimentally by other investigators.[15-16] Almost two-thirds of the points fall within ± 15 F of the trend line; this indicates reasonably close agreement. It is apparent, however, that for most of the cases showing poorer agreement the calculated transition temperature is higher than that obtained by experiment. This type of nonuniform distribution around the trend line would occur if the factor for grain size, used in the calculations, was too small. This appears to be the most likely explanation because the factor of -18 F for an increase of one ASTM grain-size number was used to calculate all but three of the points in Fig. 10. That factor, obtained from the multiple correlation analyses is smaller than the values of 20 to 25 F per grain-size number reported by others.

EXPERIMENTAL WORK ON COMMERCIAL PLATES

The National Bureau of Standards tested a number of 1-1/4-in. thick Class C and 3/4-in. thick Class B commercial ship plate. The average compositions of the two types of ship plate were:

	%C	%Mn	%Si	%Al
Class B, 3/4 in.	0.18	0.98	0.04	<0.01
Class C, 1-1/4 in.	0.16	0.71	0.24	0.04

Their results indicated that the average NDT for the Class C steels was 13 F above the average for the Class B steels.[17] This finding was disconcerting because the average CV15 TT was 21 F lower for the Class C than for the Class B steels. Furthermore, the present investigation indicates that the Class C steels made by fine-grained melting practice should have had lower NDT than the semikilled Class B steels when tested under comparable conditions. Consequently, a brief study on factors which might account for the discrepancies seemed desirable. For this reason two of the commercial steels supplied by the National Bureau of Standards were subjected to drop-weight tests in various conditions. The data are recorded in Table 8.

Table 8 shows that the NDT predicted by the regression equation developed on this project varied by only 5 F and 9 F from those measured on 2 x 5 x 5/8-in. specimens machined from the two 1-1/4-in. commercial Class C steels. The calculated and experimental data for heat-treated samples agree almost as well. In seven of eight cases, the predicted values

TABLE 8

DROP-WEIGHT TRANSITION TEMPERATURES OF CLASS C STEELS FROM NATIONAL BUREAU OF STANDARDS FOR VARIOUS CONDITIONS AND SPECIMEN SIZES[A]

				Nil-Ductility Temperature for Specimens Indicated		
			ASTM Grain	2 x 5 x 5/8 in.		3-1/2 x 14 x 1-1/4 in.
Heat	Plate	Condition	Size No.	Calculated	Measured	Measured
C 6	250	Rolled commercially	6.9	- 5 F	0 F	10, 20,[B] 30 F
C13	296	" "	7.4	- 9	0	20
C13	296	1 hour 1600 F, Furnace cooled	9.4	-30	--	0
C13	297	1 hour 1600 F, Furnace cooled	10.1	-38	-30	--
C 6	250	Rerolled to 5/8 in. in laboratory	8.3	-20	-10	--
C13	296	Rerolled to 5/8 in. in laboratory	7.9	-14	-10	--
C 6	250	Rerolled, 1 hour 1600 F, Furnace cooled	9.4	-33	-40	--
C13	296	Machined, 1 hour 1600 F, Furnace cooled	9.4	-30	-30	--
C 6	250	Rerolled, 1 hour 1600 F, Air cooled	9.2	-31	-50	--

[A] Analyses and grain sizes supplied by National Bureau of Standards for the plates rolled commercially were:

Plate 250, 0.15% C; 0.74% Mn; 0.24% Si; 0.03% Al; ferrite grain size No., 7.1
Plate 296, 0.19% C; 0.80% Mn; 0.24% Si; 0.05% Al; ferrite grain size No., 7.2
Plate 297, 0.19% C; 0.81% Mn; 0.26% Si; 0.05% Al; ferrite grain size No., 7.2

[B] In tests at the National Bureau of Standards the NDT value was 20 F at the edge and 10 F at the center of the plate.

agree with NDT measured on small specimens within 11.4 F, the standard error of the regression equation. This is as good agreement as should be expected. Therefore, the data are consistent with the opinion that steels made to fine-grained practice perform better in drop-weight tests than semikilled steels under otherwise similar conditions.

The changes in NDT associated with heat treatment, in Table 8, are of the order expected for the differences produced in ferrite grain size.

When the differences in grain size are taken into account, the NDT of the 5/8-in. plate rerolled in the laboratory agree closely with those of samples machined from the 1-1/4-in. plate rolled commercially.

Table 8 also shows that the NDT were 10 to 30 F higher on 3-1/2 x 14 x 1-1/4-in. specimens than for test on 2 x 5 x 5/8-in. specimens. The average difference of 20 F, attributable to plate thickness and testing conditions, is similar to the value of 16 F estimated from data discussed in the previous section. Apparently the effect of increasing the plate thickness from 5/8 in. to 1-1/4 in. is not entirely eliminated by the changes in specimen dimensions, span, and deflection limits recommended by investigators at the Naval Research Laboratory.[4] On the other hand, the data in Fig. 9 indicate that the 3/4- and 1-in. by 3-1/2 x 14-in. samples have an NDT comparable to those expected for 2 x 5 x 5/8-in. specimens.

CONCLUSIONS

The objective of this investigation was to establish, quantitatively, the effects of certain metallurgical variables on the performance of ship steels in the drop-weight test. To provide an internal check and to permit comparisons with other investigations, parallel studies were made on Charpy specimens.

The steels made and processed in the laboratory covered the following ranges in composition; 0.10/0.32% C, 0.30/1.31% Mn, 0.02/0.43% Si, nil/0.136% acid-soluble Al.

The information obtained during the study justify the following conclusions:

1. The ABS-Class B and ABS-Class C type ship steels made and processed in the laboratory for this study had properties comparable to those of similar materials produced commercially.
2. An equation derived from the experimental data shows, quantitatively, the effects of composition and ferrite grain size on

NDT and on CV TT, defined by seven different criteria, for pearlitic steels.

3. The drop-weight test is less sensitive than the Charpy test to variations in grain size, or in C, Mn, Si, and Al contents. Qualitatively, however, the variables investigated had similar effects on drop-weight and Charpy transition temperatures.

4. For the steels investigated and adjusted for constant grain size, raising the C content 0.01 % raised the NDT and CV15 TT 2.1 F and 3.3 F, respectively.

5. Raising the Mn content 0.01 % lowers the NDT and CV15 TT 0.16 F and 0.67 F, respectively.

6. There appears to be an optimum Si content for obtaining a low transition temperature. In the range up to 0.25 %, raising the Si content by 0.01 % lowers the NDT and CV15 TT 1.8 F and 2.7 F, respectively. There is some support for the opinion that increasing the Si content above 0.25 % raises the transition temperature.

7. Raising the Al content 0.01 % lowers the NDT 1.6 F. Charpy data indicate raising the Al content 0.01 % lowers the CV15 TT 5.1 F in a range to 0.02 % but scatter prevents further analysis.

8. Differences of 11.0 F in NDT and 18.1 F in CV15 TT are associated with a difference of one number on the ASTM grain-size scale. Finer ferrite grain sizes are preferable.

9. Drop-weight transition temperatures calculated from equations given in the report, based on 5/8 in. plate, agree quite closely with experimental values reported for Class B ship steel. The agreement is poor for Class C ship plate which is furnished and tested in heavier thicknesses.

10. The poor agreement between calculated and experimental values for 1-1/4 in. Class C steels is attributed to the failure of recommended procedures for drop-weight tests to compensate for embrittling effects of heavier plate thicknesses. It therefore appears desirable to determine the effects of variations in the geometrical and procedural factors of the drop-weight test.

11. Equations were developed for estimating the NDT from any one of seven different Charpy transition temperature criteria.

12. A critical temperature exists for each of the seven criteria whereby the CV TT is higher than the NDT above the critical temperature and lower than the NDT below the critical temperature.

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TABLE A-1

TENSILE* DATA FOR HOT-ROLLED LABORATORY STEELS FINISHED AT 1850 F

Heat Number		Yield Strength,	Tensile Strength,	Elongation Per Cent	
Battelle	Assigned	0.2% Offset	psi	in 8 in.	in 2 in.
B 6353	1T	32,800	59,700	30.9	54.0
		33,700	60,200	28.0	51.0
B 6327	2T	35,800	63,700	27.9	50.0
		36,600	64,600	28.8	52.0
B 6932	2-2	39,500	66,900	29.0	48.5
		40,600	67,900	31.0	48.0
B 6366	3T	43,000	71,600	23.5	47.0
		42,400	71,600	25.9	48.0
B 6367	4T	35,900	58,400	24.0	51.5
		36,400	59,100	28.9	52.5
B 6360	5T	39,500	69,400	22.5	36.0
		39,200	70,000	24.0	44.5
B 6368	6T	49,200	82,500	20.1	39.0
		49,400	82,300	20.0	38.5
B 6359	7T	32,500	53,300	28.0	52.0
		31,800	54,300	30.7	51.0
B 6406	8T	35,000	61,000	27.9	49.5
		35,500	61,900	30.6	51.0
B 6409	9T	36,300	63,100	29.0	51.0
		35,700	63,000	29.2	52.0
B 7064	9-2	36,000	62,600	29.5	50.0
		36,200	63,100	32.0	57.5
B 6464	10T	39,400	70,200	27.8	53.0
		39,100	69,600	27.7	50.0
B 6410	11T	35,200	57,900	30.7	57.5
		35,200	58,400	30.9	57.0
B 6405	12T	33,700	63,200	25.1	46.0
		34,200	63,300	26.1	45.0
B 6427	13T	41,400	79,300	25.0	47.5
		39,900	79,000	24.7	46.5
B 6361	14T	28,600	50,200	30.8	49.5
		30,800	52,100	**	**
B 6903	15	39,200	62,400	31.0	57.0
		38,700	62,300	32.0	57.5
B 6880	16	33,300	57,500	31.0	56.0
		33,900	57,700	31.5	53.0
B 6879	17	41,300	72,100	26.0	47.0
		44,400	73,100	27.5	48.5
B 6904	18	38,900	69,600	28.0	47.5
		39,700	70,000	28.0	49.0
B 6930	19	41,400	71,300	26.0	47.5
		41,300	71,000	26.0	**
B 6931	20	35,600	62,700	21.5	38.0
		36,200	63,800	30.0	**
B 6914	21	45,100	71,900	27.0	51.5
		45,300	71,800	28.5	49.0
B 6933	22	36,900	64,300	32.0	54.0
		37,200	64,200	29.0	53.5
B 6913	23	38,400	64,800	26.0	47.0
		39,400	65,900	26.5	50.5
B 6929	24	36,400	66,500	29.0	43.0
		37,400	65,900	28.5	54.0
B 7191	25	39,800	68,900	—	45.0
		40,300	69,000	—	42.0
B 7192	26	42,700	73,200	—	45.0
		42,800	73,100	—	44.0
B 7193	27	39,400	65,700	—	44.0
		39,900	66,000	—	48.0

*Full plate thickness tensile specimens were 21.5 in. long by 2 in. wide with a gage section 1 1/2 in. wide by 8 in. long.

**Broke on gage marks.

TABLE A-2

DROP-WEIGHT TEST DATA OF HOT-ROLLED LABORATORY STEELS FINISHED AT 1850 F*

Testing Temperature, F	Complete Fracture	Impact Energy, Ft-lb.	NDT, F
Heat Number (Battelle Assigned) B 6353 1			
100	No	150	0
100	Ditto	150	
61	"	120	
61	"	150	
10	"	150	
10	"	120	
10	"	150	
0	Yes	Ditto	
0	Ditto	"	
0	"	120	
-10	"	Ditto	
-10	"	"	
B 6327 2**			
63	No	120	-10
63	Ditto	60	
40	"	120	
20	"	Ditto	
0	"	"	
0	"	"	
0	"	"	
-10	Yes	"	
-10	No	"	
-10	No	"	
-20	Yes	"	
-20	Yes	"	
B 6932 2-2			
10	No	120	0
10	Ditto	Ditto	
10	"	"	
10	"	"	
0	"	"	
0	"	"	
0	Yes	"	
0	Ditto	"	
-10	"	"	
-10	"	"	
-10	"	"	
-10	"	"	
B 6932 2-2 (Duplicate)			
0	No	120	-10
0	Ditto	Ditto	
0	"	"	
0	"	"	
-10	Yes	"	
-10	Ditto	"	
-10	"	"	
-10	"	"	
-20	"	"	
-20	"	"	
-20	"	"	
-20	"	"	
B 6366 3			
64	No	120	-20
64	Ditto	150	
63	"	180	
40	"	Ditto	
20	"	"	
0	"	"	
-10	"	"	
-10	"	"	
-20	Yes	"	
-20	No	"	
-20	Yes	"	
-30	Yes	"	
B 6367 4			
64	No	120	-40
64	Ditto	60	
10	"	120	
0	"	Ditto	
-10	"	"	
-30	"	"	
-30	"	"	
-40	Yes	"	
-40	Ditto	"	
-40	"	"	
-50	"	"	
-50	"	"	

Testing Temperature, F	Complete Fracture	Impact Energy, Ft-lb.	NDT, F
B 6360 5			
130	No	120	0
63	Ditto	120	
63	"	60	
40	"	120	
30	"	Ditto	
20	"	"	
10	"	"	
0	Yes	"	
0	Ditto	"	
-10	"	"	
10	No	"	
-10	Yes	"	
B 6360 5 (Duplicate)			
20	No	120	10
20	Ditto	Ditto	
20	"	"	
20	"	"	
10	Yes	"	
10	Ditto	"	
10	"	"	
10	"	"	
0	"	"	
0	"	"	
0	"	"	
0	"	"	
B 6368 6			
71	No	60	-30
71	Ditto	120	
30	"	Ditto	
10	"	"	
10	"	"	
-10	"	"	
-10	"	"	
-20	"	"	
-20	"	"	
-20	"	"	
-30	Yes	"	
-30	Yes	"	
B 6368 6 (Duplicate)			
0	No	120	-10
0	Ditto	Ditto	
0	"	"	
0	"	"	
0	"	"	
-10	Yes	"	
-10	No	"	
-10	No	"	
-10	Yes	"	
-20	Ditto	"	
-20	"	"	
-30	"	"	
B 6359 7			
71	No	60	-20
71	Ditto	120	
30	"	Ditto	
10	"	"	
-10	"	"	
-10	"	"	
-10	"	"	
-20	"	"	
-20	Yes	"	
-20	No	"	
-20	Yes	"	
-30	Yes	"	
B 6406 8			
68	No	60	20
68	Ditto	120	
30	"	Ditto	
20	"	"	
20	"	"	
20	Yes	"	
10	No	"	
10	Yes	"	
10	Ditto	"	
0	"	"	
0	"	"	
0	"	"	

Testing Temperature, F	Complete Fracture	Impact Energy, Ft-lb.	NDT, F
B 6409 9			
68	No	60	0
68	Ditto	120	
30	"	Ditto	
10	"	"	
10	"	"	
10	"	"	
0	Yes	"	
0	Ditto	"	
0	"	"	
-10	"	"	
-10	"	"	
-10	"	"	
B 7064 9-2			
20	No	120	10
20	Ditto	Ditto	
20	"	"	
20	"	"	
10	Yes	"	
10	Ditto	"	
10	"	"	
10	"	"	
0	"	"	
0	"	"	
0	"	"	
0	"	"	
B 6464 10			
68	No	60	-10
68	Ditto	120	
30	"	Ditto	
10	"	"	
0	"	"	
0	"	"	
0	"	"	
-10	Yes	"	
-10	Ditto	"	
-10	"	"	
-20	"	"	
-20	"	"	
B 6410 11			
68	No	60	-20
68	Ditto	120	
30	"	Ditto	
10	"	"	
-10	"	"	
-10	"	"	
-10	"	"	
-20	Yes	"	
-20	Ditto	"	
-20	"	"	
-30	"	"	
-30	"	"	
B 6405 12			
130	No	120	30
57	Ditto	60	
57	"	120	
57	"	180	
40	"	120	
40	"	Ditto	
40	"	"	
30	Yes	"	
30	Ditto	"	
30	"	"	
20	"	"	
20	"	"	
B 6427 13			
71	No	60	20
71	Ditto	120	
30	"	Ditto	
30	"	"	
30	"	"	
20	"	"	
20	Yes	"	
20	Yes	"	
20	No	"	
10	Yes	"	
10	Ditto	"	
10	"	"	

TABLE A-2 (CONTINUED)

Testing Temperature, F	Complete Fracture	Impact Energy, Ft-lb.	NDT, F.
B 6361 14			
71	No	60	-10
71	Ditto	120	
30	"	Ditto	
10	"	"	
0	"	"	
0	"	"	
0	"	"	
-10	Yes	"	
-10	Ditto	"	
-10	"	"	
-20	"	"	
-20	"	"	
B 6903 15			
0	No	120	-20
0	Ditto	Ditto	
0	"	"	
0	"	"	
-10	"	"	
-10	"	"	
-10	"	"	
-10	"	"	
-20	Yes	"	
-20	Ditto	"	
-20	"	"	
-20	"	"	
B 6880 16			
20	No	120	0
10	Ditto	Ditto	
10	"	"	
10	"	"	
10	"	"	
0	Yes	"	
0	Ditto	"	
0	"	"	
0	No	"	
-10	Yes	"	
-10	Ditto	"	
-10	"	"	
B 6879 17			
10	No	120	0
10	Ditto	Ditto	
10	"	"	
10	"	"	
0	Yes	"	
0	Ditto	"	
0	"	"	
0	"	"	
-10	"	"	
-10	"	"	
-10	"	"	
-10	"	"	
B 6904 18			
30	No	120	20
30	Ditto	Ditto	
30	"	"	
30	"	"	
20	Yes	"	
20	Ditto	"	
20	"	"	
20	No	"	
10	Yes	"	
10	Ditto	"	
10	"	"	
0	"	"	
B 6930 19			
20	No	120	10
20	Ditto	Ditto	
20	"	"	
20	"	"	
10	"	"	
10	"	"	
10	"	"	
10	Yes	"	
0	Ditto	"	
0	"	"	
0	"	"	
0	"	"	

Testing Temperature, F	Complete Fracture	Impact Energy, Ft-lb.	NDT, F
B 6931 20			
20	No	120	10
20	Ditto	Ditto	
20	"	"	
20	"	"	
10	"	150	
10	Yes	120	
10	Ditto	Ditto	
0	"	"	
0	"	"	
0	"	"	
0	"	"	
-20	"	"	
B 6914 21			
10	No	120	-10
10	Ditto	Ditto	
10	"	"	
0	"	"	
0	"	"	
0	"	"	
-10	Yes	"	
-10	No	"	
-10	No	"	
-20	Yes	"	
-20	Ditto	"	
-30	"	"	
B 6933 22			
10	No	120	-10
10	Ditto	Ditto	
10	"	"	
0	"	"	
0	"	"	
0	"	"	
-10	Yes	"	
-10	Yes	"	
-10	No	"	
-20	Yes	"	
-20	Ditto	"	
-30	"	"	
B 6913 23			
-10	No	120	-30
-20	Ditto	Ditto	
-20	"	"	
-20	"	"	
-20	"	"	
-30	Yes	"	
-30	Ditto	"	
-30	"	"	
-30	"	"	
-40	"	"	
-40	"	"	
-40	"	"	
B 6929 24			
10	No	120	0
10	Ditto	Ditto	
10	"	"	
10	"	"	
0	Yes	"	
0	Ditto	"	
0	"	"	
0	"	"	
-10	"	"	
-10	"	"	
-10	"	"	
-10	"	"	
B 7191 25			
20	No	150	10
20	Ditto	150	
20	"	150	
10 ***	"	120	
10	"	120	
10	Yes	150	
10	No	Ditto	
10	No	"	
0	Yes	"	
0	Ditto	"	
0	"	"	
-10	"	120	

Testing Temperature, F	Complete Fracture	Impact Energy, Ft-lb.	NDT, F
B 7191 25 (Duplicate)			
10	No	150	0
10	Ditto	Ditto	
10	"	"	
10	"	"	
0	Yes	"	
0	Ditto	"	
0	"	"	
0	"	"	
-10	"	"	
-10	"	"	
-10	"	"	
-10	"	"	
B 7192 26			
10****	No	150	-10
10	Ditto	180	
10	"	Ditto	
0	"	"	
0	"	"	
0	"	"	
-10	Yes	150	
-10****	No	120	
-10	Yes	180	
-10	Ditto	Ditto	
-20	"	"	
-20***	"	"	
B 7192 26 (Duplicate)			
-10	No	150	-20
-10	Ditto	Ditto	
-10	"	"	
-10	"	"	
-20	Yes	"	
-20	Ditto	"	
-20	"	"	
-20	"	"	
-30	"	"	
-30	"	"	
-30	"	"	
-30	"	"	
B 7193 27			
0	No	120	-10
0	Ditto	120	
0****	"	120	
0	"	150	
-10	Yes	120	
-10	Ditto	150	
-10	"	Ditto	
-10	"	"	
-20	"	130	
-20	"	150	
-20	"	150	
-40	"	120	
B 7193 27 (Duplicate)			
0	No	150	-10
0	Ditto	Ditto	
0	"	"	
0	"	"	
-10	"	"	
-10	Yes	"	
-10	Ditto	"	
-10	"	"	
-20	"	"	
-20	"	"	
-20	"	"	
-30	"	"	

* Specimen dimensions were 2 x 5 x 5/8 in. Plate thickness was 5/8 in.

** Battelle-Assigned Heat No.

*** Hit off center

**** Did not mark anvil.

TABLE A-3

DROP-WEIGHT TEST DATA FOR LABORATORY STEELS HEATED FOR ONE HOUR AT 1600 F AND AIR COOLED*

Testing Temperature, F	Complete Fracture	Impact Energy, Ft-lb.	NDT, F
B 6353 1****			
80	No	120	10
20	Ditto	Ditto	
20	"	"	
20	"	"	
10	Yes	"	
10	No	"	
10	Ditto	"	
10	"	"	
10	"	"	
0	Yes	"	
0	Ditto	"	
0	"	"	
B 6327 2S16			
72**	No	90	-40
72	Ditto	120	
-10	"	150	
-30	"	Ditto	
-30	"	"	
-30	"	"	
-40	"	"	
-40	Yes	"	
-40	No	"	
-50	Yes	"	
-50	Ditto	"	
-50	"	"	
B 6366 3			
80	No	180	-60
-20	Ditto	Ditto	
-30	"	"	
-40	"	"	
-50	"	"	
-50	"	"	
-50	"	"	
-60	"	"	
-60	Yes	"	
-60	No	"	
-70	Yes	"	
-70	No	"	
B 6367 4			
80	No	120	
-40	Ditto	Ditto	
-40	"	"	
-40	"	"	
-40	"	"	
-50***	Yes	"	
-50	No	"	
-50	Ditto	"	
-50	"	"	
-60	"	"	
-60	"	"	
-70**	"	"	
B 6367 4 (Duplicate)			
-50	No	120	-60
-50	Ditto	Ditto	
-50	"	"	
-60	"	"	
-60	Yes	"	
-60	No	"	
-70	No	"	
-70	Yes	"	
-80	Ditto	"	
-80	"	"	
-80	"	"	
-80	"	"	

Testing Temperature, F	Complete Fracture	Impact Energy, Ft-lb.	NDT, F
B 6360 5			
80	No	120	-10
10	Ditto	Ditto	
0	"	"	
0	"	"	
0	"	"	
-10	"	"	
-10	Yes	"	
-10	Yes	"	
-10	No	"	
-20	Yes	"	
-20	Ditto	"	
-20	"	"	
B 6368 6			
80	No	120	-40
-30	Ditto	Ditto	
-30	"	"	
-30	"	"	
-40	"	"	
-40	"	"	
-40	Yes	"	
-40	Ditto	"	
-50	"	"	
-50	No	"	
-50	Yes	"	
-50	Yes	"	
B 6359 7			
80	No	120	-10
0	Ditto	Ditto	
0	"	"	
0	"	"	
-10	Yes	"	
-10	No	"	
-10	Ditto	"	
-10	"	"	
-20	Yes	180	
-20	Yes	120	
-20	No	Ditto	
-20	No	"	
B 6406 8			
20	No	120	10
20	Ditto	Ditto	
20	"	"	
20	"	"	
10	Yes	"	
10	Ditto	"	
10	"	"	
10	"	"	
0	"	"	
0	"	"	
0	"	"	
0	"	"	
B 6409 9S16			
71	No	120	-10
0	Ditto	Ditto	
0	"	"	
0	"	"	
-10	Yes	"	
-10	Ditto	"	
-10	"	"	
-20	"	"	
-20	"	"	
-20	"	"	

Testing Temperature, F	Complete Fracture	Impact Energy, Ft-lb.	NDT, F
B 6464 10			
-10	No	120	-20
-10	Ditto	Ditto	
-10	"	"	
-10	"	"	
-20	Yes	"	
-20	Ditto	"	
-20	"	"	
-20	"	"	
-30	"	"	
-30	"	"	
-30	"	"	
-30	"	"	
B 6410 11			
-10	No	120	-20
-10	Ditto	Ditto	
-10	"	"	
-10	"	"	
-20	Yes	"	
-20	Ditto	"	
-20	"	"	
-20	"	"	
-30	"	"	
-30	"	"	
-30	"	"	
-30	"	"	
B 6405 12			
40	No	120	30
40	Ditto	Ditto	
40	"	"	
40	"	"	
30	Yes	"	
30	Ditto	"	
30	"	"	
30	"	"	
20	"	"	
20	"	"	
20	"	"	
20	"	"	
B 6427 13			
20	No	120	10
20	Ditto	Ditto	
20	"	"	
20	"	"	
10	Yes	"	
10	Ditto	"	
10	"	"	
10	"	"	
0	"	"	
0	"	"	
0	"	"	
0	"	"	
B 6361 14			
73	No	120	-10
0	Ditto	Ditto	
0	"	"	
0	"	"	
0	"	"	
-10	"	"	
-10	"	"	
-10	"	"	
-10	Yes	"	
-20	Ditto	"	
-20	"	"	
-20	"	"	

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* Specimen dimensions were 2 in. x 5 in. x 5/8 in. Plate thickness was 5/8 in.

** Did not mark anvil.

*** Fractured 1/4 in. from weld bead.

**** Battelle-assigned heat No.

TABLE A-4. DROP-WEIGHT TEST DATA FOR LABORATORY STEELS HEATED FOR ONE HOUR AT 1900 F AND AIR COOLED*

Testing Temperature, F	Complete Fracture	Impact Energy, Ft-lb.	NDT, F
B 6327 2S19**			
20	No	150	-20
0	Ditto	Ditto	
-10	"	"	
-10	"	"	
-10	"	"	
-20	"	"	
-20	"	"	
-20	"	"	
-20	Yes	"	
-30	Yes	"	
-30	No	"	
-30	No	"	
B 6409 9S19			
30	No	150	20
30	Ditto	Ditto	
30	"	"	
30	"	"	
20	"	120	
20	"	150	
20	Yes	Ditto	
20	No	"	
10	No	120	
10	Yes	120	
10	Ditto	150	
0	"	120	

TABLE A-5. DROP-WEIGHT TEST DATA FOR LABORATORY STEELS HEATED FOR ONE HOUR AT 1900 F AND FURNACE COOLED*

Testing Temperature, F	Complete Fracture	Impact Energy, Ft-lb.	NDT, F
B 6932 2-2			
10	No	150	0
10	Ditto	Ditto	
10	"	"	
10	"	"	
0	Yes	"	
0	Ditto	"	
0	"	"	
0	"	"	
-10	"	"	
-10	"	"	
-10	"	"	
-10	"	"	
B 6367 4			
-20	No	150	-50
-40	Ditto	Ditto	
-40	"	"	
-40	"	"	
-40	"	"	
-50	Yes	"	
-50	No	"	
-50	Yes	"	
-50	Ditto	"	
-60	"	"	
-60	"	"	
-60	"	"	
B 6360 5			
40	No	150	30
40	Ditto	Ditto	
40	"	"	
40	"	"	
30	Yes	"	
30	Ditto	"	
30	"	"	
20	No	"	
20	Yes	"	
20	Ditto	"	
10	"	"	
0	"	"	
B 6368 6			
10	No	150	0
10	Ditto	Ditto	
10	"	"	
10	"	"	
0	"	"	
0	"	"	
0	"	"	
0	Yes	"	
0	Yes	"	
0	No	"	
-10	Yes	"	
-10	Ditto	"	
-10	"	"	
-10	"	"	
-20	"	"	
-20	"	"	
-20	"	"	
-20	"	"	
B 6359 7			
30	No	150	20
30	Ditto	Ditto	
30	"	"	
30	"	"	
20	Yes	"	
20	No	"	
20	Ditto	"	
20	"	"	
20	"	"	
20	"	"	
10	"	"	
10	"	"	
10	Yes	"	
10	Ditto	"	
0	"	"	
0	"	"	
0	"	"	
0	"	"	
B 7064 9-2			
50	No	150	40
50	Ditto	Ditto	
50	"	"	
40	Yes	"	
40	No	"	
40	Yes	"	
40	No	"	
30	Yes	"	
30	Ditto	"	
20	"	"	
20	"	"	
20	"	"	
B 6410 11			
30	No	150	20
30	Ditto	Ditto	
30	"	"	
30	"	"	
20	Yes	"	
20	Ditto	"	
20	"	"	
20	"	"	
10	"	"	
10	"	"	
10	"	"	
0	"	"	
B 6405 12			
80	No	150	70
80	Ditto	Ditto	
80	"	"	
80	"	"	
70	Yes	"	
70	Yes	"	
70	No	"	
60	Yes	"	
60	Ditto	"	
60	"	"	
50	"	"	
40	"	"	
B 6427 13			
70	No	150	60
70	Ditto	Ditto	
70	"	"	
70	"	"	
60	Yes	"	
60	Yes	"	
60	No	"	
60	Yes	"	
60	No	"	
60	No	"	
50	Yes	"	
50	Ditto	"	
50	"	"	
50	"	"	
40	"	"	
40	"	"	
40	"	"	
30	"	"	
B 6361 14			
50	No	150	40
50	Ditto	Ditto	
50	"	"	
50	"	"	
40	"	"	
40	"	"	
40	Yes	"	
40	Ditto	"	
30	"	"	
30	"	"	
30	"	"	
30	No	"	
20	Yes	"	
20	Ditto	"	
20	"	"	
10	"	"	

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* Specimen dimensions were 2 x 5 x 5/8 in. Plate thickness was 5/8 in

** Battelle-Assigned Heat No.

TABLE A-6

V-NOTCH CHARPY TEST DATA FOR HOT-ROLLED LABORATORY STEELS

Testing Temperature, F		Charpy Impact Energy, Ft.-lb.	Brittle Fracture, per cent	Lateral Expansion, mils
B 6353 1 *				
120		70	26.2	73-67
	Avg.			70
80		34	66.5	60-59
		67	40.0	60-59
		51	51.8	55-51
		56	46.8	68-62
		56	40.0	38-38
	Avg.	52.8	49	55
60		36	62.5	41-44
		38	62.5	40-42
	Avg.	37	62.5	41.7
50		20	68.0	47-47
		42	56.4	27-27
		33	67.5	33-37
	Avg.	31.6	63.9	36.3
40		39	64.0	42-42
		18	76.0	23-23
		13	76.9	19-17
		28	76.4	33-33
	Avg.	24.5	73.3	29
30		11	77.0	21-21
		22	74.8	26-26
		15	75.8	17-18
	Avg.	16	75.8	21.5
20		8	85.1	14-14
		10	81.0	15-16
	Avg.	9	83.0	14.7
0		7	93.1	10-10
		6	92.8	10-10
		7	91.9	7- 8
		7	92.7	12-10
	Avg.	7	92.6	9.6
B 6327 2				
140		86	15.0	73-78
	Avg.	86	15.0	75.5
100		87	17.8	74-75
		85	19.7	79-75
	Avg.	86	18.7	75.7
80		80	27.2	60-64
	Avg.	80	27.2	62
40		50	55.0	55-51
		56	54.1	52-51
	Avg.	53	54.5	52
30		45	66.0	45-46
		42	64.0	44-47
	Avg.	43.5	65.0	45.5
20		37	69.7	47-47
		45	64.6	40-39
	Avg.	41	67.2	43.2
10		39	76.4	16-16
		10	75.2	41-40
	Avg.	24.5	75.8	28.2
0		32	71.4	14-14
		25	74.8	16-17
		12	83.1	33-33
		8	82.3	26-25
	Avg.	19	78.0	22
-10		24	85.4	27-27
		23	85.3	25-25
		12	76.5	15-15
		39	75.2	39-40
	Avg.	24.5	80.7	26.6
-20		9	96.2	13-11
		20	84.1	20-21
		28	81.6	31-31
		19	88.8	21-21
	Avg.	19	87.6	21
-30		7	90.0	11-10
		8	90.0	9-10
	Avg.	7.5	90.0	10
-40		28	88.8	28-29
		11	88.8	13-13
		8	90.0	10-10
		9	90.0	10-10
		3	92.5	4- 4
		18	88.8	19-19
	Avg.	12.8	89.8	14
-60		3	97.5	2- 2
		5	97.5	5- 5
	Avg.	4	97.5	3.5
B 6327 2 (Duplicate)				
140		93	0	79-79
		87	13	83-78
	Avg.	90	6.5	80
100		79	6.9	70-75
		93	25.4	74-79
	Avg.	86	16.2	75
78		73	20.6	60-74
		74	34.6	71-70
	Avg.	73.5	27.6	69
40		50	54.0	44-44
		43	56.7	55-52
	Avg.	46.5	55.4	49
30		46	61.9	46-46
		45	61.9	43-50
	Avg.	45.5	61.9	48
20		42	67.5	43-43
		42	67.5	44-42
	Avg.	42	67.5	43
10		11	78.8	21-21
		16	76.8	16-17
	Avg.	13.5	77.8	19
0		35	70.5	38-38
		44	68.3	37-37
	Avg.	39.5	69.4	37
-10		11	76.4	26-26
		25	79.6	13-15
	Avg.	18	78.0	20
B 6327 2 (Duplicate)				
-20		9	83.2	15-16
		11	78.8	13-13
	Avg.	10	81.0	14
-30		12	85.3	15-15
		10	87.9	11-11
	Avg.	11	86.6	13
-40		6	97.4	0- 0
		4	97.4	6- 6
	Avg.	5	97.4	3
-60		5	98.8	7- 7
		5	98.8	0- 6
	Avg.	5	98.8	5
B 6932 2-2				
78		45	17.7	48-48
		75	19.6	69-71
	Avg.	60	18.6	59
60		75	32.7	68-69
		72	38.0	71-69
	Avg.	73.5	35.3	69
40		53	51.0	51-51
		36	53.1	37-38
	Avg.	44	52.0	44
20		27	76.7	32-32
		30	73.1	31-30
	Avg.	28.5	74.9	31
10		36	72.2	25-25
		23	75.3	37-35
	Avg.	29	73.7	30
0		28	72.2	25-24
		21	72.2	30-29
		24	76.5	26-26
		28	72.5	30-30
	Avg.	25	73.3	27.5
-10		29	69.2	30-29
		25	72.2	25-25
	Avg.	27	70.7	27.2

TABLE A-6 (CONTINUED)

Testing Temperature, F	Charpy Impact Energy, Ft-lb.	Brittle Fracture, per cent	Lateral Expansion, mils
B 6932 2-2			
-20	25	77.8	24-24
	11	79.0	14-11
	9	79.2	13-13
Avg.	15	78.6	16.5
-30	15	75.6	16-17
	10	82.2	13-12
	18	82.2	19-20
Avg.	14	79.3	16.1
-40	12	87.7	14-14
	17	85.2	18-18
Avg.	14.5	86.4	16
-60	3	84.2	5- 6
	10	86.2	12-11
Avg.	6.5	85.2	8.5
B 6366 3			
120	69	39.0	68-63
	75	20.4	61-63
Avg.	72	29.7	63.7
80	55	49.3	49-48
Avg.	55	49.3	48.5
40	49	59.0	47-46
	50	57.9	44-44
Avg.	49.5	58.4	45
30	39	70.5	36-36
	40	68.6	38-38
Avg.	39.5	69.5	37
20	24	77.0	30-30
	28	77.6	26-26
Avg.	26	77.3	28
10	15	79.3	19-19
	17	79.3	18-19
Avg.	16	79.3	18.7
0	23	80.7	33-32
	26	80.5	25-25
	24	79.7	24-23
	25	73.5	25-25
Avg.	24.5	78.6	26.5
B 6366 3			
-10	8	81	12-12
	28	79	28-28
Avg.	18	80	20
-20	12	73.5	31-31
	10	79.7	21-21
	7	81.5	20-21
	7	81.7	13-11
Avg.	9	79.1	21
-40	7	94.0	9- 9
	18	91.4	21-24
	7	95.2	10-10
	11	92.8	12-13
Avg.	10.7	93.3	13.5
-50	5	97.5	5- 5
	3	97.5	3- 3
Avg.	4	97.5	4
-60	3	98.8	3- 3
	3	98.8	3- 3
Avg.	3	98.8	3
-80	5	98.8	9-10
	7	98.8	7- 7
Avg.	6	98.8	8.2
B 6366 3	(Duplicate)		
120	77	21.0	67-69
	87	5.0	75-75
Avg.	82	13.0	71
80	62	46.7	64-59
	68	39.0	56-58
Avg.	65	42.6	59
40	39	65.0	38-37
	52	75.5	47-48
Avg.	46	70.2	42
30	43	60.0	40-39
	41	60.0	39-41
Avg.	42	60.0	40
B 6366 3	(Duplicate)		
20	40	69.1	40-41
	42	69.1	37-37
Avg.	41	69.1	39
10	35	73.1	34-34
	36	69.1	33-33
Avg.	36	71.1	34
0	22	78.7	28-27
	28	78.7	24-23
Avg.	25	78.7	25
-10	26	83.2	33-33
	35	73.1	27-27
	16	84.4	19-19
	29	78.7	30-30
Avg.	26	79.8	27
-20	9	78.7	12-12
	22	84.4	23-23
	33	73.1	33-33
Avg.	21	78.7	23
-40	7	96.5	9- 9
	7	86.6	21-24
	21	96.5	10-10
Avg.	12	93.2	15
-50	6	96.5	7- 8
	7	98.7	10-10
Avg.	7	97.6	9
-60	5	98.7	9- 9
	7	98.7	7- 7
Avg.	6	98.7	8
-80	3	100.0	0- 0
	4	100.0	0- 0
Avg.	4	100.0	0
B 6366 3	(Triplicate)		
120	76	37.1	63-69
	75	19.8	66-67
Avg.	75.5	28.4	66.2
80	54	49.8	49-47
	66	41.3	57-60
Avg.	60	45.3	53.2
40	50	50.6	44-46
	42	60.0	41-40
Avg.	46	55.3	42.7
30	27	65.0	31-28
	26	66.1	28-27
	46	51.2	45-45
	15	70.0	18-18
Avg.	28.5	63.0	30
20	38	58.0	37-38
	30	65.0	31-31
Avg.	34	61.5	34.2
10	30	67.3	30-32
	27	67.6	27-28
Avg.	28.5	67.4	29.2
0	21	72.2	22-23
	20	74.3	21-21
Avg.	20.5	73.2	21.7
-10	9	81.0	12-12
	22	74.7	21-22
	27	73.6	27-28
	7.5	87.5	11-19
Avg.	16.4	79.2	17.7
-20	6	86.2	8- 9
	19	75.3	20-20
	25	74.3	24-25
	27	87.3	8- 9
Avg.	14.3	80.7	15.3
-40	6	89.0	7- 8
	11	87.5	12-12
Avg.	8.5	88.2	9.8
-50	26	78.7	26-26
	7	90.0	7- 7
	3	95.5	3- 3
Avg.	12	88.0	12.0

TABLE A-6 (CONTINUED)

Testing Temperature, F	Charpy Impact Energy, Ft-lb.	Brittle Fracture, per cent	Lateral Expansion, mils
B 6366 3 (Triplicate)			
-60	6	92.7	6- 6
	3	99.0	1- 2
Avg.	4.5	95.8	3.9
-80	5	95.5	6- 4
	3	97.7	θ- 1
Avg.	4	96.6	2.9
B 6367 4			
80	109	32.4	79-88
	130	26.3	92-93
Avg.	120	29.3	88
60	86	45.3	81-85
	99	37.0	79-79
Avg.	92	41.0	81
40	89	55.2	82-78
	75	49.6	71-72
Avg.	82	52.4	75.7
30	81	59.7	75-82
	83	56.5	76-77
Avg.	82	58.1	77.5
20	48	64.6	49-50
	55	64.2	55-54
	24	77.6	37-36
	36	76.5	29-30
Avg.	41	70.7	42.5
10	83	62.0	81-82
	55	63.0	80-80
	84	57.0	78-78
	90	57.6	69-69
	75	56.9	73-73
	69	62.0	56-55
Avg.	76	59.7	72.8
0	16	79.5	22-22
	12	[illegible]	18-17
Avg.	14	[illegible]	19.7
-20	12	81.8	18-17
	12	78.7	18-16
Avg.	12	80.2	17.2
-40	10	87.5	12-12
	24	86.6	27-25
	11	90.0	14-14
	5	94.0	8- 7
	7	92.7	13-13
Avg.	11	90.1	14.5
-80	3	96.2	4- 5
	3	96.2	3- 2
Avg.	3	96.2	3.5
80	117	23.2	88-85
	117	23.2	80-91
Avg.	117	23.2	86
60	92	26.0	82-81
	122	15.1	92-88
Avg.	107	20.5	85.8
40	100	17.5	89-82
	86	30.1	77-78
Avg.	93	23.8	81.5
30	85	34.0	82-79
	90	24.5	80-85
Avg.	87.5	29.2	81.5
20	40	57.6	44-43
	20	62.6	22-23
Avg.	30	60.1	33
10	85	40.5	82-80
	43	63.0	44-45
Avg.	64	51.7	62
0	18	71.5	23-22
	32	66.6	34-35
Avg.	25	69.0	28.5
-10	75	50.0	69-75
	80	56.0	78-77
Avg.	77.5	53.0	75

Testing Temperature, F	Charpy Impact Energy, Ft-lb.	Brittle Fracture per cent	Lateral Expansion, mils
B 6367 4 (Duplicate)			
-20	6.5	83.1	10- 9
	40	67.5	44-43
	40	69.7	42-41
Avg.	28.8	73.4	30.1
-40	32	73.8	35-35
	34	73.1	32-35
	6	90.8	7- 7
Avg.	24	79.2	25
-60	7	93.0	9- 8
	4	96.7	4- 3
Avg.	5.5	94.8	6
-80	6	95.5	6- 7
	12	88.7	14-14
Avg.	9	92.1	10
B 6360 5			
160	50	13.0	55-56
	51	15.3	56-54
Avg.	50.5	14.1	55
140	45	13.3	56-59
	40	13.6	51-47
Avg.	42.5	13.4	53.2
120	36	49.9	47-44
	42	39.8	38-43
Avg.	39	44.8	43
80	31	58	34-35
	24	65.6	30-27
Avg.	27.5	61.8	31.5
70	24	63.5	28-30
	24	62.4	29-27
Avg.	24	62.9	29
60	17	69	27-28
	22	66.2	21-21
Avg.	19.5	67.6	24.2
50	20	70	25-23
	18	70	23-25
Avg.	19	70	24
40	17	75.9	21-20
	12	75.9	16-15
Avg.	14.5	75.9	18
30	16	78.8	19-19
	10	78.8	14-14
Avg.	13	78.8	16.5
20	9	83.9	12-13
	9	83.9	13-13
Avg.	9	83.9	12.7
0	7	94	6- 7
	8	92.7	10-11
	6	94	9- 9
	5	95.2	8- 9
Avg.	6.5	93.9	8.6
-20	6	97.5	6- 9
	3	97.5	4- 1
Avg.	4.5	97.5	5
B 6368 6			
120	66	0.0	60-58
	66	0.0	61-58
Avg.	66	0	59
79	60	29.6	53-51
	57	41.5	55-53
Avg.	58.5	35.5	53
60	42	35.9	41-41
	44	37.0	41-40
	46	39.5	39-38
	44	38.5	41-41
Avg.	44	37.7	41
40	45	54.0	40-41
	47	50.7	41-39
Avg.	46	52.3	40
30	29	55.5	30-31
	30	51.8	28-29
Avg.	29.5	53.6	29

TABLE A-6 (CONTINUED)

Testing Temperature, F		Charpy Impact Energy, Ft-lb.	Brittle Fracture, per cent	Lateral Expansion, mils
B 6368 6				
20		30	64.5	29-30
		25	66.3	26-26
	Avg.	27.5	65.4	28
10		27	68.2	24-24
		25	68.2	26-27
	Avg.	26	68.2	25
0		30	70.9	26-25
		28	75.8	29-28
	Avg.	29	73.3	27
-10		26	80	24-22
		22	80.7	25-25
	Avg.	24	80.4	24
-20		27	83	16-15
		16	87.9	24-25
	Avg.	22.5	85.4	20
-30		14	93.8	16-15
		18	93.8	18-18
		18	93.8	17-17
	Avg.	17	93.8	17
-40		14	98.8	14-15
		8	90.0	8- 9
	Avg.	11	94.4	11
-50		8	98.8	6- 7
		6	98.8	7- 8
	Avg.	7	98.8	7
B 6359 7				
79		110	28.1	88-95
		121	17.5	96-77
	Avg.	116	22.8	89
60		121	30.4	81-90
		124	22.8	88-81
	Avg.	122.5	26.6	85
40		115	35.6	87-81
		99	29.3	89-84
	Avg.	107	32.4	85
30		44	58.5	50-49
		70	46.7	70-70
		83	42.5	78-79
		23	65.3	31-30
	Avg.	55	53.3	57
20		21	64.3	26-27
		66	55.0	68-69
		69	53.8	70-68
		62	56.3	62-65
		19	69.0	26-27
		50	57.4	53-54
	Avg.	48	59.3	51
10		20	71.8	26-26
		15	79.0	24-23
		19	74.4	26-26
		17	74.4	21-24
	Avg.	18	75.0	25
0		16	77.7	20-21
		15	78.2	21-21
	Avg.	15.5	78	21
-10		15	80.5	21-22
		10	80.2	16-16
	Avg.	12.5	80.4	19
-20		8	84.3	11-12
		8	84.5	14-13
		6	86.5	10-10
		7	85.5	7- 8
	Avg.	7	85.2	11
-30		29	96.5	12- 9
		30	88.4	11-10
	Avg.	29.5	92.4	10.5

Testing Temperature, F		Charpy Impact Energy, Ft-lb.	Brittle Fracture, per cent	Lateral Expansion, mils
B 6406 8				
160		78	3.4	74-74
		72	2.5	75-68
	Avg.	75	2.9	72
140		70	13.3	67-72
		68	12.3	69-64
	Avg.	69	12.8	68
120		56	29.3	56-62
		62	19.6	68-59
	Avg.	59	24.4	59.7
100		42	42.0	53-59
		52	29.2	46-42
	Avg.	47	35.6	50
90		34	49.4	49-47
		43	55.2	43-43
	Avg.	38	52.3	45
80		32	55.8	32-35
		27	51.8	40-40
		37	57.0	42-40
		30	52.3	35-33
	Avg.	32	54.2	37.1
60		30	65.5	27-24
		21	61.0	34-33
	Avg.	26	63.2	27.2
50		26	65	30-31
		19	65.4	24-24
	Avg.	22	65.2	27.2
40		15	74.4	18-18
		13	74.4	16-17
	Avg.	14	74.4	17.2
20		8	85.0	10-11
		7	86.0	7- 8
	Avg.	7.5	85.5	9
10		6	93.1	9-10
		7	93.1	9- 8
		6	95.4	9- 8
		6	95.4	8- 7
	Avg.	6	94.2	8.5
0		4	96.5	3- 4
		4	96.5	4- 4
	Avg.	4	96.5	3.7
B 6409 9				
120		79	17.8	68-74
		76	26.0	71-69
	Avg.	77.5	21.9	70.5
80		60	48.2	57-61
		66	38.8	63-59
	Avg.	63	43.5	60
70		38	57.0	45-45
		45	52.3	38-41
	Avg.	42	54.6	42.2
60		45	67.1	47-46
		55	53.2	54-55
	Avg.	50	60.1	50.5
50		34	68.5	43-46
		43	70.4	36-38
		44	63.2	35-37
		33	64.9	44-44
	Avg.	38	66.7	40.3
40		15	75.9	31-32
		30	56.8	49-49
		28	36.3	32-31
		28	67.2	23-19
		19	71.5	22-22
	Avg.	24	61.5	31
30		28	75.4	32-30
		28	75.9	30-29
	Avg.	28	75.6	30.2
20		17	79.0	21-21
		20	76.8	24-24
	Avg.	18.5	77.9	22.5

TABLE A-6 (CONTINUED)

Testing Temperature, F	Charpy Impact Energy, Ft-lb.	Brittle Fracture, per cent	Lateral Expansion, mils
B 6409 9			
10	12	82.1	14-16
	10	81.3	15-15
Avg.	11	81.7	15
0	7	87.5	10- 9
	7	87.3	10-10
	6	92.8	9- 9
	7	91.5	9- 9
Avg.	7	89.7	9.3
-20	3	98.8	2- 3
	4	93.8	4- 5
Avg.	3.5	96.3	3.5
B 7064 9-2			
100	70	12.7	71-61
	65	25.3	64-65
Avg.	67.5	19.0	65.2
78	54	34.1	54-52
	45	42.5	46-47
Avg.	49.5	38.3	49.7
70	30	43.7	34-31
	39	52.5	44-41
	49	36.7	52-51
Avg.	39	44.3	42.1
60	33	50	37-40
	31	55	36-35
Avg.	32	52.5	37
50	23	65	28-27
	32	58.5	36-36
Avg.	28	61.7	31.7
40	26	66.8	30-30
	15	68.1	20-21
Avg.	20.5	67.4	25.2
30	13	72	16-18
	11	66.8	17-17
Avg.	12	69.4	17
20	13	77	17-16
	10	77.5	16-16
Avg.	11.5	77.3	16.2
10	8	85.7	11- 9
	12	84.3	16-17
	10	78.8	15-14
	9	81.0	13-12
Avg.	9.7	82.4	13.3
0	6	88.6	8-10
	8	81.0	11-12
Avg.	7	84.8	9.5
-10	6	90.2	8- 8
	5	90.0	6- 7
Avg.	5.5	90.1	7
-20	4	96.7	4- 4
	3	98.0	4- 4
Avg.	3.5	97.3	4
-30	3	96.1	2- 2
	3	90.3	3- 4
Avg.	3	93.2	3
B 6464 10			
160	97	0	75-79
	97	0	76-80
Avg.	97	0	77.5
120	90	12.8	75-71
	92	17.0	76-74
Avg.	91	14.9	74
80	70	42.0	62-62
	70	20.0	75-69
Avg.	70	31.0	67
40	44	59.3	40-40
	31	59.4	30-32
	41	59.8	30-29
	31	64.5	38-39
Avg.	37	60.7	34.7
20	51	72.4	46-45
	34	76.4	33-34
Avg.	42	74.4	39.5
B 6464 10			
0	30	78.8	30-29
	25	81.4	24-24
	13	76.4	16-16
	19	79.6	19-20
Avg.	22	79	22
-10	8	89	11- 9
	7	82.9	9-10
	8	85.8	9- 9
	12	82.7	14-14
	5	90.6	7- 7
	25	81.6	25-26
Avg.	11	85.4	12.5
-20	16	84.1	16-16
	16	84.1	18-17
	4	89.0	7- 8
	6	84.0	4- 4
	32	84.1	29-28
	23	84.1	21-23
Avg.	16	84.9	15.9
-40	3	95	2- 2
	7	93.8	7- 7
Avg.	5	94.4	4.5
B 6410 11			
120	136	0	92-90
	121	0	93-80
Avg.	128	0	88.7
80	119	21.3	88-87
	113	10.8	90-82
	132	0	86-83
	114	0	90-92
Avg.	120	8	87.2
40	135	0	85-92
	123	29.0	83-88
	126	0	92-81
	120	20.2	88-83
Avg.	126	9.8	86.5
20	87	54.6	65-66
	93	57.0	80-80
	86	42.7	77-79
Avg.	89	51.4	74.5
0	65	62.1	61-61
	69	56.4	65-67
Avg.	67	59.2	63.5
-10	9	74.8	13-15
	93	56.4	82-90
	10	77.9	7- 8
	120	19.8	81-82
Avg.	58	57.2	47.2
-20	73	61.2	72-71
	29	84.5	29-28
	32	78.0	33-32
	14	85.8	33-33
	87	60.6	77-72
	6	84.9	7- 8
Avg.	40	75.8	41.2
-30	5	90.2	6- 6
	4	94.0	4- 5
Avg.	4.5	92.1	5.2
-40	4	96.2	2- 2
	5	96.2	4- 5
Avg.	4.5	96.2	3.2
B 6405 12			
160	41	39.1	42-44
	40	34.1	44-47
Avg.	40.5	36.6	44.2
140	34	47.7	47-47
	43	49.7	41-40
Avg.	38	48.7	43.7
120	24	48	36-36
	30	61.3	30-29
	35	51	42-37
	28	50.4	33-31
Avg.	29	52.6	34.2

TABLE A-6 (CONTINUED)

Testing Temperature, F	Charpy Impact Energy, Ft-lb.	Brittle Fracture, per cent	Lateral Expansion, mils
B 6405 12			
100	22	52.8	28-29
	31	54.8	35-35
Avg.	26	53.8	31.7
90	21	67.8	20-23
	16	64.0	28-27
Avg.	18.5	65.9	24.5
80	11	71.0	19-18
	12	74.0	16-16
	12	70.0	15-14
	13	72.1	17-19
Avg.	12	71.7	16.7
70	9	73.1	12-12
	11	70.0	14-15
Avg.	10	71.5	13.2
40	7	88.4	7- 8
	6	88.1	8- 9
	7	85.0	6- 8
	6	81.0	11-11
Avg.	6.5	85.6	8.5
30	5	88.1	7- 9
	4	85.5	4- 4
	4	90.0	6- 6
	6	91.5	8- 8
Avg.	5	88.7	6.5
B 6427 13			
140	43	31.0	44-43
	43	36.6	44-44
Avg.	43	33.8	43.7
79	39	56.3	37-35
	37	60.5	35-35
Avg.	38	58.5	35.5
60	26	69.7	28-29
	35	67.2	34-34
Avg.	31	68.5	31.2
40	31	72.1	27-26
	27	76.5	30-30
Avg.	29	74.2	28.2
30	19	80.5	19-19
	15	78.2	18-18
Avg.	17	79.4	18.5
20	9	89.5	12-12
	19	84.8	20-16
	4	92.9	4- 4
	14	85.0	20-14
Avg.	11.5	88.5	12.7
10	5	93.8	7- 6
	11	92.8	12-14
	15	89.1	16-15
	14	91.2	16-16
Avg.	11	91.7	12.7
0	16	91.2	24-20
	25	87.5	24-20
	21	91.2	14-14
	14	93.5	17-18
Avg.	19	91.7	18.8
-10	14	97.5	16-15
	12	95.0	14-14
Avg.	13	98.8	14.7
-20	5	98.8	6- 6
	7	98.8	9- 9
Avg.	6	98.8	7.5
B 6361 14			
120	117	9	91-95
	112	8	93-91
Avg.	114	8.5	92.5
79	113	13.7	97-79
	108	15.0	93-87
Avg.	111	14.4	89
70	96	33.6	79-86
	71	25.2	68-67
	96	35.0	84-86
	60	18.7	64-64
Avg.	80.7	28.1	74.7
B 6361 14			
60	48	50.2	54-52
	93	26.2	83-84
	30	58.6	37-39
	42	51.7	48-44
Avg.	53	46.7	55.1
50	36	54.8	49-48
	41	48.0	43-43
Avg.	39	51.4	45.7
40	42	58.3	33-29
	25	55.2	45-46
Avg.	34	56.8	38
30	21	69.0	25-26
	19	52.0	28-29
Avg.	20	67.1	27
20	15	74.4	18-18
	13	71.5	21-21
Avg.	14	73.0	19.5
10	10	80.8	16-15
	9	82.3	12-16
Avg.	9.5	81.6	14.7
0	11	84.4	14-14
	9	82.5	14-14
Avg.	10	83.5	14
-10	8	88.2	7- 8
	7	89.4	12-11
	9	81.0	13-12
	6	84.6	16-15
Avg.	7	85.8	11.7
-20	7	93.5	7- 8
	6	94.4	10-10
Avg.	6.5	94.0	8.7
B 6903 15			
78	96	22.0	71-83
	89	24.0	88-71
Avg.	92.5	23.0	78
60	93	17.0	78-83
	80	22.5	77-77
Avg.	86.5	19.5	78
40	84	28.3	70-73
	80	32.3	78-76
Avg.	82	30.3	74.2
30	55	55.0	61-58
	80	36.1	78-77
Avg.	67.5	45.1	68.5
20	58	58.3	57-57
	52	56.3	53-51
Avg.	55	57.3	54.5
10	72	58.5	69-70
	13	79.6	18-20
Avg.	42.5	69.0	44.2
0	48	52.7	50-49
	25	72.2	53-53
	15	75.6	19-21
	40	68.2	46-43
	43	63.0	50-47
Avg.	34	65.6	44.4
-10	41	32.5	61-61
	19	81.3	22-24
	19	82.1	22-23
	25	78.7	28-28
Avg.	26	68.6	33.6
-20	8	84.3	9-10
	25	67.5	46-45
	6	88.7	8- 9
	5	90.7	7- 6
Avg.	11	82.8	17.5
-30	8	85.5	11-12
	10	84.5	11- 9
Avg.	9	85.0	10.7
-60	11	82.7	15-14
	6	95.0	7- 7
Avg.	8.5	88.8	10.7

TABLE A-6 (CONTINUED)

Testing Temperature, F		Charpy Impact Energy, Ft-lb.	Brittle Fracture, per cent	Lateral Expansion, mils
B 6880 16				
100		78	1.25	70-80
		70	9.0	77-69
	Avg.	74	5.1	74
80		65	42.8	67-67
	Avg.			67
78		52	26.7	56-60
	Avg.			58
70		61	47.5	47-47
		50	32.5	62-62
		40	43.1	49-49
		68	21.0	68-71
	Avg.	54.7	36.0	56.8
60		30	45.5	40-38
		33	46.2	38-41
	Avg.	31.5	45.8	39.2
50		25	52.5	29-30
		30	51.2	36-35
	Avg.	27.5	51.8	32.5
40		25	56.8	30-32
		19	61.6	24-26
	Avg.	22	59.2	28
30		15	72.0	21-23
		13	69.6	19-17
	Avg.	14	70.8	20
20		11	70.5	17-17
		11	74.6	14-16
		10	86.3	18-15
		9	81.8	15-15
	Avg.	10	78.3	15.8
10		6	90.0	11-11
		7	88.7	11-11
	Avg.	6.5	89.3	11
0		6	86.2	10-10
		6	84.3	10-11
	Avg.	6	85.2	10.4
-10		4	95.5	6- 6
		5	94.0	9- 9
	Avg.	4.5	94.7	7
-20		4	93.7	5- 6
		5	92.6	7- 7
	Avg.	4.5	93.1	6
-30		3	96.7	4- 4
		3	97.7	3- 4
	Avg.	3	97.2	4
B 6880 16 (Duplicate)				
100		75	20.2	70-77
		78	21.0	76-71
	Avg.	76.5	20.6	73.5
80		70	31.7	71-70
		82	22.5	78-74
	Avg.	76	27.1	73.2
70		75	39.3	74-79
		63	40.5	64-66
	Avg.	69	39.9	69
60		60	40.5	46-65
		40	43.8	41-50
	Avg.	50	42.1	52
50		38	49.3	45-48
		33	58.3	41-41
	Avg.	35.5	53.8	43.7
40		41	60.0	46-47
		40	53.6	44-45
	Avg.	40.5	56.8	45.5
30		16.5	63.7	23-24
		12.0	68.2	18-17
	Avg.	14.2	66.0	20.5
20		15	70.7	19-20
		12	72.7	17-18
		13	72.3	17-18
		12	73.8	18-19
	Avg.	13	72.4	18.2
B 6880 16 (Duplicate)				
10		11	70.0	16-18
		10	71.0	14-14
		10	82.2	13-14
		11	78.7	16-15
	Avg.	10.5	75.5	15
0		7	88.7	9- 9
		7	81.7	11-12
	Avg.	7	85.2	10.2
-10		5.5	89.6	10-10
		7.0	85.5	11-12
	Avg.	6.2	87.5	10.7
-20		4	98.0	5- 6
		4	97.0	6- 6
	Avg.	4	97.5	6
-30		3	100	3- 3
		3	100	4- 5
	Avg.	3	100	4
B 6879 17				
120		53	26.2	52-55
		52	32.7	54-53
	Avg.	52.5	29.4	53
100		43	33.6	45-45
		50	29.2	51-50
	Avg.	46.5	31.4	47.7
78		29	40.7	31-33
		40	46.5	40-43
	Avg.	34.5	43.6	36.7
70		28	46.8	32-32
		37	43.7	38-38
	Avg.	32.5	45.2	35
60		35	49.3	36-38
		35	49.6	37-37
	Avg.	35	49.4	37
50		21	60.0	25-26
		21	56.5	23-25
		24	65.0	26-26
		25	62.0	29-28
	Avg.	22.7	60.8	26
40		20	68.0	24-25
		30	65.0	29-29
	Avg.	25	66.5	26.7
30		27	64.2	26-27
		18	71.3	21-20
	Avg.	22.5	67.7	23.5
20		9	73.1	11-12
		21	65.0	11-19
		16	79.1	22-23
		9	77.8	19-14
	Avg.	13.7	73.7	16.3
10		13	77.6	16-17
		20	77.8	18-21
		14	77.2	16-16
		9	81.0	13-13
	Avg.	14	78.4	16.2
0		9	86.2	12-11
		10	83.0	13-14
	Avg.	9.5	84.6	12.5
-30		5	90.2	6- 6
		4	90.2	6- 5
	Avg.	4.5	90.2	5.7

TABLE A-6 (CONTINUED)

Testing Temperature, F		Charpy Impact Energy, Ft-lb.	Brittle Fracture, per cent	Lateral Expansion, mils
B 6879 17		(Duplicate)		
120		54	27.6	54-55
		51	26.7	52-52
	Avg.	52.5	27.1	53
100		41	43.7	44-42
		49	31.5	52-53
	Avg.	45	37.6	47
80		37	44.3	44-43
		41	43.7	41-40
	Avg.	39	44.0	42
70		30	44.3	33-32
		36	48.1	39-38
	Avg.	33	46.2	35
60		32	54.0	34-34
		37	44.0	39-38
	Avg.	34.5	49.0	36
50		26	56.2	29-30
		28	60.0	31-30
	Avg.	27	58.1	30
40		27	58.0	28-28
		27	55.6	30-28
	Avg.	27	56.8	29
30		26	61.6	27-28
		24	76.5	26-25
	Avg.	25	69.0	26.5
20		12	76.7	16-17
		20	79.1	23-24
	Avg.	16	77.9	20
10		17	72.0	17-20
		17	75.3	20-20
	Avg.	17	73.6	19
0		10	86.6	18-19
		10	87.1	15-14
		8	89.0	12-13
		9	85.0	11-10
		15	88.7	14-14
		10	88.1	14-12
	Avg.	10	87.4	13.8
-10		11	90.0	8- 9
		16	85.2	12-14
	Avg.	13.5	87.6	10.5
-30		9	89.2	8-10
		5	93.5	6- 6
	Avg.	7	91.3	7.8
B 6904 18				
140		56	10.0	53-58
		56	12.2	56-57
	Avg.	56	11.1	56
120		43	30.8	47-46
		39	29.2	39-42
	Avg.	41	30.0	43.5
110		43	44.0	49-43
		37	31.2	42-39
	Avg.	40	37.6	43.2
100		28	30.5	29-30
		40	50.7	45-44
	Avg.	34	40.6	37
90		23	49.2	26-31
		30	53.3	34-34
	Avg.	26.5	51.2	31.2
78		36	40.2	41-42
		22	48.7	26-27
		19	54.2	25-25
	Avg.	26	48.2	31
70		24	56.8	29-29
		18	61.0	26-28
	Avg.	21	58.9	28
60		16	59.5	20-21
		18	66.5	23-24
	Avg.	17	63.0	22
B 6904 18				
50		13	70.0	18-19
		25	68.6	26-27
		18	69.8	22-23
	Avg.	18.6	69.4	22.5
40		13	72.0	16-17
		13	76.0	16-17
	Avg.	13	74.0	16.5
20		6	81.0	12-12
		6	80.5	10-10
		6	86.5	9- 9
		8	79.9	10- 9
	Avg.	6.5	81.9	10.1
0		6	91.6	9-10
		5	88.2	7- 7
	Avg.	5.5	89.9	8.2
-30		3	100.0	3- 4
		2	100.0	2- 2
	Avg.	2.5	100.0	2.7
B 6930 19				
120		70	11.5	66-57
		54	23.7	59-53
	Avg.	62	17.6	58.7
100		59	24.3	55-50
		58	20.0	57-58
	Avg.	58.5	22.1	55
90		42	27.1	47-44
		52	24.0	55-53
	Avg.	47	25.5	49.7
78		52	23.6	53-53
		43	32.7	44-43
	Avg.	47.5	28.1	48.2
70		41	31.0	44-44
		32	40.2	36-36
	Avg.	36.5	35.6	40
60		39	50.0	40-40
		32	51.2	36-37
	Avg.	35.5	50.6	38.2
50		25	53	29-32
		30	51	32-31
	Avg.	27.5	52	31
40		33	58.0	34-35
		25	63.3	30-28
	Avg.	29	60.6	31.7
30		19	72.6	23-23
		16	67.5	21-22
	Avg.	17.5	70.0	22.2
20		25	70.6	26-25
		12	82.7	16-16
		22	78.3	27-26
	Avg.	19.6	77.2	22.6
10		10	80.0	14-15
		22	78.7	25-28
		10	82.1	15-18
		11	82.5	17-17
	Avg.	13.2	80.8	18.6
0		6	86.7	7- 8
		6	85.6	10- 8
	Avg.	6	86.1	8.2
-30		6	88.1	8- 7
		3	92.6	3- 3
	Avg.	4.5	90.3	5.2

TABLE A-6 (CONTINUED)

Testing Temperature, F	Charpy Impact Energy, Ft-lb.	Brittle Fracture, per cent	Lateral Expansion, mils
B 6931 20			
120	70	18.7	66-70
	75	15.7	66-77
Avg.	72.5	17.2	69.7
100	56	21.6	55-61
	56	31.5	53-50
Avg.	56	26.5	54.7
78	55	39.3	50-51
	47	35.6	49-49
Avg.	51	37.4	49.7
70	50	42.0	54-52
	59	33.2	59-60
Avg.	54.5	37.6	56.2
60	40	54.1	33-41
	40	54.3	42-44
Avg.	40	54.2	40
50	20	61.2	27-27
	43	61.5	47-47
Avg.	31.5	61.3	37
40	22	60.7	26-27
	22	62.0	22-27
Avg.	22	61.3	25.5
30	14	75.0	20-19
	30	65.7	32-32
	12	67.5	18-17
Avg.	18.6	69.4	23
20	11	80.0	17-16
	9	83.2	15-14
Avg.	10	81.6	15.5
10	6	78	14-14
	10	87	14-14
	10	78	16-16
	9	85	9-10
Avg.	8.7	82	13.3
0	10	84.3	14-14
	8	81.0	13-13
Avg.	9	82.6	13.5
-20	4	89.6	5- 6
	6	85.2	6- 8
Avg.	5	87.4	6.2
-30	4	88.1	6- 6
	3	88.1	3- 5
Avg.	3.5	88.1	5
B 6914 21			
78	62	29.2	55-64
	68	30.5	66-59
Avg.	65	29.8	61
60	48	46.8	50-49
	46	45.0	47-48
Avg.	47	45.9	48.5
40	32	53.6	35-32
	33	46.8	36-33
Avg.	32.5	50.2	34
30	39	63.2	40-40
	24	73.8	29-30
Avg.	31.5	68.5	34.7
20	30	63.0	31-36
	33	63.7	33-33
Avg.	31.5	63.4	33.2
10	30	73.1	30-29
	22	74.2	24-24
Avg.	26	73.6	26.7
0	22	76.5	22-22
	30	67.7	30-28
Avg.	26	72.1	25.5
-10	22	81.8	22-24
	26	76.5	28-29
	24	73.1	19-19
	15	77.2	26-26
Avg.	21.7	74.6	24.1
B 6914 21			
-20	16	84.1	17-22
	21	86.3	22-22
	9	88.0	14-13
	20	91.6	23-17
Avg.	16.5	87.5	18.7
-40	6	84.3	17-17
	8	84.3	9- 9
Avg.	7	84.3	13
-50	8	86.3	10-10
	10	85.3	13-13
Avg.	9	85.8	11.5
-60	5	89.0	7- 7
	7	83.0	10- 8
Avg.	6	86.0	8
B 6933 22			
80	62	37.0	60-61
	65	33.2	63-62
Avg.	63.5	35.1	61.5
78	84	34.1	64-61
	57	31.2	51-59
Avg.	70.5	32.6	58.7
60	45	46.8	47-44
	46	46.7	47-47
Avg.	45.5	46.8	46.2
40	32	54.2	34-35
	27	51.0	29-31
Avg.	29.5	52.6	32.2
30	33	65.8	36-35
	40	68.0	41-42
	59	60.5	59-59
Avg.	44	64.7	45.3
20	14	65.0	18-19
	17	71.7	16-18
Avg.	15.5	68.3	17.7
10	19	77.8	22-22
	12	76.1	16-19
Avg.	15.5	76.9	19.7
0	27	60.3	28-29
	22	68.8	22-22
	18	74.7	21-23
	11	80.0	11-13
Avg.	19.5	70.9	21.1
-10	10	80.2	13-12
	18	76.1	19-20
	11	81.0	16-13
	8	78.7	13-16
Avg.	11.7	79.0	15.2
-20	7	81.8	15-14
	7	89.6	9- 9
Avg.	7	85.7	12
-60	3	97.0	4- 3
	3	96.0	4- 3
Avg.	3	96.5	3.5
B 6913 23			
78	73	17.5	59-71
	60	29.2	61-56
Avg.	66.5	23.3	61.7
60	65	30.8	58-67
	48	30.0	48-47
Avg.	56.5	30.4	55
50	48	40.5	46-49
	49	43.7	49-47
Avg.	48.5	42.1	47.7
40	37	58.5	40-35
	42	45.3	42-42
Avg.	39.5	51.9	39.7
30	32	76.0	35-34
	35	63.0	36-36
Avg.	33.5	69.5	35.2
20	37	43.2	37-36
	30	48.1	30-28
Avg.	33.5	45.6	32.7

TABLE A-6 (CONTINUED)

Testing Temperature, F		Charpy Impact Energy, Ft-lb.	Brittle Fracture, per cent	Lateral Expansion, mils
B 6913 23				
10		30	77.0	35-37
		32	67.5	29-30
	Avg.	31	72.2	32.7
0		30	63.0	31-31
		32	60.0	34-33
		18	73.0	22-21
		22	66.0	21-21
		16	68.6	21-21
	Avg.	23.6	66.1	25.6
-10		22	82.5	25-26
		16	85.6	19-19
	Avg.	19	84.0	22.2
-20		9	75.5	12-12
		13	71.7	13-17
	Avg.	11	73.6	13.5
-30		7	86.7	16-12
		7	88.7	8-10
		11	80.0	18-17
		10	82.1	8- 8
	Avg.	8.7	84.3	12.1
-60		8	84.1	11-10
		4	87.1	4- 4
	Avg.	6	85.6	7.2
B 6929 24				
80		48	34.6	51-51
		57	35.0	56-56
	Avg.	52	34.8	53.5
70		50	42.7	50-51
		57	25.2	58-58
	Avg.	53.5	33.9	54
60		46	37.8	47-49
		51	34.6	51-52
	Avg.	48.5	36.2	50
50		42	51	43-45
		40	51	43-40
	Avg.	41	51	42.3
40		34	51.0	37-39
		40	45.6	41-41
	Avg.	37	48.3	40
30		30	50.0	33-34
		36	54.3	39-39
	Avg.	33	52.1	37
20		26	67.5	29-30
		14	71.5	20-19
	Avg.	20	69.5	24.5
10		25	74.3	27-31
		7	84.3	10-12
		15	68.6	19-21
		13	69.0	18-18
	Avg.	15	74.0	19.5
0		19	73.1	23-22
		11	79.8	16-15
		12	77.0	18-17
		31	67.7	33-34
		23	73.1	26-26
		23	68.6	26-26
	Avg.	19.8	73.2	23.5
-10		7	89.0	10-11
		7	90.0	11-11
	Avg.	7	89.5	11
-20		6	91.8	9- 8
		10	87.8	12-13
	Avg.	8	89.8	10.4
-40		6	91.1	7- 7
		6	89.0	6- 8
	Avg.	6	90.0	7
B 7191 25				
90		70.0	24.2	68-63
		76.0	27.4	65-70
	Avg.	73.0	25.8	66.5
60		45.0	47.1	44-43
		39.0	54.9	41-41
	Avg.	42.0	51.0	42.2
40		39.5	60.9	40-40
		34.0	63.7	33-34
	Avg.	36.7	62.3	36.7
30		27.0	59.6	43-44
		43.0	61.7	46-47
		28.0	63.7	31-30
		39.0	64.1	37-39
	Avg.	34.2	62.3	39.6
20		33.5	67.1	34-35
		28.5	72.0	26-25
		34.0	72.0	35-36
		31.0	72.9	30-30
	Avg.	31.7	71.0	31.4
10		40.0	68.1	40-39
		19.0	76.4	23-23
		30.0	74.4	30-29
		29.5	66.0	31-30
	Avg.	29.6	71.2	30.6
0		11.5	84.6	12-13
		14.5	81.4	17-17
		30.5	76.0	29-29
		35.0	72.0	35-36
	Avg.	22.9	78.5	23.5
-10		24.0	78.7	25-25
		19.5	81.2	20-20
	Avg.	21.7	79.9	22.5
-20		14.5	80.4	17-17
		13.5	83.2	16-15
	Avg.	14.0	81.8	16.2
-30		8.5	85.7	10- 9
		8.0	82.4	10- 9
	Avg.	8.3	84.0	9.5
-60		5.0	98.7	6- 6
		4.5	95.0	7- 5
	Avg.	4.8	96.8	6
B 7192 26				
90		48.0	41.9	47-42
		49.0	44.6	51-50
	Avg.	48.5	43.2	47.5
60		25.0	58.4	26-27
		33.0	61.4	32-34
	Avg.	29.0	59.9	29.7
30		30.0	65.4	32-31
		25.0	69.0	26-25
	Avg.	27.5	67.2	28.5
20		24.0	73.6	26-26
		27.0	69.2	28-29
	Avg.	25.5	71.4	27.2
10		14.0	70.5	17-16
		13.5	77.0	15-16
		18.5	73.1	21-19
		28.0	72.0	29-31
	Avg.	18.5	73.0	20.5
0		20.5	77.9	21-22
		24.5	72.4	25-27
		9.0	75.6	11-11
		12.0	72.2	14-13
	Avg.	16.5	74.5	18
-10		18.0	76.4	21-21
		18.5	79.0	9-10
		19.5	77.1	18-18
		7.5	76.7	19-21
	Avg.	15.9	77.3	17.1

TABLE A-6 (CONTINUED)

Testing Temperature, F	Charpy Impact Energy, Ft-lb.	Brittle Fracture, per cent	Lateral Expansion, mils
B 7192 26			
-20	9.0	81.4	12-13
	20.0	75.1	23-22
	11.0	80.7	13-14
	6.0	81.4	7- 8
Avg.	11.5	79.6	10.5
-30	5.0	80.5	7- 6
	12.0	81.4	13-12
	6.0	81.4	7- 8
	4.5	83.1	5- 6
Avg.	6.9	81.6	8
-60	6.0	87.2	7-17
	4.0	90.6	5- 5
Avg.	5.0	88.9	8.5
B 7193 27			
60	111.0	30.0	85-83
	106.0	34.0	84-80
Avg.	108.5	32.0	83
30	80.5	48.4	77-73
	78.5	52.9	74-74
Avg.	79.5	50.6	74.5
0	67.5	58.1	65-63
	43.5	72.9	43-42
	57.0	66.2	56-56
Avg.	56.0	65.7	54.1
-10	59.5	67.6	56-58
	82.0	55.7	74-77
	51.5	66.2	51-51
	86.0	60.6	77-76
Avg.	69.8	62.5	65
-20	55.0	68.1	54-53
	23.0	78.4	44-44
	61.0	64.6	55-56
Avg.	46.3	70.4	51
-30	60.0	65.7	51-50
	63.5	65.2	60-61
	57.0	67.0	54-53
Avg.	60.1	65.9	54.8
-40	26.5	81.6	27-26
	3.5	83.6	4- 4
	16.0	78.0	17-17
Avg.	15.3	81.1	15.8
-50	27.0	82.4	28-26
	17.0	80.4	17-18
	23.0	81.6	24-23
Avg.	22.3	81.5	22.6
-60	22.0	82.7	23-22
	23.0	81.9	25-23
Avg.	22.5	82.3	23.2
-70	25.0	84.9	25-25
	2.5	85.7	2- 1
Avg.	13.8	85.3	13.2
-80	2.0	90.9	4- 2
	11.5	90.6	12-12
	11.5	91.9	12-12
Avg.	8.3	91.0	9

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*Battelle-Assigned Heat No.

TABLE A-7

V-NOTCH CHARPY TEST DATA FOR LABORATORY STEELS HEATED FOR ONE HOUR AT 1600 F AND AIR COOLED

Testing Temperature, F		Charpy Impact Energy, Ft-lb.	Brittle Fracture, per cent	Lateral Expansion, mils
B 6353 1T2				
76		74	26.8	72-74
		78	21.2	75-68
	Avg.	76	24.0	72.2
70		65	42.8	67-64
		55	43.2	60-59
	Avg.	60	42.6	62.5
60		37.5	50.4	41-42
		42.5	53.4	48-46
	Avg.	40	51.9	44.2
50		50	60.0	40-40
		20	56.3	38-40
		36	43.9	53-54
		35	66.0	29-26
	Avg.	35	56.6	40
40		30	59.2	36-36
		24	63.2	30-29
	Avg.	27	61.1	32.7
30		16	69.0	25-25
		28	66.6	35-33
		13	75.2	18-19
	Avg.	19	70.3	25.8
20		13	74.4	18-18
		16	70.0	21-22
	Avg.	14.5	72.2	19.7
10		12	78.0	17-17
		13	76.5	19-17
		10	79.0	16-16
		11	77.0	16-15
		9	83.0	14-14
		10	83.4	15-15
	Avg.	11	79.5	15.9
0		10	84.4	13-13
		6	85.3	9-10
	Avg.	8	85.0	11
-10		9	87.5	14-16
		6	86.4	9-10
	Avg.	7.5	87.0	12
-20		4	95.5	10-10
		6	90.5	8- 7
	Avg.	5	93.0	9
B 6327 2S16				
100		99	0	84-70
		97	0	82-80
	Avg.	98	0	79
70		90	14.7	87-74
		102	1.2	62-85
	Avg.	96	7.9	77
30		80	30.4	75-66
		77	30.6	70-73
	Avg.	78.5	30.5	71
20		64	46.2	56-59
		60	42.0	58-63
	Avg.	62	44.1	59
10		57	45.0	53-58
		58	51.3	56-54
	Avg.	57.5	48.2	55
0		60	48.0	67-64
		72	40.5	57-57
	Avg.	66	44.3	61
-10		41	60.2	44-48
		45	62.3	42-43
	Avg.	43	61.3	44
-20		38	65.3	47-50
		49	56.3	40-40
	Avg.	43.5	60.8	44
-30		37	67.5	37-38
		32	65.3	35-33
	Avg.	34.5	66.4	36
-40		8	83.2	12-13
		10	84.0	11-11
	Avg.	9	83.6	12
B 6327 2S16				
-60		6	96.5	6- 7
		6	96.5	7- 7
	Avg.	6	96.5	7
-80		7	97.4	6- 7
		6	97.4	8- 8
	Avg.	6.5	97.4	7
B 6366 3T2				
76		93	0	76-69
		95	0	70-73
	Avg.	94	0	72
40		86	11.2	71-67
		79	25.4	70-68
	Avg.	82.5	18.3	69
20		72	30.4	61-64
		79	25.4	60-60
	Avg.	75.5	27.9	61.2
0		75	41.0	68-64
	Avg.	75	41.0	66
-20		45	64.0	43-44
		57	50.0	51-53
	Avg.	51	57.0	47.7
-30		45	52.0	44-42
		36	52.0	37-37
	Avg.	40.5	52.0	40
-40		42	66.0	39-39
		34	66.0	35-34
	Avg.	38	66.0	36.7
-50		33	69.0	33-32
		32	72.3	32-31
	Avg.	32.5	70.6	31.7
-60		25	72.8	28-28
		35	73.2	28-28
		23	73.2	25-25
		41	67.5	38-39
		18	78.8	22-22
		14	80.2	18-18
	Avg.	26	74.3	26.5
-70		--	77.3	26-26
		26	80.5	27-27
	Avg.	26	78.9	26.5
-80		19	80.5	20-20
		4.5	88.1	5- 6
		15	82.5	17-17
		7.5	80.8	15-15
	Avg.	11.5	81.6	14.3
-90		10	90.2	10-10
		3	93.1	4- 4
	Avg.	6.5	91.6	7
B 6367 4T2				
76		118	8.0	81-92
		136	2.1	91-92
	Avg.	127	5.0	89
60		140	6.2	91-81
		136	17.6	89-89
	Avg.	138	11.9	88
40		89	55.1	80-82
		90	48.3	80-80
	Avg.	89.5	51.7	80
20		52	60.0	58-57
		114	41.3	87-93
	Avg.	83	50.7	74
0		117	40.8	90-96
		67	65.3	71-69
	Avg.	92	53.1	82
-20		88	62.5	85-84
		55	73.5	58-56
		42	72.1	44-44
		35	79.0	38-38
	Avg.	55	71.8	56
-30		8	82.1	13-13
		72	69.6	71-73
	Avg.	40	75.8	42

TABLE A-7 (CONTINUED)

Testing Temperature, F	Charpy Impact Energy, Ft-lb.	Brittle Fracture, per cent	Lateral Expansion, mils
B 6367 4T2			
-40	6	84.3	9-11
	20	85.7	12-13
	9	89.2	22-21
	6	90.0	8-10
Avg.	10	87.3	13
-50	7	87.4	13-12
	7	92.0	11-13
Avg.	7	89.7	12
-60	5.5	91.5	10- 8
	9.5	88.2	12-13
	5	97.4	9- 9
	4	96.5	7- 7
	5	96.5	7- 7
	4	92.0	8- 8
Avg.	5.5	93.8	8.7
B 6360 5T2			
120	39	36.6	43-48
	36	40.8	43-44
Avg.	37.5	38.7	44
100	35	43.8	35-36
	35	44.6	38-39
Avg.	35	44.2	37
90	34	49	39-38
	33	49	38-39
Avg.	33.5	49	38.5
76	21.5	67.2	26-30
	19	68.2	25-26
Avg.	20.2	68.7	27
60	19	66.5	24-25
	19	68.0	24-21
Avg.	19	67.3	24
50	21	68	25-28
	19	68	25-23
Avg.	20	68	25
40	9	76.9	13-13
	21	69.7	23-23
Avg.	15	73.1	18
30	19	75	23-23
	11	78	17-17
Avg.	15	76.5	20
20	10	78.8	15-16
	8	78.0	9-11
Avg.	9	78.4	13
10	8	79.9	12-13
	7	83.7	10-11
Avg.	7.5	81.8	12
0	7	85.0	10- 9
	9	80.8	13-13
Avg.	8	82.9	11
-10	5	87.8	8- 6
	4	92.1	6- 6
	6	87.1	7- 7
	5	87.8	8- 7
Avg.	5	88.8	7
-20	6	86.3	9- 8
	6	89.4	9-10
Avg.	6	87.9	9
76 B 6368 6T2	70	0	63-56
	60	11.8	54-52
Avg.	65	5.9	56
60	58	25.2	52-44
	63	14.2	52-57
Avg.	60.5	19.7	51
40	43	31.5	43-39
	40	34.1	34-33
Avg.	41.5	32.8	37
20	37	39.5	34-37
	37	43.3	33-36
Avg.	37	41.4	35
10	39	49.0	34-36
	32	56.0	29-31
Avg.	35.5	52.5	32
B 6368 6T2			
0	19	70.0	16-18
	28	50.0	30-31
	22	63.0	23-22
Avg.	23	61.0	23
-10	30	62.7	30-29
	27	63.0	27-27
Avg.	28.5	62.8	28
-20	26	68.8	26-25
	21	78.3	19-22
Avg.	23.5	73.6	23
-30	21	73.1	20-20
	25	72.0	24-25
Avg.	23	72.6	22
-40	15	79.9	16-17
	18	69.3	20-19
	19	76.5	19-20
	14	79.9	13-12
Avg.	16.5	76.4	17
-50	9	80.7	12-12
	9	79.9	12-11
Avg.	9	80.3	11
-60	11	87.8	8- 7
	12	86.7	13-13
Avg.	11.5	87.3	10
-80	8	90.5	7- 8
	13	83.1	13-13
Avg.	10.5	86.8	10
B 6359 7T2			
76	128	10.1	98-105
	134	0	91-97
Avg.	131	5.05	97
60	135	0	85-94
Avg.			89.5
40	136	15.8	89-89
	125	15.0	86-88
Avg.	130.5	15.4	88
30	132	17.5	77-96
	98	28.9	83-97
	96	34.1	79-90
Avg.	109	26.8	87
20	107	26.3	89-79
	76	39.5	75-73
Avg.	91.5	32.9	79
10	119	28.1	81-93
	26	69.0	35-33
Avg.	72.5	48.6	61
0	20	70	29-25
Avg.			27
-10	18	71.6	25-26
	18	74.8	24-24
	16	77.9	21-24
Avg.	17.5	74.8	24
-20	11	78.8	17-17
Avg.			17
-40	6	82.4	8-10
Avg.			9
B 6406 8T			
120	52	25.9	53-61
	58	21.0	66-62
Avg.	55	23.2	60
100	50	33.3	52-59
	48	28.7	49-59
Avg.	49	31.0	55
90	36	47.4	45-41
	36	44.2	41-44
Avg.	36	45.8	43
76	33.5	52.8	41-39
	26.0	56.0	31-44
Avg.	29.6	54.4	36

TABLE A-7 (CONTINUED)

Testing Temperature, F		Charpy Impact Energy, Ft-lb.	Brittle Fracture, per cent	Lateral Expansion, mils
B 6406 8T				
60		15	65.0	49-50
		27	65.0	33-29
		18	60.0	23-26
		19	62.0	27-27
	Avg.	20	63.0	33
50		14	70.9	21-21
		18	69.0	25-22
	Avg.	16	70.0	22
40		11	78.8	17-17
		10	78.8	15-17
		8	74.4	14-13
		8	74.4	14-14
	Avg.	9	76.6	15
30		6	81.0	16-14
		8	77.9	10-11
	Avg.	7	79.5	13
20		5.5	81.0	10- 9
		9.0	78.8	16-14
	Avg.	7	79.9	12
10		8	92.5	12-13
		5	82.0	11-11
		6	83.9	11-11
		8	85.3	6- 8
		4	96.8	1- 8
	Avg.	6	88.1	10
0		4	89.7	7- 7
		6	87.2	10- 9
	Avg.	5	88.5	8
B 6409 9S16				
120		79	0.8	76-77
		73	4.5	68-76
	Avg.	76	2.6	74
82		53	31.9	55-58
		63	34.5	60-65
	Avg.	58	33.2	59
70		39	44.0	38-35
		31	49.1	43-44
		30	48.7	39-42
		39	42.3	42-45
	Avg.	34.7	46.2	42
60		34	47.5	41-37
		39	55.0	38-40
		37	59.0	43-44
	Avg.	36.7	53.8	41
50		28	58.9	34-35
		28	59.2	34-34
	Avg.	28	59.1	34
40		28	65.8	21-21
		14	63.0	33-33
	Avg.	21	64.4	27
30		14	75.7	19-19
		24	69.0	28-29
	Avg.	19	72.3	24
20		23	75.3	27-28
		21	72.0	26-26
	Avg.	22	73.6	27
10		12	77.7	16-16
		11	78.7	17-16
	Avg.	11.5	78.2	16
0		7	84.3	10- 9
		7	79.8	11-10
	Avg.	7	82.0	10
-10		7	87.4	9- 9
		6	83.6	8- 7
		5	86.3	9- 9
		5	82.7	8- 9
	Avg.	5.7	85.0	8
-20		5	91.9	6- 7
		3	91.7	0- 0
	Avg.	4	91.8	3

Testing Temperature, F		Charpy Impact Energy, Ft-lb.	Brittle Fracture, per cent	Lateral Expansion, mils
B 6464 10T				
76		70	36.6	61-66
		80	19.7	74-73
	Avg.	75	27.2	68
60		67	34.5	63-62
		59	35.8	56-55
	Avg.	63	35.1	59
50		59	39.4	58-57
		78	32.9	66-72
		55	50.0	56-52
		48	54.3	50-48
	Avg.	60	44.2	57
40		49	55.0	45-60
		49	56.0	50-49
	Avg.	49	55.5	47
30		45	52.0	46-47
		28	66.6	33-32
	Avg.	36.5	59.3	39
20		31	71.5	34-34
		38	62.3	39-40
	Avg.	34.5	66.9	37
10		40	73.1	40-39
		22	77.9	27-27
		12	77.0	16-17
		35	67.5	12-11
	Avg.	27.2	73.8	23.8
0		28	70.0	30-30
		24	68.6	29-29
	Avg.	26	69.3	29.5
-10		18	74.7	22-21
		15	79.6	18-17
	Avg.	16.5	77.1	19
-20		9	84.0	12-11
		9	81.4	9- 9
		7	80.5	13-13
		5	83.1	13-14
		11	83.1	15-17
	Avg.	8	82.4	13
-40		4	95.0	8- 6
		10	94.0	13-12
	Avg.	7	94.5	10
B 6410 11T				
76		111	30.0	93-86
		117	0	80-88
	Avg.	114	15.0	87
40		68	56.3	69-67
		147	0	97-90
	Avg.	107.5	28.2	81
30		110	33.8	92-93
		115	33.8	92-93
	Avg.	112.5	33.8	92
20		85	45.7	80-83
		20	65.6	29-31
		82	59.4	81-80
		104	47.5	92-89
	Avg.	72.5	54.6	70
10		100	50.0	89-94
		105	47.5	98-87
		58	63.5	62-61
		60	59.9	64-65
	Avg.	81	55.2	77
0		12	78.8	21-19
		77	62.6	79-77
		70	65.4	72-61
		30	80.8	21-21
		12	78.8	35-36
	Avg.	56	73.3	44
-20		68	81.4	15-16
		9	70.0	70-70
		17	86.6	22-22
		12	84.0	19-18
		7	85.8	13-13
		9	85.8	16-16
	Avg.	60	82.3	25

TABLE A-7 (CONTINUED)

Testing Temperature, F		Charpy Impact Energy, Ft-lb.	Brittle Fracture, per cent	Lateral Expansion, mils
B 6410 11T				
-30		5	87.3	10-10
		6	83.1	10-12
	Avg.	5.6	85.2	10
-40		4	97.5	7- 7
		7	93.8	11-11
	Avg.	5.5	95.6	9
B 6405 12T				
150		44	33.8	53-50
		43	31.8	48-52
	Avg.	43.5	32.8	50
130		27	46.5	37-36
		26	52.5	36-35
	Avg.	26.5	49.5	36
120		32	44.6	40-42
		25	52.6	35-46
	Avg.	28.5	48.6	37
110		27	64.7	34-36
		25	57.0	31-34
	Avg.	26	60.8	34
100		35	56.0	34-31
		15	61.3	24-22
		16	69.3	22-24
		19	68.3	28-28
	Avg.	21	63.7	26
90		12.5	71.0	20-19
		12.5	71.0	21-20
	Avg.	12.5	71.0	20
76		14	70.0	21-22
		8	75.5	12-11
	Avg.	11	72.8	16
70		10	77.9	16-17
		10	79.7	15-15
	Avg.	10	78.8	16
60		6	82.1	12-12
		11	77.9	18-17
		6	84.4	11- 9
	Avg.	8	81.5	13
50		6	75.0	12-10
		6.5	65.4	10- 9
	Avg.	6.25	70.2	10
40		5	81.9	9- 9
		4	84.2	5- 6
	Avg.	4.5	83.0	7
30		5	85.0	7- 8
		4	90.0	8- 7
		5	84.3	8- 9
		3	93.9	5-11
	Avg.	4	88.3	8
B 6427 13T				
90		42	39.5	40-41
		42	41.9	42-41
	Avg.	42	40.7	41
76		38	49.7	39-40
		38.5	50.0	38-38
	Avg.	38.25	49.8	39
60		33	58.0	35-34
		31	60.0	34-33
	Avg.	32	59.0	34
50		26	60.8	30-28
		30	58.4	31-30
	Avg.	28	59.6	30
40		23	67.8	26-26
		25	68.8	27-26
	Avg.	24	68.3	26
30		27	67.5	29-30
		22	72.0	24-24
	Avg.	24.5	69.8	27
20		25	68.6	26-22
		18	69.8	27-20
	Avg.	21.5	69.2	23
B 6427 13T				
10		11	83.1	18-18
		18	83.1	20-21
		15	86.7	16-17
		18	82.3	13-14
	Avg.	15.5	83.6	17
0		14	86.6	16-16
		12	79.6	16-16
	Avg.	13	83.1	16
-10		10	98.6	13-12
		11	98.6	13-13
	Avg.	10.5	98.6	13
-20		16	87.5	17-17
		10	92.5	11-12
		10	92.9	12-11
	Avg.	12	90.9	13
-30	5	5	100	6- 6
		6	100	7- 7
	Avg.	5.5	100	6.5
-40		7	97.5	9- 9
		2	100	2- 3
	Avg.	4.5	98.8	6
B 6361 14T				
76		66	33.8	67-68
		58	31.8	64-60
	Avg.	62	32.8	65
60		40	38.1	45-51
		35	51.0	42-44
		43	55.3	50-51
		38	54.0	45-45
	Avg.	39.5	49.6	46
50		48	44.7	57-53
		44	49.4	51-60
		28	61.0	33-32
		23	56.3	36-38
	Avg.	36	52.9	45
40		19	64.0	27-29
		22	65.2	31-32
		19	70.0	28-27
	Avg.	20	66.4	29
30		19	70	26-28
		22	63	32-32
	Avg.	20.5	66.7	29
20		14	72.6	22-22
		14	72.7	21-20
	Avg.	14	72.7	21
10		10	82.5	16-14
		11	75.3	18-17
	Avg.	10.5	78.9	16
0		6	79.9	11-11
		9	83.3	16-16
	Avg.	7.5	81.6	14
-10		6	81.0	10-11
		8	88.8	14-13
		6	88.8	10-10
		8	81.0	12-13
		5	95.0	9- 9
		6	98.8	8- 9
	Avg.	6.5	88.9	11
-20		4	98.8	8- 9
		4	98.8	7- 8
	Avg.	4	98.8	8

TABLE A-8

V-NOTCH CHARPY TEST DATA FOR LABORATORY STEELS HEATED FOR ONE HOUR AT 1900 F AND COOLED IN AIR

Testing Temperature, F	Charpy Impact Energy, Ft-lb.	Brittle Fracture, per cent	Lateral Expansion, mils
B 6327 2S19A			
81	95	0	82-74
	89	16.5	70-77
Avg.	92	8.2	76
60	80	32.4	71-75
	80	25.3	71-77
Avg.	80	28.8	73
40	72	39.9	85-69
	82	34.4	68-74
Avg.	77	37.1	74
30	75	39.3	69-70
	48	40.9	52-53
Avg.	61.5	40.1	61
20	67	48.9	65-63
	24	77.2	28-28
	53	70.3	55-52
	48	60.7	55-55
Avg.	48	64.3	50
10	43	63.6	52-50
	13	62.0	21-20
	49	55.5	44-46
	48	53.2	49-49
	33	54.0	39-37
Avg.	37.2	57.7	41
0	24	70.2	27-26
	61	54.4	62-59
	16	72.7	19-22
	36	59.2	40-40
Avg.	34.2	64.1	37
-10	17	76.2	22-21
	22	67.1	26-25
Avg.	19.5	71.6	24
-20	8	84.3	12-10
	9	84.8	14-16
	11	80.1	16-16
	7	84.3	12-11
Avg.	8.8	83.4	13
-30	7	86.9	12-10
	9	86.2	14-11
Avg.	8	86.5	12

Testing Temperature, F	Charpy Impact Energy, Ft-lb.	Brittle Fracture, per cent	Lateral Expansion, mils
B 6409 9S19A			
120	73	14.7	71-72
	67	22.6	70-65
Avg.	70	18.6	70
81	53	45.8	55-54
	43	59.0	71-69
Avg.	48	52.4	62
67	25	68.8	25-26
	19	68.7	32-30
Avg.	22	68.8	28
66	32	65.9	37-35
	23	69.5	28-28
Avg.	27.5	67.7	32
60	40	67.5	44-43
	15	64.0	21-21
	26	66.0	32-31
	14	69.0	19-20
Avg.	24	66.6	29
50	8	72.3	25-25
	28	70.8	22-20
	18	66.8	13-14
	15	71.7	32-32
Avg.	17.2	70.4	23
40	24	75.2	31-30
	8	77.1	12-13
	11	75.9	18-18
	8	80.7	12-12
Avg.	13.2	77.2	18
30	7	78.8	12-12
	12	84.9	17-18
	7	81.0	13-12
Avg.	8.7	81.6	14
20	5	80.5	9- 9
	8	72.5	12-12
	25	81.9	26-27
	6	90.0	9- 9
Avg.	11	81.2	14
10	6	94.0	9-10
	6	94.0	9-11
Avg.	6	94.0	10

TABLE A-9

V-NOTCH CHARPY TEST DATA FOR LABORATORY STEELS HEATED FOR ONE HOUR AT 1900 F AND FURNACE COOLED

Temperature, F		Charpy Impact Energy, Ft-lb.	Brittle Fracture per cent	Lateral Expansion, mils
B 6932 2-2				
120		60.0	30.0	65-64
		48.0	37.0	55-58
	Avg.	54.0	33.5	60.5
90		42.0	54.4	49-48
		51.0	43.5	54-56
	Avg.	46.5	48.9	51.8
60		40.0	55.6	45-46
		36.0	58.2	40-41
	Avg.	38.0	56.9	43.0
50		14.5	67.0	21-21
		27.0	68.1	31-32
	Avg.	20.7	67.5	26.3
40		31.0	60.7	36-36
		33.5	68.2	36-37
	Avg.	32.2	64.5	36.3
30		27.0	72.0	29-29
		8.0	71.1	14-14
		9.5	75.2	16-15
		8.0	76.5	13-11
	Avg.	13.1	73.7	17.6
20		7.0	76.5	11-11
		22.5	82.7	26-26
	Avg.	14.7	79.6	18.5
10		5.0	83.6	8- 7
		6.0	82.1	8- 9
	Avg.	5.5	82.8	8
0		22.5	84.8	26-27
		6.0	84.4	9-10
		4.0	85.7	7- 7
		5.5	90.6	9- 8
	Avg.	9.5	86.4	12.9
-10		4.5	91.9	6- 7
		6.0	90.4	8- 8
	Avg.	5.2	91.0	7.3
-15		7.0	90.9	9- 8
		4.5	89.0	5- 6
	Avg.	5.7	89.9	7
-20		6.0	92.7	7- 8
	Avg.	6.0	92.7	7.5
-30		3.0	94.0	4- 3
		3.5	93.1	5- 4
	Avg.	3.2	93.5	4
B 6367 4				
60		122.5	0	93-86
		127.5	0	94-90
	Avg.	125.0	0	90.8
45		114.0	24.9	99-75
		85.0	41.5	79-77
	Avg.	99.5	33.2	82.5
30		41.5	35.2	50-50
		117.5	19.5	96-79
		109.0	31.9	93-80
		81.5	32.0	79-70
	Avg.	87.4	29.6	74.6
15		117.5	11.2	81-82
		90.0	38.9	80-84
	Avg.	103.7	25.0	81.8
0		77.0	50.6	76-73
		95.0	42.9	84-84
	Avg.	86.0	46.7	79.3
-15		101.0	44.1	87-86
		80.0	55.1	84-76
	Avg.	90.5	49.6	83.3
-20		18.0	74.7	24-25
	Avg.	18.0	74.7	24.5
-30		42.0	68.1	19-19
		8.5	79.6	12-12
		8.0	85.0	15-17
		10.0	81.9	16-18
	Avg.	17.0	78.6	16
B 6367 4				
-40		8.0	80.6	13-12
		5.0	85.6	6- 6
	Avg.	6.5	83.1	9.3
-50		9.5	86.6	13-13
		11.5	89.2	14-14
	Avg.	10.5	87.9	13.5
-60		6.5	90.2	10-10
		10.5	89.0	14-13
		8.0	89.2	11-11
		6.5	88.4	9- 9
	Avg.	7.9	89.2	10.9
-80		4.0	96.0	3- 3
		3.0	94.7	5- 6
	Avg.	3.5	95.3	4.3
B 6360 5				
210		42.0	35.0	45-47
		38.5	29.6	44-47
	Avg.	40.2	32.3	45.8
180		31.0	39.0	39-38
		33.5	40.6	41-42
	Avg.	32.2	39.8	40
160		37.0	35.1	43-44
		28.5	56.2	37-36
	Avg.	32.7	45.6	40
150		30.0	54.2	33-34
		25.5	52.5	35-37
	Avg.	27.7	53.3	34.8
140		30.0	52.1	36-36
		23.0	66.2	30-30
	Avg.	26.5	59.1	33
130		24.0	58.6	31-32
		26.5	71.1	32-33
	Avg.	25.2	64.8	32
120		20.0	60.2	29-29
		22.5	66.2	28-27
	Avg.	21.2	63.2	28.3
110		19.0	67.2	26-26
		14.0	70.0	21-21
	Avg.	16.5	68.6	23.5
100		12.5	73.0	20-20
		21.0	66.0	27-28
	Avg.	16.7	69.5	23.8
90		10.5	72.0	16-16
		12.0	76.7	18-19
	Avg.	11.2	74.3	17.3
60		7.5	85.5	10-11
		10.0	81.5	15-16
	Avg.	8.7	83.5	13
30		6.0	90.2	8- 9
		6.0	100.0	9- 7
	Avg.	6.0	95.1	8.3
0		3.5	100.0	5- 3
		3.0	97.5	4- 3
	Avg.	3.2	98.7	3.8
B 6368 6				
150		50.0	25.2	52-51
		53.5	20.2	51-48
	Avg.	51.7	22.7	50.5
120		34.5	36.7	36-36
		31.5	53.0	36-36
	Avg.	33.0	44.8	36
90		27.0	43.9	30-31
		26.0	50.0	36-37
		30.0	57.0	32-32
		36.0	45.0	35-37
	Avg.	32.5	49.0	33.8
80		25.0	61.2	28-28
		28.0	61.6	30-31
	Avg.	26.5	61.4	29.3

TABLE A-9 (CONTINUED)

Temperature, F	Charpy Impact Energy, Ft-lb.	Brittle Fracture, per cent	Lateral Expansion, mils
B 6368 6			
70	23.0	59.6	26-25
	9.5	69.6	15-14
	12.5	73.6	17-17
Avg.	15.0	67.6	19
60	28.5	64.5	26-26
	10.0	77.5	14-16
	8.0	80.1	10-11
	27.0	67.5	28-28
Avg.	18.4	72.4	19.9
50	9.0	69.2	12-12
	8.0	68.0	11-11
	8.0	76.5	11-12
	7.0	77.0	11- 9
Avg.	8.0	72.7	11.1
40	20.0	78.0	20-21
	22.0	74.4	23-23
	5.5	77.0	9- 8
	5.5	83.1	8- 8
Avg.	13.3	78.1	15
30	6.0	82.1	8- 8
	7.0	80.7	10-11
Avg.	6.5	81.4	9.3
0	5.0	89.0	6- 7
	4.0	92.1	5- 5
Avg.	4.5	90.5	5.8
B 6359 7			
120	83.5	27.5	83-81
	85.0	25.1	84-87
Avg.	84.2	26.3	83.8
110	91.5	26.7	85-89
	68.0	46.1	73-74
Avg.	79.7	36.4	80.3
100	36.5	57.7	47-46
	45.0	36.0	52-53
Avg.	40.7	46.8	49.3
90	73.0	54.6	78-77
	73.0	42.7	77-75
	31.5	55.1	40-41
	56.0	56.2	63-66
Avg.	58.4	52.1	64.6
80	27.5	58.5	38-39
	32.0	54.7	37-37
Avg.	29.7	56.6	37.8
70	22.5	59.5	31-32
	22.5	66.2	31-30
Avg.	22.5	62.8	31.0
60	22.5	72.2	29-30
	17.5	73.5	26-27
Avg.	20.0	72.8	28
50	16.0	70.1	24-24
	17.0	70.1	26-25
Avg.	16.5	70.1	24.8
40	14.5	70.1	21-21
	11.0	74.4	17-17
Avg.	12.7	72.2	19
30	12.0	74.4	18-19
	11.0	79.1	17-17
Avg.	11.5	76.7	17.8
15	8.5	83.6	12-11
	7.5	80.5	12-12
Avg.	8.0	82.0	11.8
0	7.5	79.9	12-12
	7.5	81.9	12-11
Avg.	7.5	80.9	11.8

Temperature, F	Charpy Impact Energy, Ft-lb.	Brittle Fracture, per cent	Lateral Expansion, mils
B 7064 9-2			
150	44.0	32.6	51-52
	65.0	19.2	66-68
Avg.	54.5	25.9	59.3
120	43.0	43.7	50-50
	45.5	43.7	55-49
	44.0	44.6	50-50
	48.5	44.4	52-53
Avg.	45.2	44.1	51.1
90	36.0	62.6	42-43
	27.0	65.4	32-33
	45.5	60.7	52-52
	37.0	46.7	44-46
Avg.	36.4	58.8	43
80	19.0	66.2	27-28
	36.5	61.6	42-43
	32.0	67.5	38-39
	32.0	61.9	38-38
Avg.	26.9	64.3	36.6
70	19.5	71.5	25-26
	23.0	76.5	28-27
Avg.	21.2	74.0	26.5
60	9.0	74.6	14-14
	26.5	61.5	32-32
	19.0	73.1	24-24
	10.0	72.6	15-15
Avg.	16.1	70.5	21.3
50	19.5	72.2	25-24
	17.0	73.1	22-23
	11.0	80.2	16-17
Avg.	15.8	75.1	21.2
40	8.0	77.5	12-10
	7.0	80.2	11-11
Avg.	7.5	78.8	11
30	7.0	78.7	9- 8
	6.0	81.0	9-10
Avg.	6.5	79.8	9
0	4.0	83.9	5- 6
	5.0	89.4	7- 8
Avg.	4.5	86.6	6.5
B 6410 11			
90	91.0	32.7	80-89
	95.0	37.0	86-91
Avg.	93.0	34.8	86.5
80	60.5	45.0	66-66
	50.0	42.2	61-61
	90.0	31.1	84-84
Avg.	66.8	39.4	70.3
70	81.0	46.1	77-82
	26.0	52.1	37-35
	29.0	55.1	41-42
	60.0	41.0	64-65
Avg.	49.0	48.6	55.4
60	53.0	59.0	58-58
	60.0	49.9	64-67
Avg.	56.5	54.4	61.8
50	19.5	63.0	26-25
	13.0	68.2	17-19
Avg.	16.2	65.6	21.8
40	11.5	70.0	17-18
	30.0	73.1	35-36
	21.0	75.6	27-27
	11.5	74.7	17-15
Avg.	18.5	73.3	24
30	12.5	78.7	17-19
	10.5	75.2	15-16
Avg.	11.5	76.9	16.8
20	7.5	81.4	11-10
	10.5	78.7	16-16
Avg.	9.0	80.0	13.3
10	7.0	81.0	10-10
	22.0	74.7	29-29
	5.0	84.0	8- 7
	6.0	86.9	6- 7
Avg.	10.0	81.6	13.3

TABLE A-9 (CONTINUED)

Temperature, F		Charpy Impact Energy, Ft-lb.	Brittle Fracture, per cent	Lateral Expansion, mils
B 6410 11				
0		7.0	81.4	9-11
		7.5	85.5	12-10
	Avg.	7.2	83.4	10.5
-20		3.5	87.2	4- 5
		3.5	88.5	4- 3
	Avg.	3.5	87.8	4
B 6405 12				
210		33.5	45.0	42-43
		34.0	40.5	43-43
	Avg.	33.7	42.7	42.8
180		25.5	54.4	34-33
		26.0	52.7	35-36
	Avg.	25.7	53.5	34.5
170		27.5	56.0	37-38
		22.5	59.5	33-34
	Avg.	25.0	57.7	35.5
160		21.5	65.6	31-31
		13.5	70.2	19-21
	Avg.	17.5	67.9	25.5
150		15.0	62.1	23-23
		17.5	68.4	26-28
	Avg.	16.2	65.2	25
140		15.0	71.1	21-24
		16.5	62.0	28-28
	Avg.	15.7	66.5	25.3
130		15.0	69.4	23-26
		12.5	70.0	20-19
	Avg.	13.7	69.7	22
120		13.5	70.1	19-20
		12.0	76.9	19-19
	Avg.	12.7	73.5	19.3
110		9.0	73.9	15-15
		8.0	75.9	13-14
	Avg.	8.5	74.9	14.3
100		8.0	76.0	11-13
		9.5	75.0	16-15
	Avg.	8.7	75.5	13.8
90		6.0	82.5	10-11
		7.5	78.5	11-12
	Avg.	6.7	80.5	11
60		3.5	86.0	5- 5
		3.5	87.1	5- 6
	Avg.	3.5	86.5	5.3
30		3.0	90.6	4- 2
		2.5	91.9	4- 3
	Avg.	2.7	91.2	3.3
0		2.5	95.5	3- 2
		2.5	95.5	4- 3
	Avg.	2.5	95.5	3
B 6361 13				
180		38.0	41.8	42-41
	Avg.	38.0	41.8	41.5
150		28.5	55.7	34-34
		34.0	54.6	40-39
	Avg.	31.2	55.1	36.8
120		15.0	54.7	22-23
		28.0	63.0	32-29
		24.0	61.5	33-27
		25.0	66.0	28-28
	Avg.	23.0	61.3	27.8
110		29.0	62.0	31-32
		22.0	77.0	26-26
	Avg.	25.5	69.5	28.8
100		24.0	62.3	28-27
		26.0	68.1	30-29
	Avg.	25.0	65.2	28.5
B 6361 13				
90		23.0	66.7	25-26
		12.0	77.3	18-18
		24.5	71.5	28-28
		20.0	72.2	22-23
	Avg.	20.0	71.9	23.5
80		20.0	81.6	24-23
		18.5	77.9	22-23
	Avg.	19.2	79.7	23
70		12.0	78.7	16-16
		18.5	82.7	18-18
	Avg.	15.2	80.7	17
60		6.0	83.1	9- 8
		17.0	87.6	19-19
		17.0	81.3	21-21
		14.5	78.1	17-17
	Avg.	13.6	82.5	16.4
45		6.5	88.1	9-10
		7.0	86.3	10- 9
	Avg.	6.7	87.2	9.5
30		6.0	88.1	9- 8
		6.5	89.4	9-10
	Avg.	6.2	88.7	9
0		3.5	93.1	5- 4
		7.0	93.1	3- 3
	Avg.	5.2	93.1	4
B 6361 14				
150		72.0	22.6	76-77
		76.0	20.5	79-80
	Avg.	74.0	21.5	78
120		53.0	31.6	62-63
		41.0	36.0	50-52
	Avg.	47.0	33.8	56.8
110		34.5	38.4	46-47
		39.0	40.6	48-52
	Avg.	36.7	39.5	48.3
100		39.5	45.6	50-50
		30.0	52.5	40-41
	Avg.	34.7	49.0	45.3
90		26.5	55.2	37-39
		24.0	60.9	35-35
	Avg.	25.2	58.0	36.5
80		17.0	66.6	26-26
		23.5	63.7	33-35
	Avg.	20.2	65.1	30
70		18.0	68.3	26-27
		16.0	70.2	21-22
	Avg.	17.0	69.2	24
60		15.5	72.1	23-23
		12.5	68.0	19-20
	Avg.	14.0	70.0	21.3
50		12.5	71.1	20-19
		12.0	66.6	18-19
	Avg.	12.2	68.8	19
40		10.0	70.0	16-15
		10.0	73.0	15-16
	Avg.	10.0	71.5	15.5
30		8.0	80.7	13-14
		8.5	78.6	13-13
	Avg.	8.2	79.6	13.3
0		4.5	87.1	7- 6
		6.0	87.3	9- 9
	Avg.	5.2	87.2	7.8

TABLE A-10

DROP-WEIGHT TEST DATA FOR NATIONAL BUREAU OF STANDARDS COMMERCIAL GRADE CLASS C STEEL. NBS PLATE 250

Specimen	Specimen Size, in.	Specimen Condition	Temperature, F	Complete Fracture	Impact Energy, Ft-lb.	NDT, F
250-AR2*	3-1/2 x 14 x 1-1/4	As received	40	No	650	30
-AR3	Ditto	Ditto	40	Ditto	1300	
AR7	"	"	40	"	1300	
AR8	"	"	40	"	1300	
AR4	"	"	30	"	1300	
AR5	"	"	30	Yes	1300	
AR6	"	"	30	No	1300	
AR1	"	"	20	Yes	1300	
AR9	"	"	20	Ditto	1300	
AR10	"	"	20	"	1300	
250-E	2 x 5 x 5/8	As machined	20	No	150	0
F	Ditto	Ditto	20	Ditto	150	
G	"	"	20	"	150	
B	"	"	10	"	150	
C	"	"	10	"	150	
D	"	"	10	"	150	
A	"	"	0	Yes	150	
H	"	"	0	Yes	150	
J	"	"	0	No	150	
250-2	2 x 5 x 5/8	As hot rolled at 1850 F	0	No	150	-10
4	Ditto	Ditto	0	Ditto	150	
5	"	"	0	"	150	
6	"	"	0	"	150	
3	"	"	-10	Yes	150	
7	"	"	-10	Ditto	150	
8	"	"	-10	"	150	
1	"	"	-20	"	150	
9	"	"	-20	"	150	
10	"	"	-20	"	150	
250-11	2 x 5 x 5/8	Normalized from 1600 F	-30	No	150	-50
12	Ditto	Ditto	-40	Ditto	150	
18	"	"	-40	"	150	
19	"	"	-40	"	150	
13	"	"	-50	"	150	
16	"	"	-50	Yes	150	
17	"	"	-50	No	150	
15	"	"	-60	Yes	150	
20	"	"	-60	Yes	150	
14	"	"	-70	Yes	150	
250-21	2 x 5 x 5/8	Heated one hour at 1600 F, furnace cooled to 800 F	20	No	150	-40
22	Ditto	Ditto	0	Ditto	150	
23	"	"	-20	"	150	
25	"	"	-30	"	150	
26	"	"	-30	"	150	
27	"	"	-30	"	150	
24	"	"	-40	Yes	150	
28	"	"	-40	Ditto	150	
29	"	"	-40	"	150	
30	"	"	-50	"	150	

* Did not mark anvil.

TABLE A-11

DROP-WEIGHT TEST DATA FOR NATIONAL BUREAU OF STANDARDS COMMERCIAL GRADE CLASS C STEEL. NBS PLATE 296

Specimen	Specimen Size, in.	Specimen Condition	Temperature, F	Complete Fracture	Impact Energy Ft-lb.	NDT, F
296-B*	3-1/2 x 14 x 1-1/4	As received	30	No	600	20
C*	Ditto	Ditto	30	Ditto	720	
J	"	"	30	"	1300	
D	"	"	20	"	1300	
H**	"	"	20	Yes	1300	
A	"	"	10	Yes	720	
F	"	"	10	No	1300	
G***	"	"	10	Yes	1300	
E	"	"	0	Yes	1300	
296-C	2 x 5 x 5/8	As machined	20	No	150	0
D	Ditto	Ditto	10	Ditto	150	
E	"	"	10	"	150	
F	"	"	10	"	150	
B	"	"	0	Yes	150	
G	"	"	0	Ditto	150	
A	"	"	-10	"	150	
H	"	"	-10	"	150	
296-AN	3-1/2 x 14 x 1-1/4	Heated one hour at 1600 F, furnace cooled to 800 F	40	No	1300	0
BN	Ditto	Ditto	10	No	1300	
DN	"	"	0	No	1300	
EN	"	"	0	Yes	1300	
FN	"	"	0	No	1300	
GN	"	"	-10	Yes	1300	
HN	"	"	-10	Ditto	1300	
JN	"	"	-10	"	1300	
CN	"	"	-20	"	1300	
296-BN	2 x 5 x 5/8	Heated one hour at 1600 F, furnace cooled to 800 F	-20	No	150	-30
DN	Ditto	Ditto	-20	No	150	
EN	"	"	-20	No	150	
CN	"	"	-30	Yes	150	
FN	"	"	-30	No	150	
GN	"	"	-30	Yes	150	
AN	"	"	-40	Ditto	150	
HN	"	"	-40	"	150	
JN	"	"	-40	"	150	

* Did not mark anvil.
** Fractured 5/8 in. from weld bead notch.
*** Fractured 1 in. from weld bead notch.

TABLE A-12

DROP-WEIGHT TEST DATA FOR PROJECT SR-139 COMMERCIAL GRADE CLASS C STEEL. NBS PLATE 297

Specimen	Specimen Size, in.	Specimen Condition	Temperature, F	Complete Fracture	Impact Energy, Ft-lb.	NDT, F
297-A	2 x 5 x 5/8	As hot rolled at 1850 F	0	No	150	-10
H	Ditto	Ditto	0	Ditto	150	
J	"	"	0	"	150	
B	"	"	-10	"	150	
F	"	"	-10	"	150	
G	"	"	-10	Yes	150	
K	"	"	-10	No	150	
L	"	"	-10	Yes	150	
C	"	"	-20	Ditto	150	
D	"	"	-20	"	150	
E	"	"	-20	"	150	
297-NA	2 x 5 x 5/8	1-1/4" plate heated one hour at 1600 F, furnace cooled to 800 F, then machined	0	No	150	-30
NB	Ditto	Ditto	-10	Ditto	150	
NC	"	"	-20	"	150	
NH	"	"	-20	"	150	
NJ	"	"	-20	"	150	
ND	"	"	-30	"	150	
NF	"	"	-30	Yes	150	
NG	"	"	-30	No	150	
NK	"	"	-30	Yes	150	
NE	"	"	-40	Ditto	150	
NL	"	"	-40	"	150	
NM	"	"	-40	"	150	

TABLE A-13

STEELS[A] USED FOR COMPARISON OF PROJECT SR-151 DROP-WEIGHT AND CHARPY V-NOTCH DATA WITH THAT OF OTHER INVESTIGATORS

Steel Identification	Reference	Ferrite ASTM Grain Size[B] Number	Composition, per cent				Transition Temperature, F			
							Drop Weight		Charpy V-15 Ft-lb.	
			C	Mn	Si	Al	Experimental	Calculated	Experimental	Calculated
		Commercial Steels, Tested at 5/8" Thickness								
5	1, 5	--	0.31	0.49	0.10	--	10	32	--	--
6	1, 5	--	0.25	0.36	0.04	--	20	28	--	--
22	1	--	0.19	0.38	0.01	--	0	17	--	--
23	1	--	0.25	0.49	0.01	--	0	26	--	--
		Commercial Steels, Tested at 3/4" Thickness								
13	1,5	--	0.29	0.42	0.07	--	30	33	--	--
14	1,5	--	0.23	0.49	0.05	--	40	20	--	--
27	1	--	0.18	0.33	0.02	--	20	16	--	--
28	1	--	0.25	0.50	0.05	--	20	24	--	--
201	17	7.7	0.21	0.74	0.051	<0.01	5	16	21	50
226	Ditto	7.6	0.22	0.80	0.053	<0.01	0	18	18	41
227	"	7.4	0.20	0.79	0.052	0.01	0	16	29	35
212	"	7.7	0.19	0.81	0.047	<0.01	0	11	26	30
279	"	7.8	0.18	0.99	0.034	0.01	0	7	13	11
284	"	7.5	0.16	1.09	0.061	0.02	-10	-3	6	-13
233	"	7.8	0.15	0.93	0.049	0.02	-10	-4	6	-1
236	"	8.1	0.20	1.00	0.074	0.01	-10	2	12	16
241	"	8.0	0.19	0.96	0.062	0.02	0	0	8	5
271	"	7.8	0.18	1.03	0.074	<0.01	0	0	-4	8
275	"	7.9	0.20	0.94	0.093	<0.01	0	3	25	16

TABLE A-13 (Continued)

Steel Identification	Reference	Ferrite ASTM Grain Size Number[B]	Composition, per cent				Transition Temperature, F			
							Drop Weight		Charpy V-15 Ft-lb.	
			C	Mn	Si	Al	Experimental	Calculated	Experimental	Calculated
Laboratory Steels, Tested at 3/4" Thickness										
1-B	16	7.5	0.18	1.28	0.043	--	-20	4	-24[C]	1
2-B	16	7.5	0.16	1.04	0.017	--	10	8	-8[C]	13
Commercial Steels, Tested at 1" Thickness										
A	11	--	0.20	0.49	0.04	0.007	30	15	68	65
B	11	--	0.14	0.51	0.20	--	10	-6	26	29
C	11	--	0.32	0.71	0.24	0.005	50	21	80	32
17	1, 5	--	0.23	0.41	0.04	--	40	23	--	--
18	1, 5	--	0.19	0.48	0.09	--	40	11	--	--
33	1	--	0.19	0.49	0.05	--	20	13	--	--
34	1	--	0.24	0.45	0.05	--	20	23	--	--
A-7RW	9	--	0.20	0.75	--	--	5	13	--	--
A-7W	Ditto	--	0.27	0.60	--	--	35	29	--	--
A-201RB	"	--	0.12	0.48	0.18	--	-5	-8	--	--
A-201Y	"	--	0.11	0.51	0.20	--	10	-11	--	--
A-212KC	"	--	0.25	0.66	0.19	--	15	3	--	--
A-212T	"	--	0.32	0.56	0.26	--	35	23	--	--
A-285RG	"	--	0.09	0.49	--	--	5	-3	--	--
P	15	6.7	0.18	0.54	0.04	0.005	32	25	61	60
Q	15	6.8	0.15	1.07	0.02	0.001	14	13	3	10
R	15	8.1	0.12	1.43	0.18	0.070	-22	-45	-76	-64
S	15	8.4	0.15	1.05	0.17	0.006	-13	-21	-50	-26
T	15	8.7	0.15	1.44	0.28	0.080	-90	-51	-89	-61
Laboratory Steels, Tested at 1" Thickness[D]										
1-D	16	5.9	0.16	1.25	0.044	0.006	0	17	1[E]	22
2-A	16	6.4	0.16	1.10	0.020	0.003	-10	18	-10[E]	27
2-D	16	5.8	0.13	0.99	0.015	0.004	10	21	1[C]	36
Commercial Steels, Tested at 1-1/4" Thickness										
2	3	--	0.23	0.45	0.10	--	50	18	--	--
80	Ditto	--	0.14	0.71	0.22	--	10	-11	--	--
81	"	--	0.16	0.68	0.22	--	30	-7	--	--
85	"	--	0.16	0.79	0.32	--	-20	-15	--	--
86	"	--	0.15	0.71	0.27	--	-10	-12	--	--
87	"	--	0.15	0.74	0.24	---	10	-11	--	--
242	17	7.6	0.16	0.73	0.23	0.03	20	-14	-1	-6
247	Ditto	7.6	0.14	0.66	0.21	0.03	20	-17	-13	11
214	"	7.1	0.15	0.73	0.20	0.045	-15	-14	-16	-2
219	"	6.8	0.16	0.69	0.21	0.047	-5	-9	-26	7
224	"	6.7	0.13	0.71	0.21	0.052	20	-14	-2	8
252	"	7.2	0.15	0.74	0.25	0.02	-5	-12	-11	-3
258	"	7.5	0.16	0.84	0.29	0.04	5	-17	-7	-15
263	"	7.7	0.16	0.78	0.30	0.04	-15	-18	-37	-16
243	"	7.1	0.16	0.73	0.22	0.03	20	-5	-10	3
248	"	7.3	0.16	0.73	0.21	0.03	15	-10	+5	1
Laboratory Steels, Tested at 1-1/4" Thickness										
54	3	--	0.19	1.33	0.03	--	20	-3	--	--
1-C	16	6.7	0.17	1.28	0.041	0.006	0	10	-12[E]	-2
2-C	16	6.6	0.16	1.04	0.016	0.004	10	18	-8	26

[A] Commercial and laboratory steels other than those tested under Project SR-151. All steels were tested as 3-1/2 in. x 14 in. specimens except A, B, and C which were tested as 3-1/2 in. x 18 in. samples.

[B] Dashes indicate ferrite grain size numbers were not given in the references cited. In these cases the transition temperatures were calculated with the following formulas:

NDT, F = 0 + 135 (%C) - 20 (%Mn)-60 (%Si)-180 (%Al)

V_{15}, F = 80 + 180 (%C)-85 (%Mn)-200 (%Si)-800 (%Al)

Where grain size data was available the transition temperatures were calculated with the formulas given in Table 6 of the report.

[C] Average for five tests made by four different laboratories.

[D] Specimens were cut from plates 1-3/4 in. thick. All other specimens were tested in the full plate thickness.

[E] Average for four tests made by three different laboratories.

APPENDIX B

STATISTICAL ANALYSIS

The more important results of the multiple regression analysis are given in Tables B-1 through B-3. For the benefit of readers who are unfamiliar with this type of analysis, the terminology will be discussed briefly.

Multiple Regression Analysis

In its simplest form, regression analysis is a statistical method for using the value of one variable to predict the value of another. This is done by means of a mathematical equation such as

$$y = a + bx,$$
$$y = a + bx + cx^2,$$
$$\text{etc.},$$

which is computed from values of (x, y) obtained experimentally. Geometrically, the method amounts to finding the line or curve which best fits the data points.

Multiple regression analysis is an extension of this method for the situation in which the relationship of more than two variables is needed. The mathematical equation has a form such as

$$y = a + bx_1 + cx_2 + dx_2^2 + \dots,$$

which is computed from values of $(y, x_1, x_2, x_3, \dots)$ obtained experimentally. The relationship it expresses may be either linear or curvilinear. Geometrically, the method consists of finding the plane or curved surface in three-dimensional space (in the case of three variables), or the hyperplane or hypersurface in a space of four or more dimensions (in the case of four or more variables), which best fits the data points.

In the present case, the equations that were fitted to the data have the form

$$y = a + bx_1 + cx_2 + dx_3 + ex_3^2 + fx_2x_3 + gx_4 + hx_4^2 + ix_3x_4 + jx_5,$$

where the independent variables are:

x_1 = carbon (per cent)
x_2 = manganese (per cent)
x_3 = silicon (per cent)
x_4 = aluminum (per cent)
x_5 = ASTM Ferrite grain size number

and y represents successively the following eight dependent variables, each of which is considered separately with the independent variables listed above:

Drop weight, NDT
Charpy V-notch, 15 ft-lb
" " 25 ft-lb
" " 50% maximum energy
" " 15% shear fracture
" " 30% shear fracture
" " 50% shear fracture
" " lateral expansion at 15 mils

The terms in x_3^2 and x_4^2 were included in the regression equations because preliminary examination of the data and previous experience suggested that Si and Al both have a curvilinear effect on the dependent variables. The terms in x_2x_3 and x_3x_4 were included because examination and experience suggested that Si interacts with Mn and also with Al to produce changes in the dependent variables which cannot be detected by measuring the separate effects of these additives.

Conclusions

Tables B-1 and B-2 lead to the following general conclusions:

1) Increasing C definitely causes an increase in all eight dependent variables.
2) Increasing Mn causes a decrease in all eight dependent variables.
3) Increasing Si causes a decrease in the dependent variables, which is fairly marked for most of these variables.
4) The curvilinear effect of Si is too weak to be established by the present data.

5) Only in its effect on 50% maximum energy does Si interact appreciably with Mn.

6) There is weak evidence that increasing Al causes a decrease in the dependent variables.

7) The analysis fails to show any appreciable curvilinear effect of Al or any appreciable interaction of Al with Si.

8) The analysis provides very strong evidence that increases in ASTM grain size number mean corresponding decreases in the dependent variable.

TABLE B-1

REGRESSION COEFFICIENTS AND STANDARD DEVIATION OF REGRESSION COEFFICIENTS

	Carbon		Manganese		Silicon		(Si)*		SiXMn		Aluminum		(Al)**		AlXSi		ASTM Ferrite Grain Size Number		Constant	
									Drop Weight Test											
Criterion	C*	SD**	C	SD	C	SD	C	SD	C	SD	C	SD	C	SD	C	SD	C	SD	C	SD
NDT	210	27	-15.9	9.6	-182	85	377	165	-6.9	57.4	-159	215	321	1600	-258	481	-11.0	1.4	77.2	84.9
									Charpy V-Notch											
15 Ft-lb	333	40	-66.6	14.2	-269	125	210	244	116	85	-512	317	2849	2362	367	711	-18.1	2.1	168	125
25 Ft-lb	456	39	-61.3	14.1	-265	124	216	242	111	84	-583	315	3228	2346	360	706	-20.2	2.1	178	125
50% max engery	291	36	-68.3	12.9	-352	114	332	221	211	77	-356	288	2601	2144	-135	645	-15.5	1.9	189	114
15% shear fracture	297	33	-22.0	12.0	-8.6	106	-118	206	5.8	71.8	-449	268	2580	1998	-128	601	-12.1	1.8	60.5	106
30% shear fracture	347	34	-27.8	12.4	-141	109	171	211	24.0	73.6	-334	275	1329	2049	282	617	-15.3	1.8	119	109
50% shear fracture	439	43	-36.1	15.5	-257	136	246	265	84.6	92.5	-375	346	1121	2574	975	775	-18.9	2.3	177	137
Lateral Expansion at 15 mils	331	32	-52.0	11.6	-237	102	173	198	105	69	-458	258	3056	1919	131	578	-16.0	1.7	129	102

*C = Regression coefficient.

**SD = Standard deviation of regression coefficient.

Partial Regression Coefficient

The change in the dependent variable (transition temperature) associated with a unit increase in a particular independent variable when the other variables of regression are held constant.

Standard Deviation of Regression Coefficient

An estimate of the variaibility which would be encountered among corresponding regression coefficients if the experiment and consequent regression analysis were repeated many times.

TABLE B-2

VALUES OF t RATIO AND STATISTICAL SIGNIFICANCE OF REGRESSION COEFFICIENTS

	Carbon		Manganese		Silicon		$(Si)^2$		SiXMn		Aluminum		$(Al)^2$		AlXSi		ASTM Ferrite Grain Size Number		Constant	
											Drop Weight Test									
Criterion	t[A]	S[B]	t	S	t	S	t	S	t	S	t	S	t	S	t	S	t	S	t	S
NDT	7.85	>99.9	1.65	>80	2.15	>95	2.29	>95	0.12	<80	0.74	<80	0.20	<80	0.54	<80	7.79	>99.9	0.97	<80
											Charpy V-Notch									
15 Ft-lb	8.41	>99.9	4.68	>99.9	2.15	>95	0.86	<80	1.37	>80	1.61	>80	1.21	<80	0.52	<80	8.70	>99.9	1.41	>80
25 Ft-lb	11.6	>99.9	4.33	>99.9	2.13	>95	0.89	<80	1.32	>80	1.85	>90	1.38	>80	0.51	<80	9.76	>99.9	1.50	>80
50% max energy	8.11	>99.9	5.28	>99.9	3.10	>99	1.50	>80	2.74	>99	1.24	<80	1.21	<80	0.21	<80	8.19	>99.9	1.73	>90
15% shear fracture	8.88	>99.9	1.83	>90	0.08	<80	0.57	<80	0.08	<80	1.67	90	1.29	<80	0.21	<80	6.87	>99.9	0.63	<80
30% shear fracture	10.1	>99.9	2.25	>95	1.30	80	0.81	<80	0.33	<80	1.21	<80	0.65	<80	0.46	<80	8.48	>99.9	1.17	<80
50% shear fracture	10.2	>99.9	2.32	>95	1.89	>90	0.93	<80	0.92	<80	1.09	<80	0.44	<80	1.26	<80	8.33	>99.9	1.36	>80
Lateral Expansion at 15 mils	10.3	>99.9	4.50	>99.9	2.33	>95	0.88	<80	1.52	>80	1.78	>90	1.59	>80	0.23	<80	9.47	>99.9	1.35	>80

---

t[A] = t ratio This statistic compares the observed difference between averages with the inherent variability within the data to determine whether the difference is significant.

S[B] = statistical significance of the regression coefficients as determined by the t-ratio. The statistical significance is the degree of certainty (%) that the true regression coefficient is not zero.

TABLE B-2

t-Ratio

In Table B-2, column t is the ratio of the regression coefficient to its standard deviation and is used for testing the statistical significance of the regression coefficient for each independent variable. If this ratio is large (relative to tabular theoretical values), then the regression coefficient is significant. The t-ratios in Table B-2 are accompanied by significance levels (in per cent), which may be thought of as the degree of certainty that each true regression coefficient (for which the computed regression coefficient is an estimate) is different from zero.

NOTE: Below are two alternative methods of presenting the significance of t-ratios in Table B-2.

<u>Method A</u>. Significance levels between 80% and 99% can be presented to the nearest whole per cent.

<u>Method B</u>. All significance levels can be presented in coded form, such as

NS = less than 80%
? = 80% up to but not including 95%
* = 95% up to but not including 99%
** = 99% up to but not including 99.9%
*** = 99.9% and over

TABLE B-3

Standard Error of Estimate

A measure of how nearly the regression estimates agree with the values actually observed for the variable being estimated (transition temperature).

Multiple Correlation Coefficient

A measure of the proportion of the total variation in the dependent variable (transition temperature) which can be accounted for on the basis of the linear relations to the several independent variables.

Coefficient of Multiple Determination

The square of the multiple correlation coefficient, R. A measure of what proportion of the variance in the values of the dependent variable (transition temperature) can be explained by, or estimated from, the concomitant variation in the values of the independent variables.

F-Ratio

In Table B-3, column F is the ratio $45R^2/(9-9R^2)$ for testing the statistical significance of the multiple correlation coefficient. If this ratio is large (relative to tabular theoretical values), then R^2 (and R) is significant. The F-ratios in Table B-3 are all larger than 3.77, which is the tabular value of F for 9 and 45 degrees of freedom at the 99.9% significance level, and therefore very high statistical significance can be attached to the multiple correlation coefficient. In other words, in every case we can be extremely confident that the dependent variable is really dependent to some degree on at least one of the independent regression variables.

TABLE B-3

SUMMARY OF STATISTICAL ANALYSIS

Criterion	S.E.E.[a]	R[b]	R^2[c]	F[d]
	Drop-Weight Test			
NDT	11.4	0.917	0.841	26.4
	Charpy V-Notch			
15 Ft-lb	16.9	0.932	0.869	33.0
25 Ft-lb	16.8	0.946	0.894	42.3
50% maximum energy	15.3	0.919	0.845	27.3
15% shear fracture	14.3	0.906	0.820	22.8
30% shear fracture	14.7	0.920	0.846	27.6
50% shear fracture	18.4	0.912	0.832	24.7
Lateral expansion at 15 mils	13.7	0.941	0.886	38.9

S.E.E.[a] = Standard error of estimate. This is a measure of the precision for estimating transition temperatures if all of the regression coefficients (Table B-1) for a given criterion are combined into one equation.

R[b] = Multiple correlation coefficient. It indicates the efficiency of the estimating equation in describing the effects of the observations on the transition temperature.

R^2[c] = Square of the multiple correlation coefficient. This is a measure of the fraction of variance removed or accounted for by the correlation analysis.

F[d] = F - ratio. A measure of how well the whole equation fits the data. For this study F at a confidence level of 99.9% equals 3.77.

TABLE C-1

GRAIN SIZE DATA FOR HOT-ROLLED LABORATORY STEELS*

Steel Identification	ASTM Ferrite Grain Size Number Corrected for Pearlite Content**		Pearlite Content, per cent	
	Area Count	Lineal Count	Area Count	Lineal Count
1	7.9	7.9	22.9	19.1
2	7.6	8.0	21.8	20.4
2-2	--	8.2	--	25.6
3	8.7	9.4	31.9	32.0
4	7.2	7.5	14.2	11.5
5	8.2	8.7	22.9	31.3
6	9.2	10.1	41.6	50.7
7	6.9	6.9	9.4	8.6
8	8.1	8.0	31.9	16.7
9	8.0	8.4	32.4	21.0
9-2	--	8.1	--	21.9
10	8.4	8.6	45.5	30.8
11	7.3	8.0	18.2	15.3
12	7.8	8.6	41.4	31.2
13	8.9	9.3	62.9	51.2
14	7.0	7.4	16.2	8.2
15	--	7.4	--	17.6
16	--	7.7	--	10.5
17	--	8.5	--	31.9
18	--	9.0	--	30.5
19	--	8.2	--	28.0
20	--	8.6	--	33.9
21	--	8.6	--	24.1
22	--	8.3	--	25.0
23	--	8.9	--	25.7
24	--	8.0	--	25.9
25	--	8.3	--	28.3
26	--	8.4	--	29.3
27	--	8.2	--	20.1

*Data listed are the average of at least two measurements. Dashes indicate determinations were not made.

**Grain size number based on area occupied by the ferrite phase only.

TABLE C-2

GRAIN SIZE DATA FOR STEELS NORMALIZED FROM 1600 AND 1900 F*

Steel Identification	ASTM Ferrite Grain Size Number Corrected for Pearlite Content**		Pearlite Content, per cent	
	Area Count	Lineal Count	Area Count	Lineal Count
		1600 F		
1	8.3	9.3	15.9	18.6
2	8.9	9.3	33.5	22.6
3	9.4	10.1	29.7	30.7
4	7.9	8.1	10.5	11.8
5	8.9	9.1	26.8	30.4
6	9.9	10.8	40.5	44.6
7	7.6	8.2	11.5	9.9
8	7.7	8.2	21.0	20.7
9	8.3	8.1	27.8	24.4
10	8.0	8.9	35.8	33.5
11	7.5	8.6	14.6	14.7
12	7.8	8.8	34.9	30.6
13	8.7	9.7	54.8	46.1
14	7.2	7.8	13.8	7.9
		1900 F		
2	--	8.0	--	23.2
9	--	7.5	--	24.0

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*Data listed are the average of at least two measurements. Dashes indicate determinations were not made.

**Grain size number based on area occupied by the ferrite phase only.

TABLE C-3

GRAIN SIZE DATA FOR STEELS HEATED AT 1900 F AND FURNACE COOLED TO 800 F*

Steel Identification	ASTM Ferrite Grain Size Number Lineal Count Corrected for Pearlite Content**	Pearlite Content, per cent
2-2	5.5	28.0
4	7.2	15.7
5	6.1	38.1
6	7.1	57.8
7	4.5	10.3
9-2	5.5	27.1
11	5.8	12.9
12	5.9	30.0
13	6.9	60.4
14	4.8	14.9

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*Data listed are the average for at least two measurements.

**ASTM number is based on the area occupied by the ferrite phase only.

TABLE C-4

GRAIN SIZE DATA FOR COMMERCIAL (PROJECT SR-139) STEELS

Steel	Condition	Heat Treatment	ASTM Ferrite Grain Size Number	Pearlite Content, per cent	Specimen Thickness, inches
250	Rerolled in laboratory	None	8.1	14.7	5/8
			8.4	18.9	5/8
250	As commercially rolled	None	7.0	17.9	1-1/4
			6.7	16.0	1-1/4
			6.9	14.2	5/8
			6.9	18.6	5/8
250	Rerolled in laboratory	1600 F, furnace cooled	9.4	18.6	5/8
			9.4	23.8	5/8
250	Rerolled in laboratory	1600 F, air cooled	9.2	10.1	5/8
			9.2	15.5	5/8
297	Rerolled in laboratory	None	7.4	16.6	5/8
			8.4	25.5	5/8
			8.0	20.4	5/8
296	As commercially rolled	None	7.5	16.7	5/8
			7.5	18.8	5/8
			7.3	25.6	1-1/4
			7.4	20.4	1-1/4
296	Machined from 1-1/4 in. plate before heat treatment or testing	1600 F, furnace cooled	9.4	24.3	5/8
			9.4	25.7	5/8
			9.4	44.2	1-1/4
			9.4	41.8	1-1/4
297	Machined from heat treated 1-1/4 in. plate	1600 F, furnace cooled	9.8	35.4	5/8
			10.4	43.9	5/8

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