SSC-101

IMPROVED NOTCH TOUGHNESS OF EXPERIMENTAL SEMIKILLED STEELS OVER ONE INCH IN THICKNESS

by

R. W. Vanderbeck

SHIP STRUCTURE COMMITTEE

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ADDRESS CORRESPONDENCE TO:

SECRETARY
SHIP STRUCTURE COMMITTEE
U. S. COAST GUARD HEADQUARTERS
WASHINGTON 25, D. C.

August 1, 1956

Dear Sir:

Under the auspices of the Ship Structure Committee, an investigation is currently under way to study improvements in the notch-toughness properties of semikilled ship steel plate over one inch thick by altering the chemical composition. Herewith is the First Progress Report of Project SR-141, Serial No. SSC-101, entitled "Improved Notch Toughness of Experimental Semikilled Steels over One Inch in Thickness," by R. W. Vanderbeck.

This project is being advised and administered by the Committee on Ship Steel of the National Academy of Sciences-National Research Council.

Will you please send any comments which you may have regarding this report to the Secretary, Ship Structure Committee.

This report is being distributed to individuals and groups associated with and interested in the Ship Structure Committee program.

Yours sincerely,

K. K. Cowart

K. K. COWART
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

Serial No. SSC-101

First Progress Report
of
Project SR-141

to the

SHIP STRUCTURE COMMITTEE

on

IMPROVED NOTCH TOUGHNESS OF EXPERIMENTAL SEMIKILLED STEELS OVER ONE INCH IN THICKNESS

by

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Monroeville, Pennsylvania

transmitted through

Committee on Ship Steel
Division of Engineering and Industrial Research
National Academy of Sciences-National Research Council

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Washington, D. C.
National Academy of Sciences-National Research Council

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IMPROVED NOTCH TOUGHNESS OF EXPERIMENTAL SEMIKILLED STEELS OVER ONE INCH IN THICKNESS

ABSTRACT

A substitute for ABS Class C killed ship plate steel (over 1 in. thick) is desirable because it is likely that during an emergency hot-topping capacity would not be available for the production of ship plate. To provide a semikilled steel of suitable toughness, a cooperative investigation was undertaken to produce and test two 25-ton basic open-hearth semikilled heats containing lower carbon and higher manganese than present ship plate steels. Tests on the plate product indicate that this steel is tougher than presently used semikilled grades and should be sufficiently tough to consider as an emergency substitute, or possibly as an alternate, for ABS Class C steel in thicknesses over 1 in. to 1 3/4 in. inclusive. To meet the tensile properties specified by the American Bureau of Shipping for hull steel, it is tentatively recommended that the composition range for the proposed steel be 0.20% carbon maximum and 1.00 to 1.35% manganese. The proposed steel should have about the same sensitivity to underbead cracking as ABS Class C steel. It is recommended that a number of full-size heats be made and tested so that average properties and the likely range of properties may be better determined and optimum deoxidation practices established.

INTRODUCTION

An interpretive report will shortly be published on the "Metallurgical and Economic Aspects of Ship Steels and Their Relation to Ship Failures," by W. J. Harris, Jr., and Clyde Williams of Battelle Memorial Institute, prepared for the Ship Structure Committee[1]. One of the tentative recommendations of this study is that, as an emergency substitute for ABS Class C* killed steel, consideration be given to the use of a semi-killed steel containing lower carbon and higher manganese than ABS Class B semikilled steel. It is desirable to obtain a substitute for the killed Class C steel because during an emergency it is likely that hot-topping capacity would not be available for the production of ship plate. Harris and Williams conclude from their analysis of the notch toughness behavior of plates that failed in ship service that for satisfactory service performance the alternate steel should have an average 15 ft-lb Charpy V-notch transition temperature not exceeding about 0°F in 1-in. thick plate.

The Advisory Committee on Project SR-141 was formed to develop a program for the procurement and testing of semikilled steel plate of the proposed lower-carbon, higher-manganese variety,

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*All references to American Bureau of Shipping specifications for steel in this report relate to Section 39 of the 1955 edition of the Rules for Building and Classing Steel Vessels.

for few data were available to indicate the combination of properties that would be obtained in such a steel. Based upon the analysis of Harris and Williams, plus suggestions made by the Advisory Committee, it was proposed to make and test two 25-ton heats of semikilled steel containing about 0.15% C and somewhat over 1.00% Mn. The objective was to obtain a 15 ft-lb Charpy V-notch transition temperature of 0°F or lower in 1-in. plate thickness since it was believed that this would provide satisfactory performance in service. It was also desired to maintain the tensile properties presently specified by ABS. Since the principal use of the alternate grade would be in thicknesses over 1 in. up to possibly 1 3/4 in. (like ABS Class C), the heats were to be rolled to several different thicknesses that would encompass this range. The thicknesses selected were 3/4 in., 1 1/4 in., and 1 3/4 in. The 3/4-in. thickness would be useful for making comparisons with 3/4-in. ABS Class B steel, on which considerable data were available. A detailed testing program was outlined, and the heats were made and were tested by various investigators as described below.

MELTING AND PROCESSING OF HEATS

The two heats were made at the Gary Steel Works of the United States Steel Corporation in their 25-ton foundry, basic open-hearth furnace to the following composition:

Carbon	0.15 aim
Manganese	1.05 aim
Phosphorus	0.04 max.
Sulphur	0.05 max.
Silicon	0.10 max. (semikilled)

Table 1 shows pertinent melting and processing data on these heats. One 30-in. by 64-in. by 89 1/2-in. ingot was cast from each heat, and four slabs, numbered A, B, C, and D, were produced from each ingot. Slab A was the top slab of the ingot. In the first heat, the top cut was lost because of pipe. As a result, slab A was not obtained. The second heat was deoxidized to a lesser extent (lower silicon), and all four slabs were obtained as planned. The slabs were rolled to plates of 3/4 in., 1 1/4 in., and 1 3/4 in. thickness as noted in Table 1, and samples were then cut from each plate in the manner shown in Fig. 1 for distribution to the various investigating laboratories.

TESTS CONDUCTED

The various groups which conducted tests on these steels in this cooperative program were the American Bureau of Shipping, Esso Research and Engineering Company, Naval Construction Research Establishment (Scotland), Naval Research Laboratory, New York Naval Shipyard, and United States Steel Corporation. These names are henceforth abbreviated as shown in Fig. 1.

The tests that were conducted by these organizations are outlined in Table 2. A few of these tests require some further explanation. The crack-starter drop-weight test has been fully

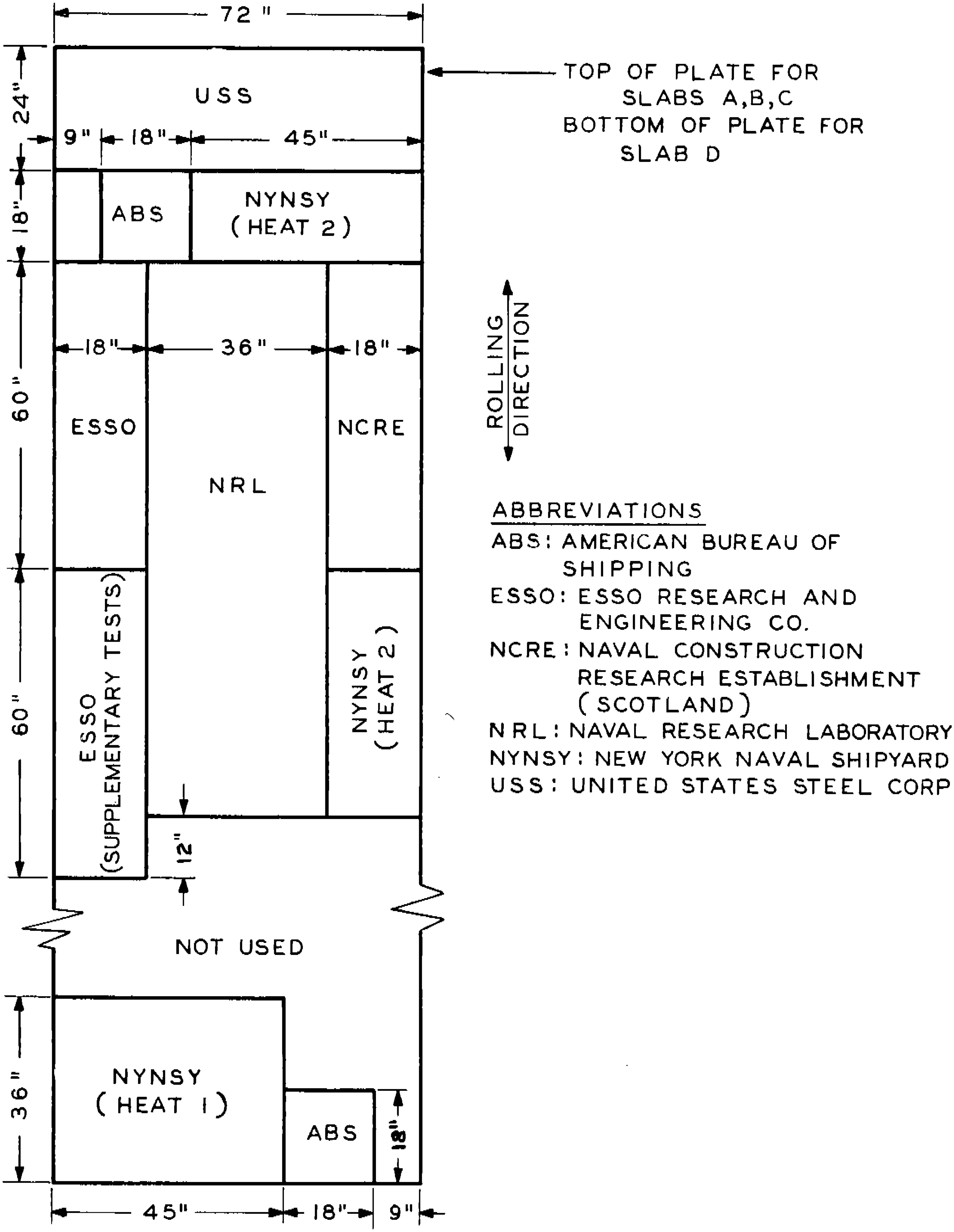

FIGURE 1 : DISTRIBUTION OF SAMPLES FROM EACH PLATE

TABLE 1

Melting and Processing Data

	Heat 1 (2G2850)	Heat 2 (2G2883)
Additions		
Bath	400 lb medium C FeMn 145 lb 25% FeSi	350 lb medium C FeMn 150 lb SiMn
Ladle	375 lb medium C FeMn 11 lb graphite	388 lb medium C FeMn 18 lb Recarb-X
Mold	1 lb Al	2 1/2 lb Al
Total Weight Produced	47,000 lb	52,500 lb
Tap Temperature	2995 F (optical)	2935 F (optical)
Pour Temperature	2875 F (optical)	2840 F (optical)
Ingot Size	30" x 64" x 89 1/2"	30" x 64" x 89 1/2"
Slab Size	8" x 62" x 65" long	8" x 62" x 65" long
Slab Finishing Temp.	2035 F (optical)	1980 F (optical)
Slab Reheating Temp.	2420 F	2420 F

Heat	Slab	Plate Size, Inches	Plate Finishing Temp, F
Heat 1	B	3/4 x 72 x 220 (B-1) 3/4 x 72 x 220 (B-2)	1840
	C	1 1/4 x 72 x 275	1940
	D	1 3/4 x 72 x 180	2000
Heat 2	A	1 3/4 x 72 x 180	1940
	B	3/4 x 72 x 220 (B-1) 3/4 x 72 x 220 (B-2)	1800
	C	1 1/4 x 72 x 260	1905
	D	1 3/4 x 72 x 180	1980

TABLE 2

Tests Conducted by the Investigators

Type Test	Investigating Laboratory ABS	Esso	NCRE	NRL	NYNSY	USS
Chemical Analysis	*	*		*		*
Tensile Properties	*					*
Ferrite Grain Size		*				*
McQuaid-Ehn Grain Size	*					
Grain Coarsening	*					
Keyhole Charpy	*			*		*
V-Notch Charpy	*	*		*		*
Crack-Starter Drop-Weight				*		
Crack-Starter Explosion				*		
SOD		*				
Robertson			*			
Navy Tear					*	
Underbead Cracking						*

explained by Puzak et al.[2,3]. This test is used to determine the nil-ductility transition temperature (N. D. T.) below which fracture may be readily initiated but above which considerable forcing is required to initiate failure.

The crack-starter explosion test is used to determine the fracture-transition temperature. Fracture, once initiated, will propagate through elastically loaded regions below the fracture-transition temperature, while above this temperature it will not. Lately, this temperature has been referred to as the fracture transition for elastic loading (F. T. E.). It corresponds quite well to the transition from shear to predominantly cleavage fracture in notched wide-plate specimens.

The SOD test[4] was conducted at a nominal tensile stress of 18,000 psi, using a 15° wedge and backing up the specimens with a 5000-lb weight. In this test fracture is initiated by an impact load acting upon the wedge, and the lowest temperature at which the crack will not propagate across the test specimen (at 18,000 psi tensile stress) is called the SOD transition temperature.

The Robertson test[5] is similar to the SOD test. The plate specimen is placed under load, and fracture is initiated by an impact load on the edge of the specimen. The Robertson test is usually run with a temperature gradient across the specimen, the crack being initiated at the cold temperature. The temperature of the plate where the crack stops is referred to as the Robertson-test transition temperature.

The Navy tear test has been fully described by Kahn[6]. This test is used to determine the fracture-transition temperature at which the mode of failure changes from shear to predominantly cleavage.

Van der Veen notch toughness tests[7] are also to be conducted, and the results will be reported at a later date.

In general the notch toughness tests may be divided into two groups, those that measure a ductility-transition temperature and those that measure a fracture-transition temperature. The ductility (or nil-ductility) transition indicates the temperature (in the particular test) above which fracture is not likely to initiate unless forced by appreciable deformation. The fracture-transition temperature indicates the temperature above which fracture is not likely to propagate. Between these two transitions crack propagation can occur providing that fracture is initiated by forcing. Of the notch-toughness tests discussed, the crack-starter explosion, SOD, Robertson, and Navy tear (and also van der Veen) measure fracture transitions. The crack-starter drop-weight measures a ductility transition. Evaluations of keyhole and V-notch Charpy data at about the 15 ft-lb level are also considered to provide measures of ductility-transition temperatures. More detailed explanations of these transition temperatures and of the test specimens used may be found in the listed references.

The underbead-cracking test[8] was used to determine the amount of cracking that could be expected adjacent to a weld bead when welding at various temperatures. This test is rather severe and usually provides much higher precentages of underbead cracking than are obtained in normal welding operations. The percentage of cracking is equal to the length of the cracked area, times 100, divided by the total length of the weld bead.

DISCUSSION OF TEST RESULTS

Composition and Tensile Properties. Check analyses on the two heats (referred to as the SR-141 heats) are listed in Table 3, and tensile properties in Table 4. It will be seen from the results on slab D, Heat 2, that about 0.12 or 0.13% C and 1.00 % Mn in 1 3/4-in. thick plate are not sufficient to meet the tensile strength range of 58,000 to 71,000 psi specified by ABS. Also, about 0.18% C and 1.25% Mn in 3/4-in. plate (slab B, Heat 1) are slightly too high to meet this tensile strength range. It appears that a carbon content of 0.15 or 0.16% and a manganese content of about 1.20% should be the aim to meet this range for plate thicknesses over 1 in. to 1 3/4 in., inclusive. Heat 1 comes close to this composition. It might also be possible, if necessary, to adjust the aim slightly, depending upon the particular thicknesses required.

The minimum yield point specified by ABS is 32,000 psi, and those standard plate test specimens that show less than 58,000 psi

TABLE 3

Chemical Composition

Ladle Analyses, percent

Heat 1 (Heat 2G2850)   0.16 C   1.30 Mn   0.010 P   0.021 S   0.08 Si

Check Analyses on Plates from Heat 1, percent

Slab	Plate Thick., Inches	Laboratory	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	Total Al	Acid-sol Al	N
B	3/4	USS (C)[1]	0.18	1.26			0.044							
		USS (Q)[2]	0.17	1.26			0.040							
		ABS[3]	0.18	1.31	0.018	0.035	0.040							
		Esso[4]	0.18	1.27	0.018	0.021	0.039							
		NRL	0.21	1.31	0.013	0.017	0.050							
C	1 1/4	USS (C)	0.16	1.26			0.040							
		USS (Q)	0.16	1.24			0.040					0.008	0.006	
		ABS	0.17	1.30	0.016	0.032	0.040							
		Esso	0.18	1.35	0.014	0.021	0.033							
		NRL	0.16	1.26	0.012	0.018	0.050							
D	1 3/4	USS (C)	0.14	1.22			0.043							
		USS (Q)	0.14	1.22	0.010	0.019	0.043	0.06	0.13	0.08	0.01	0.008	0.006	0.002
		ABS	0.16	1.26	0.014	0.027	0.040							
		Esso	0.18	1.27	0.013	0.019	0.033							
		NRL	0.16	1.26	0.010	0.018	0.050							

(Continued)

TABLE 3 (Continued)

Chemical Composition

Ladle Analyses, percent

Heat 2 (Heat 2G2883)   0.15 C   1.04 Mn   0.013 P   0.022 S   0.021 Si

Check Analyses on Plates from Heat 2 percent

Slab	Plate Thick., Inches	Laboratory	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	Total Al	Acid-sol Al	N
A	1 3/4	USS (C)[1]	0.15	1.13			0.015							
		USS (Q)[2]	0.15	1.15	0.011	0.024	0.014	0.04	0.02	0.04	None	0.006	0.003	0.003
		ABS[3]	0.15	1.08	0.011	0.028	0.030							
		Esso[4]	0.18	1.08	0.013	0.025								
		NRL	0.17	1.06	0.010	0.024	0.02							
B	3/4	USS (C)	0.16	1.04			0.017							
		USS (Q)	0.15	1.02			0.016							
		ABS	0.18	1.04	0.010	0.038	0.020							
		Esso	0.14	1.09	0.012	0.027	0.014							
		NRL	0.16	1.01	0.009	0.028	0.020							
C	1 1/4	USS (C)	0.15	1.02			0.016							
		USS (Q)	0.15	1.02			0.018					0.006	0.004	
		ABS	0.16	1.03	0.009	0.033	0.010							
		Esso	0.16	1.06	0.012	0.023	0.014							
		NRL	0.17	1.06	0.006	0.024	0.020							

(Continued)

TABLE 3 (Continued)

Chemical Composition

Ladle Analyses, percent

Heat 2 (Heat 2G2883) 0.15 C 1.04 Mn 0.013 P 0.022 S 0.021 Si

Check Analyses on Plates from Heat 2 percent

Slab	Plate Thick., Inches	Laboratory	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	Total Al	Acid-sol Al	N
D	1 3/4	USS (C)	0.11	0.99			0.020							
		USS (Q)	0.12	0.99	0.011	0.019	0.017	0.03	0.02	0.04	None	0.008	0.004	0.004
		ABS	0.14	0.96	0.011	0.022	0.020							
		Esso	0.13	1.02	0.015	0.021	0.019							
		NRL	0.14	0.97	0.005	0.022	0.020							

1. C = centerline position in plate
2. Q = quarter-width position in plate
3. Analyses conducted by R. W. Hunt Company
4. Analyses conducted by New York Testing Laboratories

TABLE 4

Tensile Properties

Heat	Plate Thick., Inches	Laboratory	Yield Point, psi	Tensile Strength, psi	% Elong. in 2"	% Elong. in 8"	% R. A.
Heat 1	3/4	USS (C)*	42,300	71,360		30	
		USS (Q)**	42,500	71,060		30	
		ABS	41,800	69,300		30	
	1 1/4	USS (C)	39,240	66,430		31	
		USS (Q)	37,760	66,520		30	
		ABS	36,400	65,000		32	
	1 3/4	USS (C)	33,030	62,150		35	
		USS (Q)	33,160	61,970		34	
		ABS	32,100	60,600		34	
		USS (C)†	33,950	61,900	39		69.3
		USS (Q)†	35,670	61,660	38		68.8
Heat 2	3/4	USS (C)	35,020	61,580		33	
		USS (Q)	37,790	61,660		34	
		ABS	35,150	60,200		33	
	1 1/4	USS (C)	33,050	60,270		32	
		USS (Q)	33,650	60,200		37	
		ABS	31,300	57,500		35	
	1 3/4 (Slab D)	USS (C)	29,350	55,140		38	
		USS (Q)	29,390	55,030		38	
		ABS	29,400	54,200		37	
		USS (C)†	29,220	55,720	42		71.6
		USS (Q)†	28,480	55,970	42		72.1
	1 3/4 (Slab A)	USS (C)	32,230	60,050		37	
		USS (Q)	32,360	59,930		38	
		ABS	32,600	58,900		34	
		USS (C)†	31,450	60,670	41		72.7
		USS (Q)†	31,450	60,920	42		70.4

*C = centerline position in plate.
**Q = quarter-width position.
†0.505" rd tensile tests.

tensile strength also have yield points under 32,000 psi.

Fig. 2 shows the yield points and tensile strengths of some foreign steels, similar in composition to the SR-141 heats, plotted versus carbon content. Data for the SR-141 heats are also plotted, using the U. S. Steel data on strength and composition. The data on just the Colvilles plates indicate that variations in manganese in the range of 1.00 to 1.32% have a negligible effect on tensile strength. Probably more data would be needed to establish significant effects. The effect of carbon is also difficult to detect over the narrow range of 0.12 to 0.15% for the Colvilles plates, but there is an indication that tensile strength increases with carbon content as expected. The three English steels and the SR-141 heats have lower tensile strength in general than the Colvilles plates for the same carbon content, but the former plates are thicker, except for the 3/4-in. SR-141 plates. The yield points of the thicker plates are also lower. Different rolling procedures, as well as the differences in thickness, could account for some of the strength differences among these groups of steel.

Grain Size. Various grain size evaluations are reported in Table 5. The U. S. Steel and Esso evaluations of ferrite grain size do not agree very closely, but different methods of evaluating grain size and, to some extent, different observers can bring about such discrepancies. The U. S. Steel evaluations are averages based upon 12 to 18 independent ratings (made by comparison

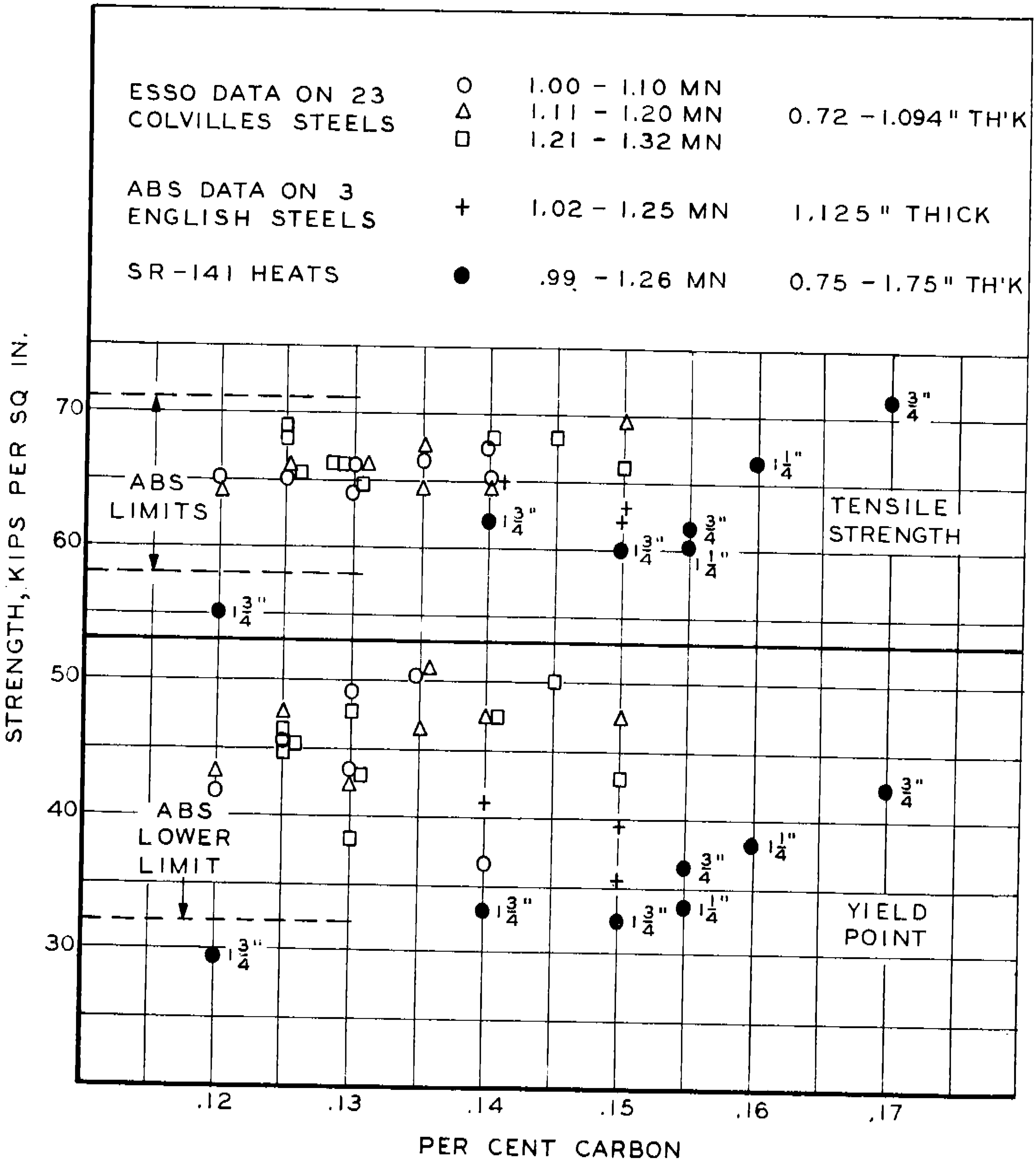

FIGURE 2 : EFFECT OF CARBON CONTENT ON YIELD POINT AND TENSILE STRENGTH

TABLE 5

Grain Size Evaluations

Heat	Plate Thick., Inches	ASTM Ferrite Grain Size USS	ASTM Ferrite Grain Size Esso	McQuaid-Ehn Grain Size
Heat 1	3/4	7.5	8	2-4
	1 1/4	6.7	9	2-4
	1 3/4	5.9	7	2-4
Heat 2	3/4	7.5	8	1-4
	1 1/4	6.6	8	1-4
	1 3/4 (D)	5.8	8	1-4
	1 3/4 (A)	6.4	8	1-4

Austenitizing Temp, F	Grain-Coarsening Characteristics (of the 1 1/4" plate material only) ASTM Grain Size Heat 1	Heat 2
1550	7	7
1600	7	7
1650	6 1/2	7
1700	7(50%) and 3(50%)	7
1750	2	7(70%) and 3 to 5(30%)
1800	2	1 to 2 (some 6)
1850	2	1 to 2

with standard ASTM grain size charts) and are therefore fairly precise. This is believed to be borne out by the regular manner in which grain size increases with plate thickness for each heat and by the correspondence of grain sizes for the same thicknesses in the two heats. The 1 3/4-in. plate from Slab A in Heat 2 is an exception to this consistent pattern in that its ferrite grain size is slightly finer than that for the other 1 3/4-in. plates, possibly because of its somewhat lower finishing temperature. These ferrite grain sizes seem normal for structural carbon steels in these thicknesses.

The McQuaid-Ehn grain size is that resulting from heating samples at 1700 F in a carburizing atmosphere. The grain size is coarse as would be expected for steel of this deoxidation practice.

The coarsening behavior of the heats is shown in the lower portion of Table 5. The samples were austenitized at various temperatures for 30 minutes and were then cooled at a rate suitable to provide good delineation of the grain boundaries. The grain size ratings were based upon comparison with standard ASTM grain size charts. These ratings are only rough estimates, especially where mixed grain sizes were obtained. A coarse-grained steel is said to coarsen gradually and consistently as the austenitizing temperature is increased, whereas a socalled fine-grained steel coarsens only slightly, if at all, up to a certain temperature and then coarsens abruptly. The tabulated data show that these heats apparently have coarsening characteristics similar to steels made to fine-grain deoxidation practice, despite the fact that only small amounts of aluminum were added to the mold and none to the ladle or bath (Table 1). For the approximately 20-ton ingots that were poured, the Al addition was 0.8 oz per ton for Heat 1 and 2 oz per ton for Heat 2. As noted in Table 3, the aluminum content in both heats was low. Rather abrupt coarsening of steels made to coarse-grain deoxidation practice may also be noted in data presented by Miller(9) so the behavior obtained here need not be considered exceptional.

It will be observed that coarse grains were obtained for Heat 2 in the McQuaid-Ehn test at 1700 F but not in the coarsening studies at 1700 F. This is explained by the fact that the specimen is at temperature for a longer time in the McQuaid-Ehn test.

The coarsening behavior does not influence the grain size of the hot-rolled product. It would only have an influence upon grain size if the steel were reheated.

With regard to deoxidation practice, it might be well to restate that Heat 1 was too heavily deoxidized, which resulted in pipe. The overdeoxidation was believed to be due mainly to the silicon content (0.04%), which is slightly high for semikilled steel of this composition. In Heat 2 with about 0.017% Si, the deoxidation was much more satisfactory, and there was no evidence of pipe in the rolled product. Suitable deoxidation practices may be better established if and when additional heats of this steel are produced, and it would be of interest to study further the grain coarsening characteristics of some of these heats.

Charpy Impact Properties. Individual Charpy impact test results are listed in the Appendix, Tables A-1 to A-7. The percentages of shear fracture in the broken impact specimens are also listed for the specimens tested by U. S. Steel. All specimens were longitudinal with the notch normal to the plate surface.

Keyhole Charpy ductility-transition temperatures were obtained by drawing what was judged to be the best straight line through the averages of the energy values in the ductility-transition-temperature range (the range showing appreciable scatter of energy values from about 3 to about 35 ft-lb in these heats) and then selecting the transition temperature from this line at an energy level judged to be about midway between the high and the low energy values in this range. Examples of this technique are shown in Fig. 3, in which transition temperatures were selected at 22 ft-lb for the 1 1/4-in. plate and at 24 ft-lb for the 1 3/4-in. (D) plate. In this figure, each circle represents a single test, and the X's indicate the average of the energy values at each of the test temperatures. Curves have been drawn outlining the ductility-transition zone for these keyhole tests to show the extent of scatter.

Typical V-notch Charpy data are shown in Fig. 4. An average line was drawn through the averages (the X's), and the transition temperature was selected at 15 ft-lb for all of the plates.

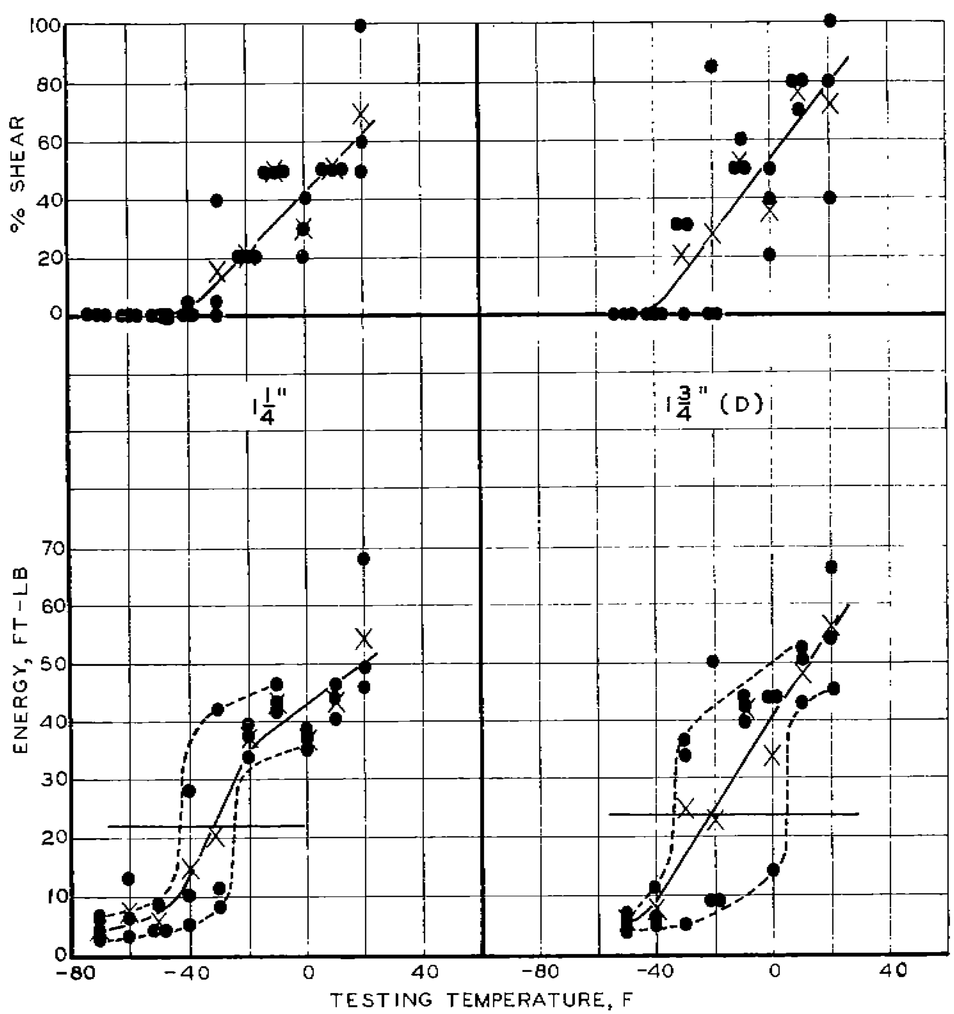

FIGURE 3: USS KEYHOLE-NOTCH CHARPY DATA, HEAT 2

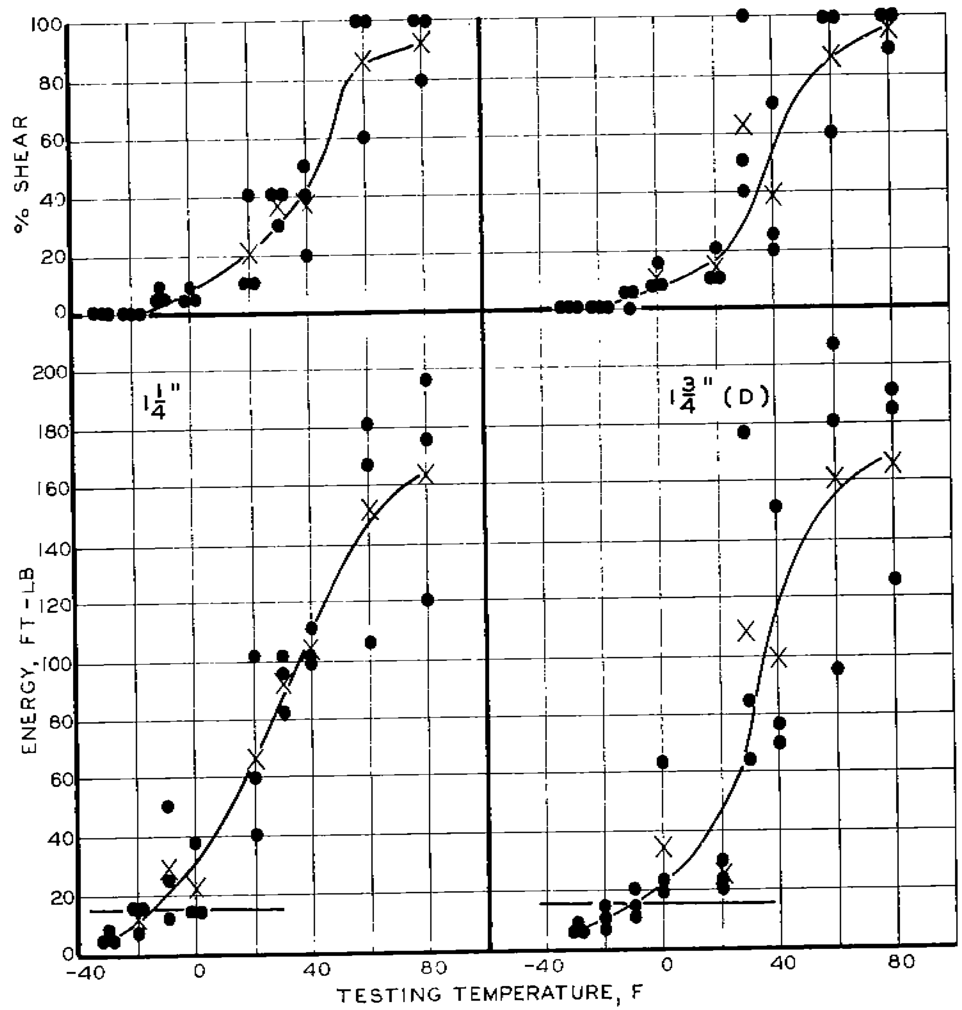

FIGURE 4: USS V-NOTCH CHARPY DATA, HEAT 2

The percentage of shear fracture (as opposed to cleavage) was observed for the broken U. S. Steel impact specimens, and typical plots of the data are also shown in Figs. 3 and 4. Fracture-transition temperatures were arbitrarily selected at 50% shear fracture.

The average curves for the impact data obtained by the various laboratories are presented in Figs. 5 through 8. The keyhole Charpy curves are in fair agreement, but the V-notch curves differ appreciably in some instances at the higher energy levels. The reasons for this are not known; the differences may be associated with machine differences and with real differences in material. It will be noted, however, that the curves for any one laboratory are not consistently high or low. At the 15 ft-lb level at which the V-notch transition temperatures were selected, the agreement is generally better than at higher energy levels. It will be seen from Figs. 5 and 6 that the keyhole Charpy transition temperatures were selected at the 16, 22, and 25 ft-lb levels for the 3/4-in., 1 1/4-in., and 1 3/4-in. plates of Heat 1 and at the 20, 22, and 24 ft-lb levels for the plates of the same thicknesses of Heat 2. These levels seemed most in keeping with the method of selection previously mentioned.

The Charpy transition temperature evaluations of the SR-141 heats are listed in Table 6 along with similar evaluations of ABS Class B (0.60 to 0.90% Mn) and Class C steels. The keyhole

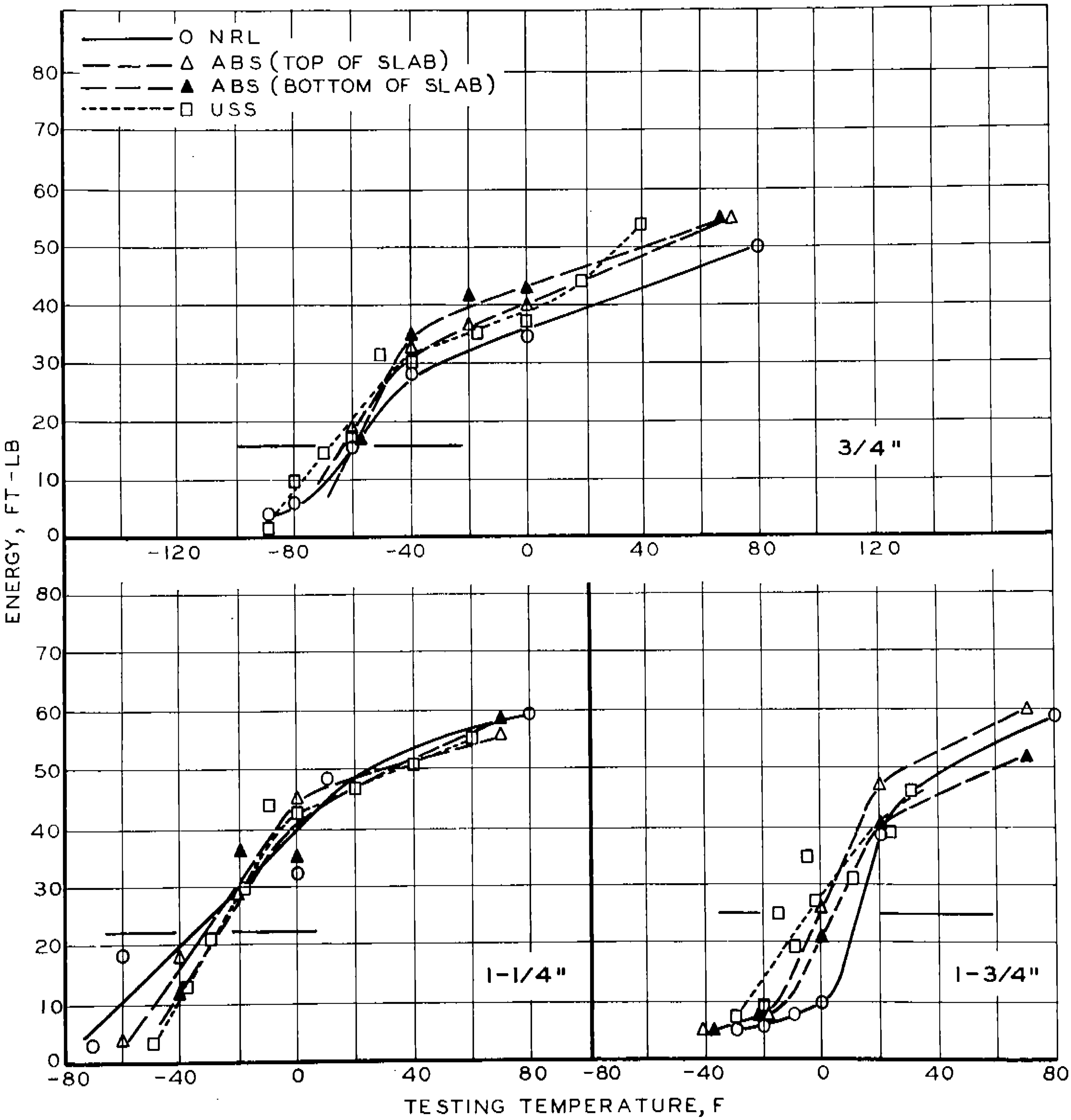

FIGURE 5 : KEYHOLE NOTCH CHARPY DATA FOR HEAT 1

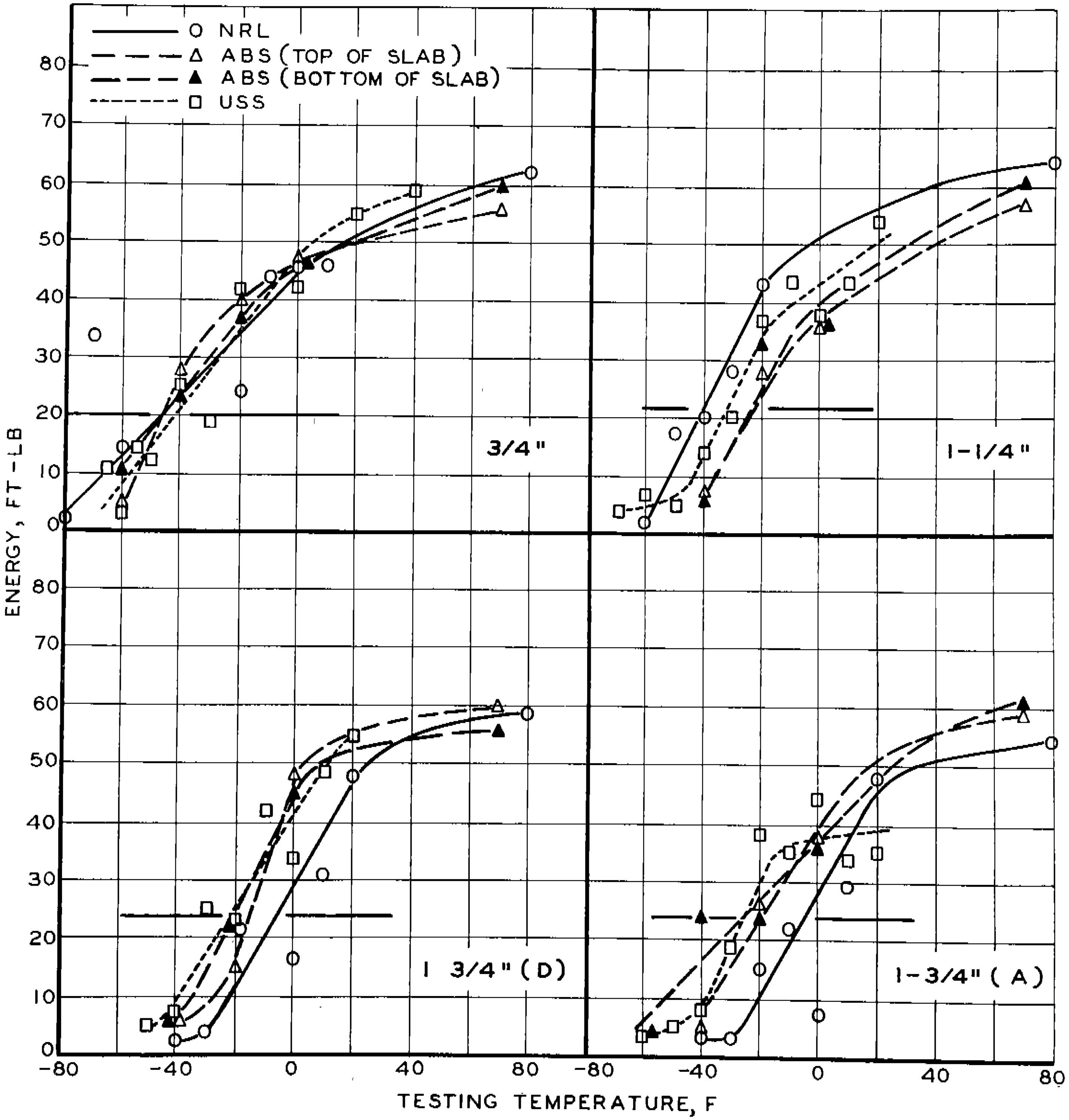

FIGURE 6 : KEYHOLE NOTCH CHARPY DATA FOR HEAT 2

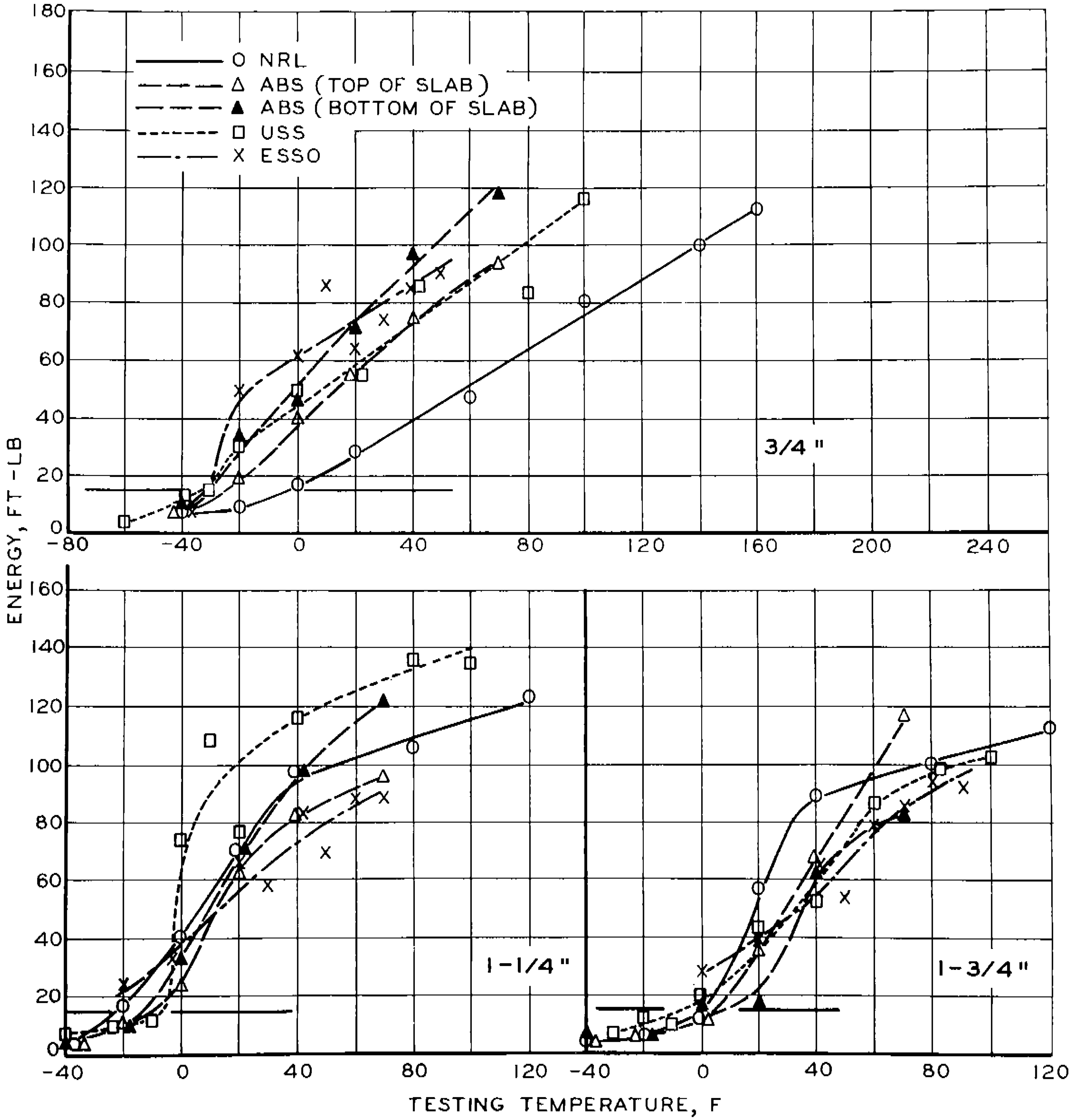

FIGURE 7 : V-NOTCH CHARPY DATA FOR HEAT I

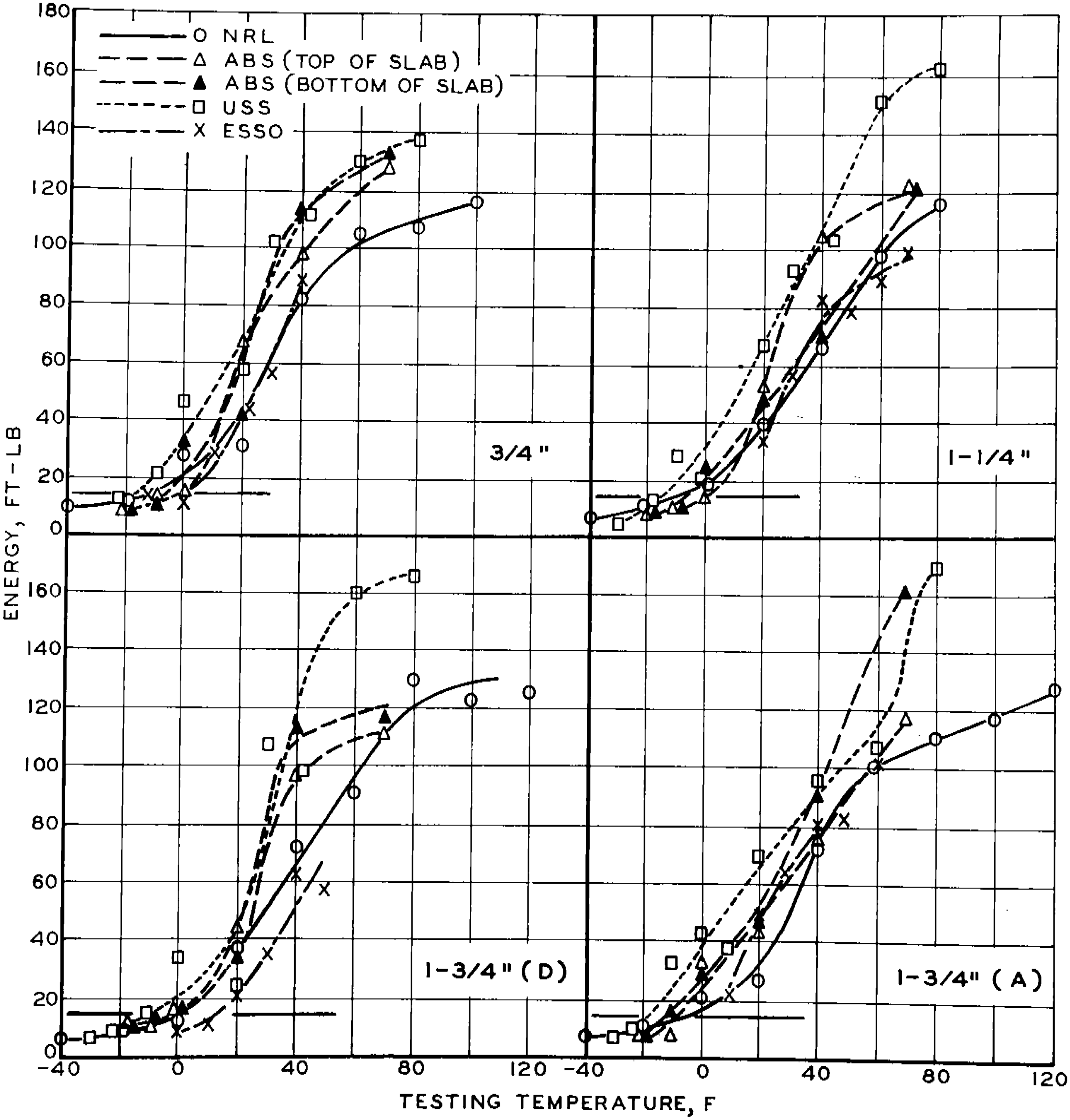

FIGURE 8 : V-NOTCH CHARPY DATA FOR HEAT 2

TABLE 6

Charpy Impact Properties

Steel	Plate Thick., Inches	Charpy V-Notch 15 ft-lb Transition Temperature, F — ABS	NRL	USS	Esso	Keyhole Charpy Ductility Transition Temperature, F — ABS	NRL	USS
Heat 1	3/4	-25, -30	- 3	-32	-30	-64, -61	-60	-68
Heat 2	3/4	- 2, - 8	-12	-16	0	-46, -46	-47	-42
ABS Class B	5/8	23 avg (15 to 35) (8 hts)* 27 avg (15 to 35) (3 hts)**				-5 avg (-30 to 20) (8 hts)* -24 avg (-45 to 10) (9 hts)**		
	3/4	21 avg (4 to 41) (8 hts)* 26 avg (10 to 50) (4 hts)** 25 avg (21 to 35) (4 hts)†				-6 avg (-15 to 5) (8 hts)* -10 avg (-46 to 21) (6 hts)**		
	1	45 avg (39 to 51) (5 hts)* 23 avg (15 to 27) (3 hts)** 38 avg (30 to 60) (11 hts)				14 avg (5 to 20) (5 hts)* -4 avg (-25 to 10) (3 hts)** +4 avg (-17 to 17) (4 hts)†		
Heat 1	1 1/4	-10, -12	-21	- 6	<-20	-32, -28	-37	-28
	1 3/4	5, 5	0	- 6	<0	- 2, 4	12	- 5
Heat 2	1 1/4	0, - 6	-11	-15	<20	-22, -24	-40	-32
	1 3/4 (D)	0, 0	+ 2	-10	14	-15, -20	- 6	-22
	1 3/4 (A)	- 9, -12	- 5	-16	<10	-20, -25	- 4	-25
ABS Class C	1	18 avg (8 to 35) (4 hts)[3]				-41 avg (-54 to -22) (4 hts)†		
	1 1/8--1 1/4	-23 avg (-35 to -10) (14 hts)** -8 avg (-16 to -2) (4 hts)*				-68 avg (-92 to -34) (20 hts)** -42 avg (-55 to -20) (4 hts)*		
	1 3/8--1 1/2	-11 avg (-40 to 17) (14 hts)** -10 avg (-23 to 3) (2 hts)*				-47 avg (-65 to -30) (15 hts)** -45 avg (-55 to -35) (2 hts)*		
	Over 1 1/2--2	-13 avg (-40 to 5) (10 hts)**				-46 avg (-70 to -20) (11 hts)**		

*Data from SR-125 (Ref. 11)
**Data provided by ABS
†Data provided by NRL

Charpy portion of these data are plotted in Fig. 9. The two SR-141 heats have the same notch toughness in 1 1/4-in. plate thickness, and differ slightly in the 3/4-in. and 1 3/4-in. thicknesses. Their transition temperatures are not so good as those of the ABS Class C steels, but even the heaviest plates have keyhole Charpy transition temperatures that are about as low as those of 3/4-in. Class B plates.

The Charpy V-notch transition temperatures are plotted in Fig. 10. The 15 ft-lb temperatures of the SR-141 heats, even in 1 3/4-in. plate thickness, are considerably lower than those of the Class B heats and are almost as low as those of the Class C steels. An objective of this project was to obtain an average Charpy V-notch 15 ft-lb transition temperature of 0°F or lower for 1-in. plate thicknesses, since it was believed that such a transition temperature would provide sufficient toughness to practically eliminate brittle failures in ship service. This objective has been achieved in the SR-141 heats, for even the 1 3/4-in. plates have transition temperatures no higher than about 0°F. Moreover, the SR-141 heats are appreciably tougher in all thicknesses than the ABS Class B steels, and the latter steels have performed very well in ship service.

The V-notch Charpy results are believed to provide a better indication of service behavior than the keyhole Charpy results because of the correlation that has been developed between V-notch

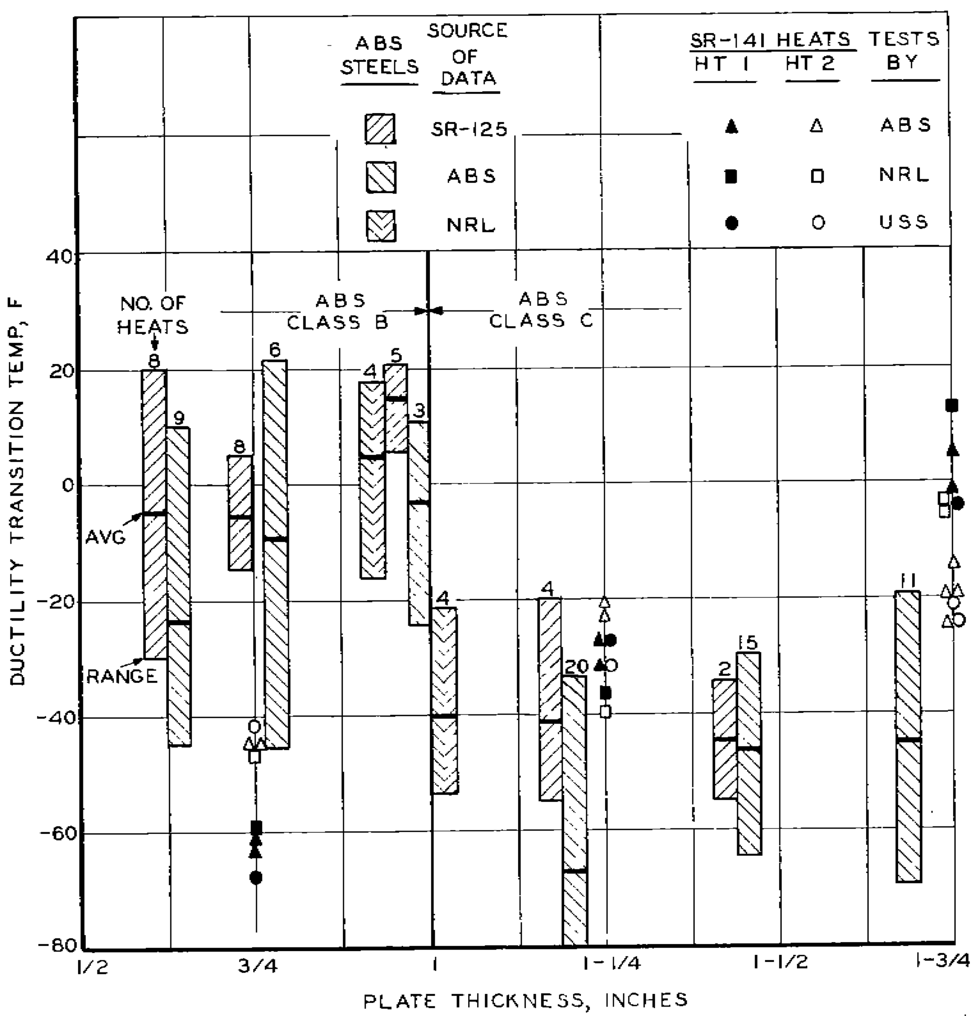

FIGURE 9 : KEYHOLE CHARPY DUCTILITY TRANSITION TEMPERATURES OF ABS AND SR-141 HEATS

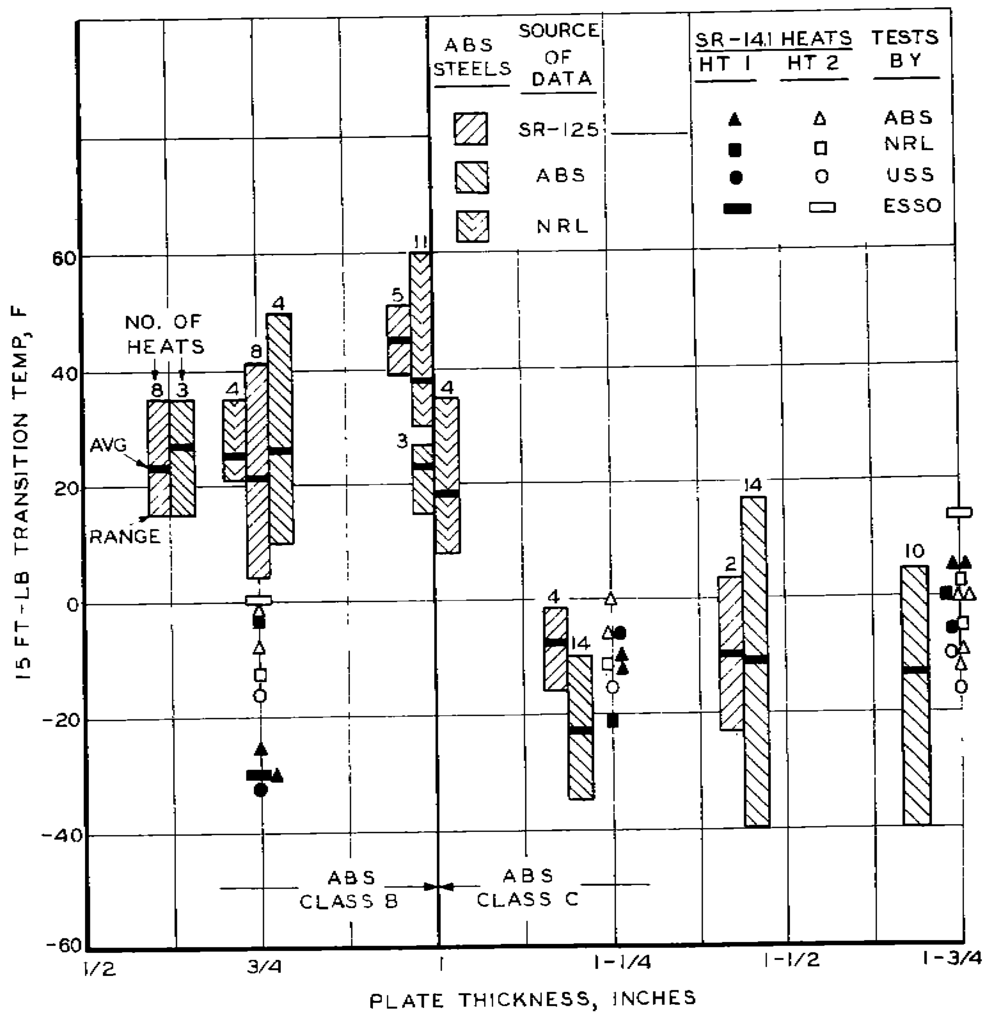

FIGURE 10: V-NOTCH CHARPY 15 FT-LB TRANSITION TEMPERATURES OF ABS AND SR-141 HEATS

test data and ship performance[10], but both the keyhole and V-notch tests do provide roughly the same relative ranking of these steels.

Fig. 11 provides V-notch Charpy data on a number of semi-killed, high-manganese steels of foreign manufacture for comparison with similar data on the SR-141 steels. The selected data on the SR-141 heats are average values (of the tests conducted by the various laboratories) for each of the seven plates tested. All of the steels are within the composition range of 0.12 to 0.17% C and 0.99 to 1.43% Mn, and all show rather similar notch-toughness behavior.

Table 7 shows an interesting evaluation of the differences between the 15 ft-lb V-notch and the keyhole Charpy ductility-transition temperatures of the SR-141 heats. For the evaluations by each laboratory, this difference decreases as plate thickness increases. This has not been previously realized, nor is it known if this is generally the case. For the 1 3/4-in. plate of Heat 1, the keyhole transition temperatures are about the same as the 15 ft-lb V-notch temperatures.

Since fracture appearance was recorded for the Charpy specimens tested by U. S. Steel a list of the fracture-transition temperatures (at 50% shear) is presented in Table 8. For all plate thicknesses, the V-notch fracture transitions are approximately 45 F higher than the keyhole. The V-notch fracture transitions, like the V-notch 15 ft-lb transitions, are believed to provide

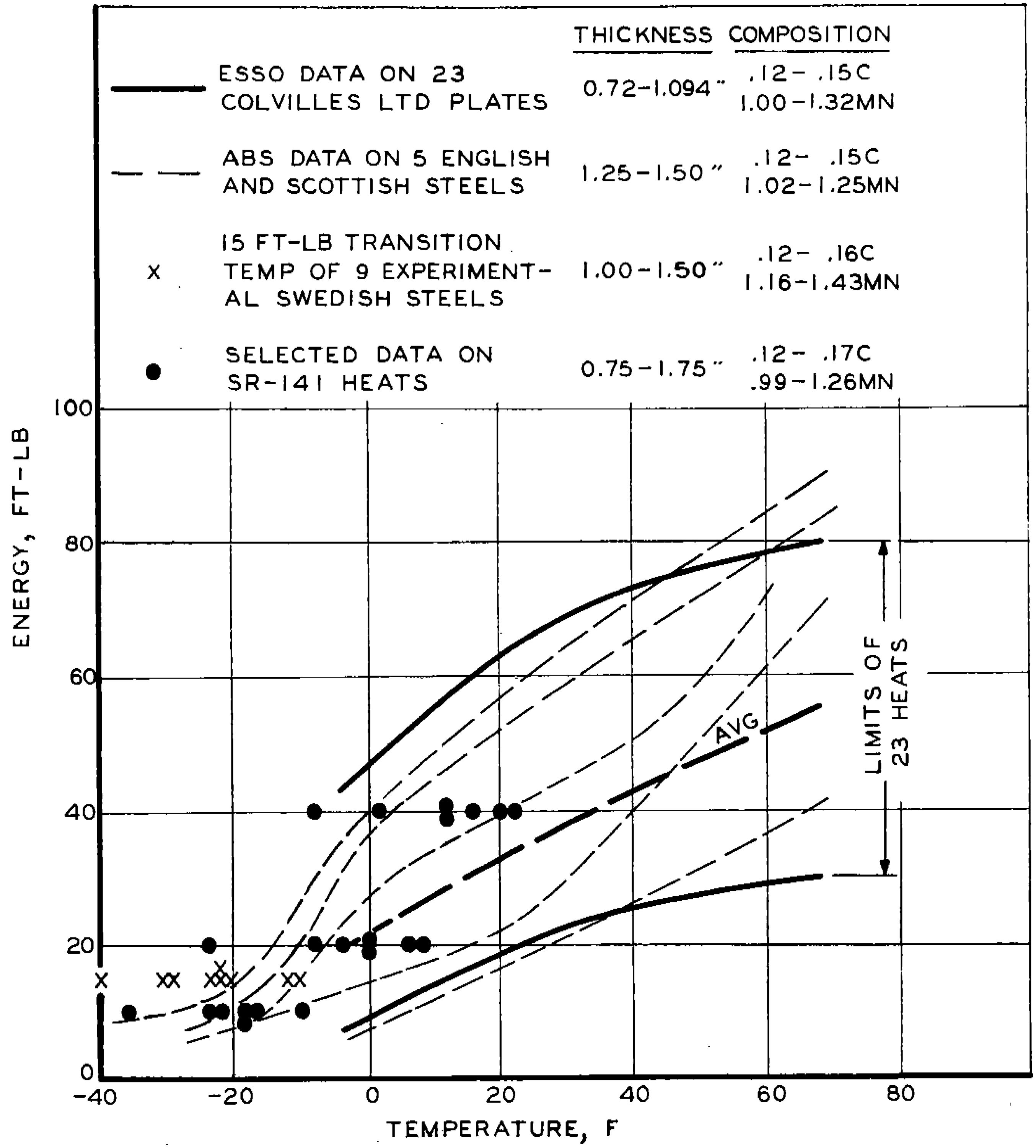

FIGURE 11: CHARPY V-NOTCH IMPACT BEHAVIOR OF HIGH-MANGANESE SEMIKILLED STEELS

TABLE 7

Difference Between 15 ft-lb V-Notch and Keyhole Charpy Ductility Transition Temperatures

Heat	Plate Thick., Inches	15 ft-lb V-Notch Temp. Minus Keyhole Charpy Ductility Transition Temperature, F			
		ABS	NRL	USS	Average
Heat 1	3/4	39,31	57	36	41
	1 1/4	22,16	16	22	19
	1 3/4	7,1	-12	-1	-1
Heat 2	3/4	44,38	35	26	36
	1 1/4	22,18	29	17	22
	1 3/4 (D)	15,20	8	12	14
	1 3/4 (A)	11,13	-1	9	8

TABLE 8

Fracture Transition Temperatures of Charpy Specimens Tested by USS

Heat	Plate Thick., Inches	Fracture Trans. Temp, F, at 50% Shear		Difference*
		V-Notch	Keyhole	
Heat 1	3/4	40	4	36
	1 1/4	30	-12	42
	1 3/4	44	-9	53
				44 avg.
Heat 2	3/4	42	-18	60
	1 1/4	44	8	36
	1 3/4(D)	38	-4	42
	1 3/4(A)	66	25	41
				45 avg.

*Difference between V-notch and keyhole fracture transition temperatures.

better indications of critical temperatures in service than the keyhole Charpy evaluations. As discussed earlier, however, the 15 ft-lb and the fracture transitions evaluate different aspects of behavior.

Crack-Starter Drop-Weight Tests. The results of the crack-starter drop-weight tests are reported in Table 9, together with the energy absorbed in the Charpy V-notch test (NRL test data) at the crack-starter transition temperatures. The Charpy energy absorbed at the drop-weight transition is generally higher for the SR-141 heats than for ABS steels. Most of the SR-141 plates, however, are thicker than the ABS plates listed under Note 2, Table 9. The drop-weight transition temperatures are also listed in Table 10, where they may be compared with similar data on ABS steels and with V-notch Charpy 15 ft-lb transition temperatures (these two transition temperatures are considered to be ductility-transition temperatures). The V-notch Charpy transitions are averages obtained from the data in Table 6.

The interpretation placed upon the drop-weight test by NRL is that brittle failure is a possibility at operating temperatures below the drop-weight transition temperature, but is not likely at temperatures above this transition unless crack initiation is forced. This interpretation is based upon the correlation with service behavior that was obtained with ship plate steels of World War II manufacture, with some alloy pressure

TABLE 9

Crack-Starter and Charpy V-Notch Test Data Obtained at NRL

Heat	Plate Thick., Inches	Drop-Wt. Trans. N.D.T., F	Charpy V Energy at N.D.T., ft-lb	Explosion Crack-Starter Trans., F.T.E., F	Charpy V Energy at F.T.E. ft-lb
Heat 1	3/4	-20	9	15	25
	1 1/4	0	40	35	91
	1 3/4	0	15	45	89
Heat 2	3/4	-10	16	25	53
	1 1/4	10	28	35	58
	1 3/4(D)	10	22	35	60
	1 3/4(A)	10	23	45	84

Note 1: Drop-weight transitions were determined on full-thickness specimens except for the 1 3/4 inch-thick plate specimens which were machined to 1 inch thick. Explosion tests were on full-thickness specimens.

Note 2: The V-notch Charpy energy absorbed at the drop-weight N.D.T. for as-rolled ABS steel is, according to NRL tests, as follows:

ABS Steel	Plate Thick., Inches	No. of Heats	Charpy V Energy at N.D.T., ft-lb Average	Range	Charpy V Energy at F.T.E., ft-lb Average	Range
Class B	3/4	5	9	7 to 12		
	1	11	15	8 to 32		
Class C	1	4	13	10 to 17	45*	26 to 62*

*Based on 3 heats

TABLE 10

Various Transition Temperature Evaluations

Steel	Plate Thick., Inches	Ductility Transitions: Drop-Weight Transition, N.D.T., F	Ductility Transitions: Average Charpy V 15 ft-lb Temp, F	Fracture Transitions: Crack-Starter-Explosion Transition, F.T.E., F	Fracture Transitions: SOD Transition, F	Fracture Transitions: Robertson Test Transition, F	Fracture Transitions: Tear-Test Transition, F	Fracture Transitions: Charpy-V Transition at 50% Shear, F
Heat 1	3/4	-20	-24	15	20		70	40
Heat 2	3/4	-10	- 8	25	20	18	60	42
ABS Class B	5/8		24				60 avg[1] (8 hts) 64 avg[2] (40 to 90) 8 hts	
	3/4	4 avg (0 to 10) 5 hts	23				75 avg[1] (8 hts) 92 avg[2] (70 to 110) 9 hts 70 avg[3] (55 to 85)	
	1	35 avg (10 to 60) 11 hts	38		40 (1 ht)	(65)[4]	85 avg[1] (5 hts) 109 avg[2] (50 to 140) 21 hts	
Heat 1	1 1/4	0	-12	35	50		70	30
	1 3/4	0	1	45	70		90	44
Heat 2	1 1/4	10	- 8	35	50		90	44
	1 3/4 (D)	10	1	35	30		90	38
	1 3/4 (A)	10	-10	45	40		120	66

1. Estimated from very limited tear test data in SR-125 (Ref.11).
2. Kahn et al (Ref.6).
3. Frazier et al (Ref.12).
4. A rough estimate based on limited data available (Ref.5).

(Continued)

TABLE 10 Continued

Various Transition Temperature Evaluations

		Ductility Transitions		Fracture Transitions				
Steel	Plate Thick., Inches	Drop-Weight Transition, N.D.T., F	Average Charpy V 15 ft-lb Temp, F	Crack-Starter-Explosion Transition, F.T.E., F	SOD Transition, F	Robertson Test Transition, F	Tear-Test Transition, F	Charpy-V Transition at 50% Shear, F
ABS Class C	1	8 avg (0 to 10) 4 hts	18	57 avg (30 to 70) 3 hts	23 avg* (0 to 50) 6 hts			
	1 1/8-- 1 1/2		-16				80 avg[1] 6 hts	

1. Estimated from very limited tear test data in SR-125 (Ref.11).
2. Kahn et al (Ref.6).
3. Frazier et al (Ref.12).
4. A rough estimate based on limited data available (Ref.5).

*Reportedly all fine-grain-practice heats, but Al contents were low in some of the heats.

vessel steels, and with some other steels in special applications. Based on this experience, NRL believes that the correlation would hold for a broad variety of steels.

Table 10 shows that eleven 1-in. ABS Class B plates had an average drop-weight transition of 35 F, and ABS Class B plates have so far performed well in service; in two instances, service failures have occurred in plates slightly outside the ABS Class B limits. The SR-141 plates over 1-in. thick, with drop-weight transitions of 0 to 10 F, are considerably better than the 1-in. Class B plates and similar in toughness to the 3/4-in. Class B. According to the V-notch Charpy transitions, however, the heavy-gage SR-141 plates are considerably tougher than even the 3/4-in. and 5/8-in. Class B plates. The two types of tests are therefore providing somewhat different evaluations of behavior. The V-notch Charpy transitions on the 1-in. ABS Class C steel are unusually high for this grade, so it would not be advisable to consider the average drop-weight transition of 8 F for these same heats as representative of the grade. (These high V-notch transitions for the 1-in. Class C plate show up clearly in Fig. 10; yet the keyhole Charpy transitions for these steels, Fig. 9, are not unusually high). Additional drop-weight tests on Class C steel are needed for a suitable comparison with the SR-141 heats.

<u>Fracture-Transition Evaluations</u>. The fracture-transition temperatures as determined by the various test methods are also listed in Table 10. Evaluation of these results is hindered by the lack

of comparable data for the ABS steels.

Crack-starter-explosion transition temperatures have been shown to agree quite well with fracture-transition temperatures obtained by centrally-notched wide plate tests[3] which have been used extensively in testing certain pedigreed steels. The crack-starter-explosion transition temperatures for the SR-141 plates over 1 in. thick range from 35 to 45 F. This would seem to indicate that these plates would be highly likely to stop any cracks that might be initiated so long as the operating temperature is no lower than slightly above freezing. As a matter of interest, the Charpy V-notch energy absorbed at these transition temperatures is shown in Table 9.

The SOD transition temperatures agree fairly well with the crack-starter-explosion transitions except for the 1 3/4-in. plate of Heat 1. Also, the transition of the 1 1/4-in. plate of Heat 2 seems out of line with the data on the 1 3/4-in. plates. Esso felt that the heavy thickness of these plate specimens may have been affecting the results appreciably and wished to conduct tests on samples planed down to 1 in. thick (all from one surface of the plate). Previous SOD tests by Esso have all been on plates no thicker than 1 in. Suitable supplementary samples were obtained (according to Fig. 1), and tests were run on the 1 1/4-in. and 1 3/4-in. plates planed down to 1 in. The resulting SOD transitions were 20 F for the 1 3/4-in. plate of Heat 1 (as opposed to

70 F, not planed) and 30 F for the 1 1/4-in. plate of Heat 2 (as opposed to 50 F). Esso cannot fully explain these results at this time other than to say that they may indicate the existence of a specimen size effect.

The Esso tests on the ABS steels[4] were not conducted under the same conditions as those on the SR-141 heats. On the SR-141 material, the specimen was backed up with a 5000-lb weight, and a heavy charge was used to initiate fracture. On the other steels, no backing-up weight was used, and a reduced charge was employed. Esso reports that these two techniques have been shown to give very nearly the same SOD transition temperature.

The 23 F average SOD transition reported for 1-in. ABS Class C actually represents various grades of steel whose compositions fell within the ABS limits. However, the aluminum contents were quite low for some of these steels, which makes it questionable whether they were all made by fine-grain practice.

Robertson tests have been completed on just one plate to date, and detailed results are reported in the Appendix, Table A-8. The transition temperature for the 3/4-in. plate, Heat 2, is shown in Table 10. It agrees quite well with the crack-starter-explosion and SOD transitions.

Detailed tear test data are listed in the Appendix, Table A-9. Each tear-test transition temperature recorded in Table 10 represents the highest temperature at which 50% or more cleavage fracture was obtained in at least one out of four test specimens. This is the usual method of selection. All of the tear-test transitions are considerably higher than the fracture transitions obtained by the other test methods, and this has been the general experience with this test. The tear-test transitions on the SR-141 1 1/4-in. and 1 3/4-in. plates are as high or higher than those obtained on the ABS steels.

Charpy V-notch fracture transitions are also listed, and in the heavier plate thicknesses they agree quite well with the crack-starter-explosion transition temperatures.

Underbead Cracking. The underbead-cracking test results are portrayed in Table 11 and are plotted versus carbon equivalent in Fig. 12, together with data on other types of steel, including ABS Classes A, B, and C, HTS (Mn-V-Ti), X 52 line pipe (0.25% C, 1.00% Mn), and silicon-killed, structural carbon steel. The figure shows that the amount of underbead cracking in all of these steels depends mainly upon the carbon equivalent, which is taken as being equal to the carbon content plus manganese over four plus silicon over four.

This underbead-cracking test is rather severe and often produces greater amounts of cracking than are obtained in actual welds. For example, 50% underbead cracking in this test on X 52 line pipe steel corresponds approximately to zero underbead cracking in field girth welds on line pipe.

It will be noted that greater amounts of underbead cracking are encountered at 0°F than at 60--70 F.

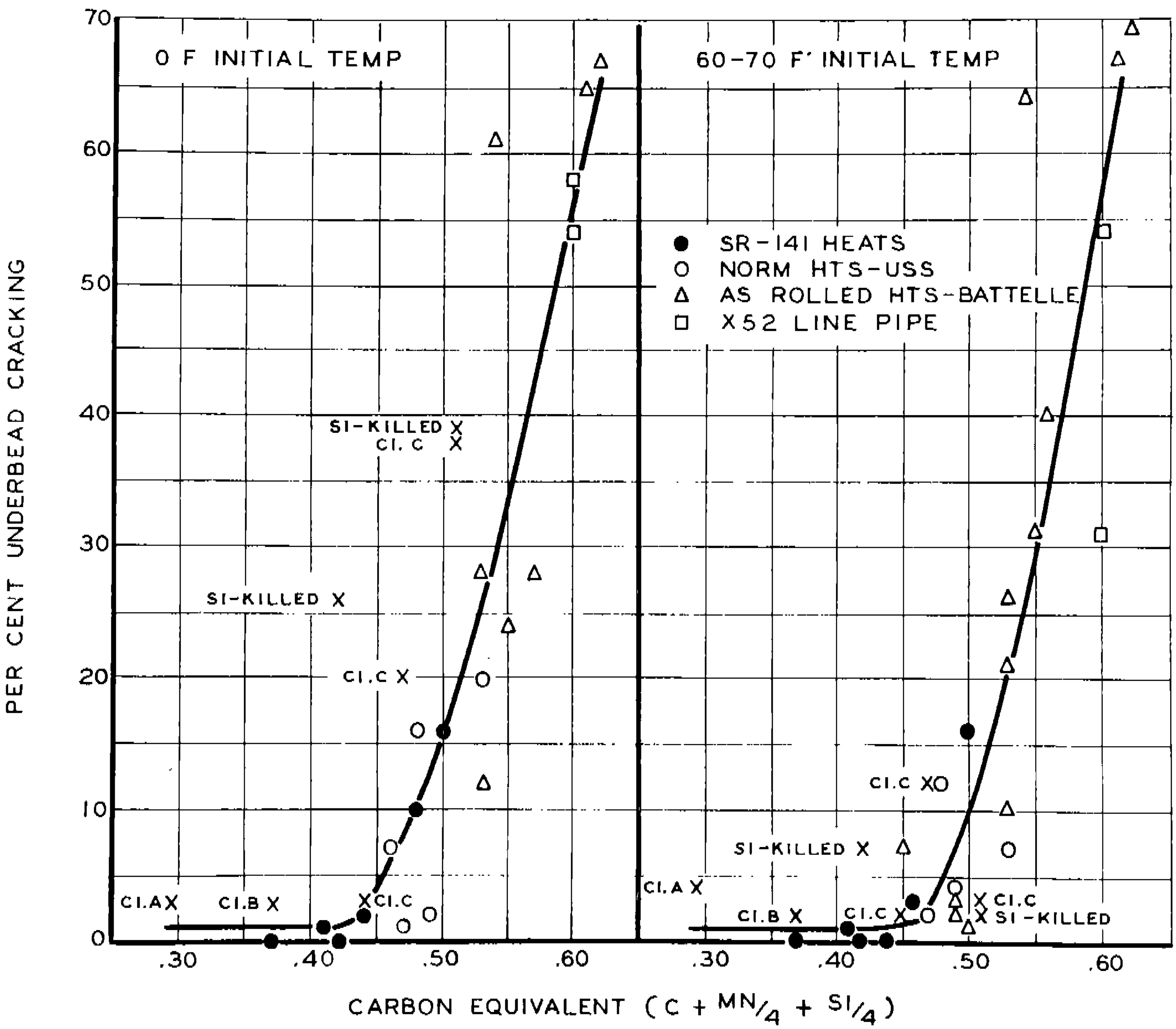

FIGURE 12: STANDARD UNDERBEAD CRACKING TESTS USING E6010 ELECTRODES

TABLE 11

Standard Underbead Cracking Tests

Heat	Plate Thick., Inches	Carbon Equivalent*	% Underbead Cracking** at 0°F	70 F	212 F
Heat 1	3/4	0.50	16	16	13
	1 1/4	0.48	10	7	1
	1 3/4	0.46	7	3	1
Heat 2	3/4	0.42	0	0	0
	1 1/4	0.41	1	1	0
	1 3/4 (D)	0.37	0	0	0
	1 3/4 (A)	0.44	2	0	1

*C + Mn/4 + Si/4 (based on USS check analyses)

**Using an E6010 electrode. When an E7016 low-hydrogen electrode was used, the underbead cracking at an initial temperature of 70 F was 0 to 2% for all plates.

NOTE: For ABS Class C, the average C equivalent is about 0.43; the maximum possible would be 0.55.
For a 0.20 C max, 1.00-1.35 Mn semikilled steel, the average C equivalent (0.16 C, 1.20 Mn) is about 0.46; the maximum possible would be 0.54.

In general, these data indicate that SR-141 heats would have about the same tendency to underbead crack as ABS Class C steel.

CONCLUSIONS

The objective of obtaining an average V-notch Charpy 15 ft-lb transition temperature of 0°F or lower in 1-in. thick semikilled plate was achieved in two heats containing about 0.15% C and 1.05--1.25% Mn. Even the 1 3/4-in. plates had transition temperatures no higher than about 0°F. According to V-notch Charpy tests, these heats were considerably more notch tough than ABS Class B steel and almost as good as ABS Class C. The crack-starter drop-weight tests also indicated good notch toughness but not as good as indicated by the Charpy V-notch tests. These tests imply that fracture would not start in these SR-141 heats, unless forced, at temperatures above approximately 0°F. The crack-starter-explosion tests indicate that the SR-141 steels would be highly likely to stop any cracks that might be started so long as service temperatures were no lower than about 40 F. These behavior characteristics compare favorably with those of ABS Class B steel and seem by some of the tests to be nearly as good as those of ABS Class C killed steel, but additional data are needed to make a suitable comparison in the latter case.

The test results are believed to indicate that a semikilled steel containing about 0.15% C and 1.20% Mn should have sufficient notch toughness to be considered as an emergency substitute, or possibly as an alternate, for ABS Class C killed steel in thicknesses over 1 in. to 1 3/4 in. inclusive.

To meet the tensile properties for hull steel specified by the American Bureau of Shipping, it is tentatively recommended that the composition range for the proposed steel be 0.20% C maximum and 1.00 to 1.35% Mn.

Underbead cracking tests indicate that the proposed steel should have about the same sensitivity to underbead cracking as ABS Class C steel.

FUTURE WORK

Only two 25-ton heats of the proposed steel have been tested to date. It has been the Project Advisory Committee's intention to consider making and testing full-size heats of this steel if the results obtained on these two heats were promising. Since promising results have been obtained, it is believed that making selected tests on plates from a number of full-size heats is an appropriate step in order to establish better the average properties and the likely range of properties that might be expected. Also, additional mill experience is needed to establish optimum deoxidation practices for this steel.

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The members of Project SR-141 Advisory Committee, who planned and guided this study, are:

M. W. Lightner, Chairman
W. J. Harris, Jr.
W. S. Pellini
T. S. Washburn
T. T. Watson

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A P P E N D I X

TABLE A-1

V-Notch Charpy Data from ABS

Heat 1

Temp., F	Energy, Ft-Lb: 3/4" Plate Top	3/4" Plate Bottom	1 1/4" Plate Top	1 1/4" Plate Bottom	1 3/4" Plate(D) Top	1 3/4" Plate(D) Bottom	1 3/4" Plate(A) Top	1 3/4" Plate(A) Bottom
70	104,94,84	148,104,102	101,99,88	154,110,102	129,115,108	89,81,77		
40	90,80,77,52	110,107,101,69	96,86,73,71	113,105,101,74	99,87,62,20	78,60,59,56		
20	86,71,51,51,16	90,85,68,59,54	85,72,65,52,41	88,87,70 60,50	57,51,41,16,13	20,18,16,16,13		
0	64,55,36 25,20	70,54,52,40,16	48,45,9,8,8	71,52,24,11,8	16,13,13,10,9	25,20,18,12,11		
-20	42,16,15,12,10	61,45,29,16,15	18,11,11,10,6	18,11,9,7,7	10,8,7 6,5	7,6,6,6,6		
-40	9,8,7,6,4	16,11,8,7,6	5,4,4	5,4,4	4,4,4	6,6,6		

Heat 2

Temp., F	3/4" Plate Top	3/4" Plate Bottom	1 1/4" Plate Top	1 1/4" Plate Bottom	1 3/4" Plate(D) Top	1 3/4" Plate(D) Bottom	1 3/4" Plate(A) Top	1 3/4" Plate(A) Bottom
70	160,123,102	160,125,115	158,109,98	149,111,104	145,101,92	129,112,111	125,116,113	162,160 160
40	105,103,86	150,97,92	126,102,87	88,66,58	158,80,52	129,108,102	85,76,65	110,82,81
20	95,82,58,54,48	62,52,46 38,14	85,69,45,41,18	120,75,18,14,13	75,66,46,18,14	50,43,36 24,22	64,44,43,38,33	99,59,38,22,18
0	22,17,14,12,11	76,42,20,15,7	31,13,13 11,7	35,32,27,18,13	21,20,12,11,11	18,18,14,14,13	69,55,14,11,10	68,32,22 14,13
-10	30,11,10,9,8	19,12,8,6,5	14,11,10,9,8	11,11,10 10,7	19,11,10,10,8	16,14,13,13,11	11,8,7,7,6	41,11,10,9,7
-20	16,11,7,7,6	14,10,9 8,4	16,9,6,6,4	11,11,8,7,7	11,11,11,11,9	12,12,10,9,9	99,8,8,7	11,9,7,6,6
-40	6	5	7	5	5	8	4	4

TABLE A-2

V-Notch Charpy Data from Esso

Heat 1

Temp, F	Energy, Ft-Lb 3/4" Plate	1 1/4" Plate	1 3/4" Plate(D)	1 3/4" Plate(A)
90			85,96,95	
80			113,88,81	
70		83,87,95	76,87,91	
60		92,91,82	79,86,73	
50	85,93,94	83,42,81	39,58,62	
40	78,86,90	87,88,75	51,69,75	
30	59,91,74	37,85,48		
20	85,25,83	36,66,83,74	29,73,14	
10	89,82,87			
0	49,57,77	12,44,42	9,39,35	
-20	55,33,60	9,40		
-40	10,4,6			

Heat 2

Temp, F	3/4" Plate	1 1/4" Plate	1 3/4" Plate(D)	1 3/4" Plate(A)
70		101,94,105		
60		97,83,90		115,100,90
50		56,90,90	30,71,69	83,72,93
40	85,89,91	81,86,81	62,59,67	73,95,75
30	49,49,70	39,60,72	25,48,32	86,51,55
20	38,57,34	22,42,38	27,21,14	37,15,66,48,73
10	44,28,14		11,12,11	16,40,11
0	12,11,13		10,11,8	
-10	14,14,15			

TABLE A-3

V-Notch Charpy Data from NRL

Heat 1

Temp, F	Energy, Ft-Lb 3/4" Plate	1 1/4" Plate	1 3/4" Plate(D)	1 3/4" Plate(A)
160	109,117			
140	96,107		114,120	
120		115,126,130	110,113,115	
100	75,82,87			
80		105,106,107	96,98,106	
60	33,47,60			
40		90,97,106	88,88,90	
20	21,22,40	19,66,98,98	43,56,73	
0	11,12,29	16,19,58,69	8,8,10,14,24	
-20	7,8,9,9,11	7,14,29	5,6,8	
-40	6,7,8	4,4,5	4,5	

Heat 2

Temp, F	3/4" Plate	1 1/4" Plate	1 3/4" Plate(D)	1 3/4" Plate(A)
120			125,126	126,130
100	112,121		115,132	113,123
80	105,107,108	112,112,118,121	120,127,129 130,136,137	104,111,112 113,117
60	103,103,108	94,95,105	64,89,94,102,104	78,82,116,134
40	57,93,95	35,70,96	64,68,70,73,87	29,69,76,83,85,98
20	24,26,34,42	36,40,45	19,21,24,25 43,52,77	15,17,19,26,60
0	12,35,39	10,14,16,28,29	12,13,14,14,16	12,12,13,16,19,54
-20	9,13,14	8,11,17	9,9,10	8,9,9,13
-40	7,11,12	6,7,7	5,5,8	5,7,8

TABLE A-4

V-Notch Charpy Data from USS

Heat 1

Temp., F	3/4" Plate Energy Ft-Lb	3/4" Plate % Shear	1 1/4" Plate Energy Ft-Lb	1 1/4" Plate % Shear	1 3/4" Plate(D) Energy Ft-Lb	1 3/4" Plate(D) % Shear	1 3/4" Plate(A) Energy Ft-Lb	1 3/4" Plate(A) % Shear
100	112,114,126	70,80,85	166,123,119	100,85,80	102,105,100	97,95,98		
80	68,94,91	50,60,60	170,116,126	100,60,70	90,109,98	80,95,85		
60					83,87,90	70,70,70		
40	77,81,99	50,45,60	119,113,116	60,60,60	54,42,63	20,30,60		
20	62,59,44	10,10,10	110,91,29	40,40,5	54,25,50	30,30,30		
10			109,112,106	30,30,30				
0	62,25,59	10,5,10	86,57,80	20,10,15	13,33,11	5,10,5		
-10			18,10,9	5,5,5	10,10,10	5,5,5		
-20	30,22,40	5,5,5	13,8,9	5,5,5	8,19,9	0,5,0		
-30	12,20,13	5,5,5			7,4,7	0,0,0		
-40	18,10,4	5,5,5	9,6,5	5,5,5				
-60	3,4,3	1,1,1						

Heat 2

Temp., F	3/4" Plate Energy Ft-Lb	3/4" Plate % Shear	1 1/4" Plate Energy Ft-Lb	1 1/4" Plate % Shear	1 3/4" Plate(D) Energy Ft-Lb	1 3/4" Plate(D) % Shear	1 3/4" Plate(A) Energy Ft-Lb	1 3/4" Plate(A) % Shear
80	120,161,134	80,95,80	176,196,121	100,100,80	190,125,184	100,90,100	122,208,182	70,100,100
60	119,112,162	60,60,97	106,168,182	60,100,100	180,206,94	100,100,60	109,112,105	40,40,50
40	131,99,107	50,20,40	100,111,102	20,50,40	69,75,151	20,25,70	107,112,68	40,40,15
30	98,103,105	40,50,50	96,82,102	40,30,40	176,63,84	100,50,40		
20	70,83,24	15,15,10	60,39,102	10,10,40	29,22,21	20,10,10	60,46,107	15,10,40
10							17,85,14	5,20,5
0	66,61,14	15,10,5	14,38,14	5,8,5	19,22,63	8,8,15	10,57,63	5,10,15
-10	8,35,23	0,5,4	12,51,25	5,9,5	13,20,11	0,5,5	12,7,80	0,0,15
-20	21,8,10	5,0,0	15,15,7	0,0,0	8,13,9	0,0,0	13,11,8	0,0,0
-30	6,7,12	0,0,0	7,4,4	0,0,0	6,7,6	0,0,0	5,6,10	0,0,0

TABLE A-5

Keyhole-Notch Charpy Data from ABS

Heat 1

Temp., F	3/4" Plate Top	3/4" Plate Bottom	1 1/4" Plate Top	1 1/4" Plate Bottom	1 3/4" Plate(D) Top	1 3/4" Plate(D) Bottom	1 3/4" Plate(A) Top	1 3/4" Plate(A) Bottom
	Energy, Ft-Lb							
70	58,51	61,53	58,53	59,58	63,56	52,51		
20					51,47,43	47,37,35		
0	44,40,39, 38	45,44,41	49,45,44, 41	44,43,42, 31,14	41,40,25 12,10	35,23,17 16,14		
-20	41,35,35, 35	44,44,40 38	46,41,41, 9,8	45,41,39, 38,17	10,8,8, 7,6	10,9,9, 8,6		
-40	35,33,31	38,34,33,	39,33,6, 6,5	35,6,6, 6,5	6,5,5	6,5,4		
-60	30,30,30, 3,3	32,30,15 5,5	4,3	4				

Heat 2

Temp., F	3/4" Plate Top	3/4" Plate Bottom	1 1/4" Plate Top	1 1/4" Plate Bottom	1 3/4" Plate(D) Top	1 3/4" Plate(D) Bottom	1 3/4" Plate(A) Top	1 3/4" Plate(A) Bottom
70	59,53	61,59	59,54	62,59	60,59	56,55	60,59	62,60
0	52,49,43, 42	48,47,43	45,44,41, 40,8	51,44,42 27,15	58,51,50, 45,38	51,50,48, 44,33	49,44,41, 39,11	46,46,41, 11
-20	44,40,40, 36	46,45,45, 10	37,33,31, 29,9	41,40,38 35,10	37,13,11, 8,8	34,33,24, 10,9	44,37,35, 8,8	41,40,7, 6
-40	41,35,32, 28,6	37,36,35, 8,6	10,8,7, 5,4	7,7,7, 6,5	7,6,6, 6,6	7,7,6, 6,5	5,5,5, 5,4	39,38,36, 5,5
-60	7,4,3	34,4,3, 3	3	4	4	4	3	6,3,3

TABLE A-6

Keyhole-Notch Charpy Data from NRL

Heat 1

Temp, F	Energy, Ft-Lb 3/4" Plate	1 1/4" Plate	1 3/4" Plate(D)	1 3/4" Plate(A)
80	49,51	59,60	58,60	
20			20,44,46,47	
10		48,48,49,49		
0	31,39	16,49	8,11	
-10			8	
-20			6,6	
-30			5,5,5,6,6,	
-40	23,30,34			
-60	7,26	3,34		
-70		3,3,3,3,3,3		
-80	4,4,6,6,8			
-90	4,4			

Heat 2

Temp, F	3/4" Plate	1 1/4" Plate	1 3/4" Plate(D)	1 3/4" Plate(A)
80	62,63	63,65	59,59	50,59
20			44,48,48,50,52	45,48,49,50
10	46		19,43	15,43
0	46,46		12,21	5,10
-10	43,45			5,39
-20	6,43	40,43,46	5,38	4,4,36
-30		5,40,40	3,3,3,4,6	3,3
-40		3,37	2,3	3,4
-50		2,33		
-60	3,26	2,2,2,2		
-70	33			
-80	2,2,2,2			

TABLE A-7

Keyhole Charpy Data from USS

Heat 1

Temp., F	3/4" Plate Energy Ft-Lb	3/4" Plate % Shear	1 1/4" Plate Energy Ft-Lb	1 1/4" Plate % Shear	1 3/4" Plate(D) Energy Ft-Lb	1 3/4" Plate(D) % Shear	1 3/4" Plate(A) Energy Ft-Lb	1 3/4" Plate(A) % Shear
60			56,54,56	90,90,90				
40	55	95	51,52,50	80,80,85				
30					40,46,52	90,100,100		
20	44,46,44	70,70,70	42,50,50	70,80,70	42,37,40	90,80,80		
10					16,36,42	50,60,100		
0	38,36,40	30,30,40	44,40,45	60,60,60	16,18,47	60,60,100		
-5					34,37,33	70,70,50		
-10			46,40,46	60,40,60	36,10,13	70,10,15		
-15					33,28,14	60,40,10		
-20	38,35,36	40,30,40	8,44,36	0,50,30	10,9,8	5,5,5		
-30			36,4,23	15,0,10	8,6,8	5,5,5		
-40	32,33,28	15,20,10	28,6,4	10,0,0				
-50	30,34,31	10,15,10	4,3,4	0,0,0				
-60	6,29,21	0,10,5						
-70	14,26,3	5,10,0						
-80	5,24,2	0,10,0						
-90	2,2,2	0,0,0						

Heat 2

Temp., F	3/4" Plate Energy Ft-Lb	3/4" Plate % Shear	1 1/4" Plate Energy Ft-Lb	1 1/4" Plate % Shear	1 3/4" Plate(D) Energy Ft-Lb	1 3/4" Plate(D) % Shear	1 3/4" Plate(A) Energy Ft-Lb	1 3/4" Plate(A) % Shear
40	66,57,54	100,90,85						
20	48,65,52	70,100,80	46,49,68	50,60,100	45,66,54	40,100,80	16,46,44	15,60,50
10			44,40,46	50,50,50	43,51,52	70,80,80	41,16,46	30,10,40
0	42,43,42	70,70,70	36,38,37	20,30,40	44,44,14	50,40,20	45,44,44	50,40,30
-10			42,46,43	50,50,50	39,43,44	50,50,60	11,49,46	5,60,70
-20	40,40,43	50,50,40	34,38,39	20,20,20	9,9,50	0,0,85	32,45,39	20,30,25
-30	40,7,9	30,5,5	8,42,11	0,40,5	34,36,5	30,30,0	10,6,40	0,0,40
-40	6,35,34	5,15,15	10,5,28	0,0,5	6,5,11	0,0,0	4,16,4	0,5,0
-50	5,6,27	5,5,10	8,4,4	0,0,0	5,4,6	0,0,0	4,8,4	0,0,0
-55	5,34,4	5,10,5						
-60	3,4,3	0,0,0	6,3,13	0,0,0			3,3,4	0,0,0
-65	26,3,3	10,0,0						
-70			3,4,6	0,0,0				

TABLE A-8

Robertson Test Data

Steel	Stress, psi	Arrest Temp, F	Remarks
Heat 2, 3/4" plate	22,400	14	
	17,920	18	
	13,440	18	
	11,200	-2	
	8,960	-23	
	7,840	-98	
	17,920* at 13 F		Crack ran through.
	17,920* at 32 F		Crack arrested and repropagated.

*These tests were conducted at the constant temperatures indicated except for a 2-inch-long low-temperature zone under the notch. This zone was cooled so that fracture could be readily started.

TABLE A-9

Navy Tear Test Data

Temp, F	Shear in Fracture, %			
	3/4" Plate	1 1/4" Plate	1 3/4" Plate(D)	1 3/4" Plate(A)
Heat 1				
100			100,75,95,95	
90			100,65,75,10	
80	100,100,100,95	100,100,100,55	50,65,70,5	
70	100,100,75,5	100,55,35,5		
60	100,100,0,0	30,15,10,0	35,40,0,100	
50	55,45,10,0	65,35,15,0	10,5,10,5	
40	15,5,0,0	75,35,35,25	25,5,5,5	
30		25,0,0,0		
Heat 2				
140				100,100
130				100,100,100,100
120				100,40,100,100
100	100	100,100,100,65	100,100,100,95	90,20,100,45
90		70,35,30,0	100,100,100,30	20,10,0,60
80	100,90,75,70	70,40,40,0	95,95,60,35	0,10,45,5
70	100,90,75,50	15,10,0,0	100,85,75,15	
60	90,65,35,25	0	65,0	0,5
50	80,55,25,0		80,70,10,0	
40	75,65,0,0		80,5,0,0	
30	20,0,0,0		30,25,0,0	
20	0	0	25,0	20,0,0

Note: The tear test specimens from the 1 3/4-in. thick plate were machined to 1 1/4-in. thick for testing purposes by removing metal from one plate surface only. The tear test specimens from the 3/4-in. and 1 1/4-in. plates were full plate thickness.