UNCLASSIFIED

AD NUMBER

AD459670

NEW LIMITATION CHANGE

TO

Approved for public release, distribution unlimited

FROM

Distribution authorized to U.S. Gov't. agencies and their contractors; Administrative/Operational Use; 31 MAY 1963. Other requests shall be referred to Bureau of Naval Ships, Washington, DC 20360.

AUTHORITY

buships ltr, 17 may 1965

THIS PAGE IS UNCLASSIFIED

UNCLASSIFIED

AD 459670

DEFENSE DOCUMENTATION CENTER

FOR

SCIENTIFIC AND TECHNICAL INFORMATION

CAMERON STATION ALEXANDRIA, VIRGINIA

UNCLASSIFIED

Technical Report

Effect of Carbon, Phosphorus, Sulfur, and Nickel Content on the Mechanical Properties of Laboratory-Melted Ni-Cr-Mo Steels

Applied Research Laboratory
United States Steel
Monroeville, Pennsylvania

May 31, 1963 **Project No. 40.18-001(2)**

S-11107

DDC AVAILABILITY NOTICE
QU[illegible] MAY OBTAIN COPIES
OF [illegible] DDC.

(5) United [illegible] Corp., Monroeville, Pa., Applied [illegible] Lab.

(9) Progress rept., (15) Contract N[illegible] [illegible]540,

(11) 31 May 65, (16) Proj. 40.1[illegible]-001(2)

(14) [illegible] no. S-11107

(6) EFFECT OF CARBON, PHOSPHORUS, SULFUR, AND NICKEL CONTENT ON THE MECHANICAL PROPERTIES OF LABORATORY-MELTED NI-CR-MO STEELS, (40.18-001)(2)(Progress Report)(a-AS-NP-36)(S-11107)

(10) By J. V. Alger, R. M. Brown, D. S. Dabkowski, K. H. Kramer and W. J. Murphy, [redacted]

Approved by J. H. Gross, ~~Division Chief~~

Abstract

During the interval 1960 to 1962, the Applied Research Laboratory developed a Ni-Cr-Mo steel meeting most of the Navy requirements for an HY-150 steel that would permit submarines to operate at depths substantially greater than those now attainable with HY-80 steel. To better define the effect of variations in carbon, phosphorus, sulfur, and nickel on the strength and notch toughness of this steel, a central composite rotatable second-order statistically designed experimental program was conducted.

The results were obtained in the form of a series of equations that predict for Laboratory-produced Ni-Cr-Mo steel the effect of the elements studied on the yield strength, tensile strength, elongation, reduction of area, Charpy V-notch energy absorption at +80 F and -80 F, lateral expansion at +80 F and -80 F, and shear-fracture appearance at -80 F.

The equations predict that (1) an increase in carbon content from 0.10 to 0.20 percent would increase the yield strength about 14,000 psi, correspondingly decrease the elongation about 2 percent, and decrease the energy absorption at +80 F about 17 ft-lb; (2) an increase in sulfur from 0.005 to 0.010 percent would decrease the reduction of area about 2 percent and reduce the energy absorption at +80 F about 10 ft-lb; (3) an increase in nickel content from 4.0 to 8.0 percent would decrease the energy absorption at +80 F about 5 ft-lb and lower the transition temperature; and (4) variations in phosphorus content between 0.004 and 0.018 percent would not influence the tensile and impact properties.

These results are being used to guide the alloy development of steels with optimum compositions to meet revised Navy requirements for a submarine-hull weldment having a yield strength of 130 to 150 ksi.

Introduction

The Applied Research Laboratory has been conducting investigations to develop high-yield-strength steels that the U. S. Navy Bureau of Ships has indicated are needed for future submarine-hull construction. Such steels would permit submarines to operate at depths significantly greater than those now attainable with HY-80 steel. For this application, the Navy requires, as an immediate goal, a steel that will exhibit a yield strength in the range 130,000 to 150,000 psi with good toughness at ice-water temperatures, good fabricability, and good weldability in plate thicknesses through 4 inches.[1)*]

From studies conducted from 1960 to 1962, the Laboratory developed a 7½Ni-Cr-Mo steel that met most of the Navy requirements for an HY-150 steel.[2)] However, to establish the optimum yield-strength—toughness relation with respect to variations in carbon, phosphorus, sulfur, and nickel content, the Laboratory investigated the effect of these elements on the mechanical properties of Ni-Cr-Mo type steels by using a central composite rotatable second-order statistically designed program. The particular elements studied were selected because they were expected to exert the most important influence on the mechanical properties of the steel. The present report summarizes the results of the statistical

---

*See References.

evaluation conducted to determine the effects of carbon, phosphorus, sulfur, and nickel on the tensile properties and Charpy V-notch impact properties of quenched and tempered Ni-Cr-Mo type steels.

Materials and Experimental Work

Chemical Composition

The composition levels desired for the elements studied and the composition ranges for the elements held constant are listed in Table I. The chemical compositions of the individual steels investigated are shown in Table II.

Melting and Rolling Procedures

To furnish material for the aforementioned statistical study, thirty-one 100-pound Laboratory air-induction silicon-aluminum-killed heats were melted and air-cast into 3- by 8-inch slab ingots. The melting procedure for the heats is described in detail in Appendix A. The resulting slab ingots were heated to 2180 F, rolled parallel to the ingot axis to 1-inch-thick plate, air-cooled, and cut into three equal lengths. The 1-inch-thick plate sections of each steel were then heated to 2150 F, cross-rolled to 1/2-inch-thick plate, and air-cooled.

Heat Treatment

An 8- by 8- by 1/2-inch cross-rolled plate for each steel was austenitized for 1 hour at 1475 F, water-quenched, tempered for 1 hour at 1025 F, and water-quenched. This treatment was selected on the basis of a previous study[2] which indicated that the $7\frac{1}{2}$Ni-Cr-Mo steel exhibited optimum yield strength and notch toughness when heat-treated in this way.

Mechanical Tests

Duplicate longitudinal (parallel to the final rolling direction) and transverse 0.252-inch-diameter tension-test specimens and triplicate longitudinal and transverse Charpy V-notch impact-test specimens were machined from the midthickness of each quenched and tempered plate. The tension-test specimens were tested at room temperature, and the impact-test specimens were tested at +80 F and -80 F.

Statistical Design

The central composite rotatable second-order statistically designed program, described in Appendix B, was selected as the experimental design for the investigation so that the main effects and second-order interactions of the elements (C, P, S, and Ni) on the tensile and the Charpy V-notch impact properties of a Ni-Cr-Mo type steel could be evaluated. The effects of other elements (Mn, Si, Cr, Mo, Al, and N) on these properties had been evaluated in an earlier study.[2]

Results and Discussion

Tensile Properties

The longitudinal and transverse tensile properties of the heat-treated plates of the experimental steels are shown in Tables III and IV.

The tensile strengths—when grouped by the carbon content ranges 0.10 to 0.13, 0.14 to 0.17, and 0.18 to 0.20 percent—were 165 to 175, 170 to 176, and 177 to 184 ksi, respectively, for longitudinally oriented specimens, and 165 to 170, 171 to 179, and 175 to 184 ksi for transversely oriented specimens. The yield strengths (0.2% offset) for the aforementioned carbon ranges were 152 to 156, 155 to 161, and 159 to 165 ksi for longitudinally oriented specimens, and 151 to 157, 151 to 161, and 159 to 167 ksi for transversely oriented specimens.

For the entire carbon-content range, the experimental steels exhibited elongation values of 17.0 to 20.0 percent and reduction-of-area values of 53.0 to 68.1 percent in the longitudinal direction, and values of 16.5 to 21.0 percent elongation and 59.9 and 68.9 percent reduction of area in the transverse direction.* These data indicate that all the steels studied achieved, in 1/2-inch-thick, cross-rolled, quenched and tempered plate, the minimum tensile-property requirements for an HY-150 type steel and that no large differences between longitudinal and transverse tensile properties existed.

Charpy V-Notch Impact Properties

The longitudinal and transverse Charpy V-notch impact properties (at test temperatures of +80 F and -80 F) for the cross-rolled, 1/2-inch-

*Transverse ductility is slightly higher than longitudinal ductility because the 1/2-inch-thick plate received more work in the transverse direction than in the longitudinal direction.

thick, quenched and tempered plates are shown in Tables III and IV.

Steels C, E, and T exhibited the best energy-absorption values for transversely oriented specimens tested at -80 F (values of 57, 57, and 58 ft-lb, respectively). These three steels were low in sulfur (0.004 to 0.006%) and relatively high in nickel (6.42 to 7.66%). The other low-sulfur steel studied (Steel JJ) contained a considerably lower nickel content (5.20%), and although its transverse impact-test shelf-energy value was high at the +80 F test temperature, the transverse energy absorption at -80 F was low (63 and 35 ft-lb, respectively).

Longitudinally and transversely oriented specimens of all the steels exhibited 100 percent Charpy V-notch shear-fracture appearance at a test temperature of +80 F except for Steel Z, which exhibited 95 percent shear-fracture appearance. Steel Z had the lowest nickel content of any of the steels studied. At a test temperature of -80 F, it was observed that the Charpy V-notch shear-fracture appearance decreased from 100 to 35 percent as the nickel content of the steels decreased.

Equations for Predicting the Mechanical Properties of a Ni-Cr-Mo Type Steel

Shown in Table V are equations statistically relating the composition to the room-temperature tensile properties and to the Charpy V-notch impact properties at test temperatures of +80 F and -80 F for the

31 steels investigated. The equations permit an approximation* of the longitudinal and transverse mechanical properties of 1/2-inch-thick cross-rolled plate from Laboratory-melted Ni-Cr-Mo type steel water-quenched and tempered at 1025 F.

Examination of the equations reveals that in the ranges studied, phosphorus content had no effect on the tensile and impact properties. Yield strength, tensile strength, and elongation were influenced by carbon content alone, reduction of area by carbon and sulfur content, and impact properties by carbon, sulfur, and nickel content with the exception of shear-fracture appearance, which depended only on nickel content.

Tensile Properties - Equations 1 through 4, Table V, present the relations between the longitudinal room-temperature tensile properties and the chemical composition. Equations 10 through 13 give the transverse room-temperature tensile properties and are generally similar to the equations for predicting the longitudinal tensile properties. Figure 1 graphically represents the aforementioned transverse equations**

---

*Valid only for the composition ranges studied, Table I.

**Transverse properties are presented in the examples because the 1/2-inch-thick plate received more work in the transverse direction than in the longitudinal direction, and thus, the transverse properties are slightly superior to the longitudinal properties.

for the composition levels studied. The relations shown in the figures were calculated from the equations by using the average value of the factors for the element involved.

The equations and figures illustrate the sensitivity of the tensile properties of the steels studied to variations in chemical composition. For example, Equations 10 through 12 and Figure 1A indicate that an increase in carbon content from 0.10 to 0.20 percent will result in an increase in transverse yield strength of 14,000 psi (from 151 ksi to 165 ksi), an increase in transverse tensile strength of 17,000 psi (from 165 ksi to 182 ksi), and a decrease in transverse elongation from 19 to 17 percent. Equation 13 and Figure 1B show that a simultaneous decrease in the carbon content from 0.20 to 0.10 percent and in the sulfur content from 0.010 to 0.005 percent will result in an increase in transverse reduction of area from 62.4 to 68.8 percent. Examination of Equations 1 through 4 shows that the longitudinal tensile properties are influenced by chemical composition in a manner similar to the transverse tensile properties. Longitudinal yield strength, tensile strength, and elongation appear to be somewhat less sensitive to variations in the carbon content of the steel than the corresponding transverse properties. Longitudinal reduction of area is considerably more sensitive to variations in sulfur content than transverse reduction of area.

Charpy V-Notch Impact Properties - Equations 14 through 18 show the effect of the elements studied on the transverse Charpy V-notch impact properties of the steels at +80 F and -80 F, and Figure 2 graphically represents Equations 14 and 15. As in Figure 1, the relations shown in Figure 2 are calculated from the appropriate equations (Equations 14 and 15) by using the average values of the factors for the elements involved. Equations 5 through 9 show the effect of the elements studied on the longitudinal Charpy V-notch impact properties at test temperatures of +80 F and -80 F, and are generally similar to the equations for predicting the transverse Charpy V-notch properties. The equations for longitudinal and transverse impact properties indicate that the energy absorption and lateral expansion at +80 F and -80 F of Laboratory heats of Ni-Cr-Mo type steels depend only on the carbon, sulfur, and nickel contents, whereas the shear-fracture appearance at a test temperature of -80 F depends only on the nickel content.

Careful comparison of equations for longitudinal Charpy V-notch energy absorption at +80 F and -80 F (Equations 5 and 6) with the corresponding equations for transverse Charpy V-notch energy absorption (Equations 14 and 15) shows that, although the average longitudinal impact energies were about 8 ft-lb lower than the average transverse impact energies, the variations in the elements carbon and sulfur have about the same or slightly less influence on the longitudinal impact energies than on the transverse impact energies. These results were particularly surprising when compared with the previously discussed results which indicated that an increase in sulfur content caused a considerably larger decrease in longitudinal reduction of area than in transverse reduction of area. It is also important to note that increasing the nickel content lowers the impact energy at +80 F (shelf energy) but raises the impact energy at -80 F; that is, nickel lowers the transition temperature of the steel.

Use of these equations in the following example illustrates the effect of variations in the applicable elements on the Charpy V-notch impact properties of Laboratory Ni-Cr-Mo type steels. Equations 14 through 18 predict that at a nickel content of 4 percent, a decrease in carbon content from 0.20 to 0.10 percent and a decrease in sulfur content from 0.010 to 0.005 percent would result in the following changes in transverse Charpy V-notch impact properties at test temperatures of +80 F and -80 F:

1. Energy absorption at +80 F would <u>increase</u> 27 ft-lb (from 41 to 68 ft-lb).

2. Energy absorption at -80 F would <u>increase</u> 20 ft-lb (from 24 to 44 ft-lb).

3. Lateral expansion at +80 F would <u>increase</u> 20 mils (from 27 to 47 mils).

4. Lateral expansion at -80 F would <u>increase</u> 12 mils (from 14 to 26 mils).

5. The change in shear-fracture appearance was independent of the carbon and sulfur contents.

If the nickel content were increased from 4 to 8 percent while the carbon and sulfur contents were maintained constant (0.10 and 0.005%, respectively), transverse Charpy V-notch impact properties of the Laboratory steels would be predicted to change as follows:

1. Energy absorption at +80 F would <u>decrease</u> 5 ft-lb (from 68 to 63), and energy absorption at -80 F would <u>increase</u> 12 ft-lb (from 44 to 56).

2. Lateral expansion at +80 F would <u>decrease</u> 4 mils (from 48 to 44), and lateral expansion at -80 F would <u>increase</u> 7 mils (from 26 to 33).

3. Shear-fracture appearance at -80 F would <u>increase</u> from 44 to 98 percent.

The effect of carbon content on notch toughness is not clearly defined in this study because a decrease in carbon content causes a decrease in the yield strength at the same time that it causes an increase in the Charpy V-notch impact energy, and thus the effect of carbon on the notch toughness at a given yield strength cannot be determined. However, when steels with different carbon contents are compared at the same yield strength, the steel with the lower carbon content would be expected to be somewhat tougher, if similar quenched microstructure were obtained, because it would contain a smaller percentage of brittle carbide phase.

Thus, it is concluded that to obtain the best impact properties in a Laboratory Ni-Cr-Mo type steel, cross-rolled, quenched, and tempered at 1025 F, the carbon content should probably be kept as low as possible consistent with the required strength level, the sulfur content as low as possible, and the nickel content at an optimum level consistent with economic factors, necessary impact properties (particularly, fracture-appearance transition temperature), and weldability.

Summary

The results of the present investigation may be summarized as follows:

1. On the basis of a statistically designed study of cross-rolled plates from 31 Laboratory induction-furnace heats, equations were developed that predict the effects of variations in carbon, phosphorus, sulfur, and nickel content on the longitudinal and transverse room-temperature tensile properties and on the Charpy V-notch impact properties (at test temperatures of +80 F and -80 F) of quenched and tempered Ni-Cr-Mo type steels.

2. The equations predict (a) that an increase in carbon content from 0.10 to 0.20 percent would cause an increase in transverse yield strength of about 14,000 psi, a slight decrease in transverse elongation and reduction of area, and a decrease in transverse Charpy V-notch energy absorption at +80 F of about 17 ft-lb; (b) that an increase in sulfur from 0.005 to 0.010 percent would cause a decrease in reduction of area of transversely oriented specimens (about 2%), a larger decrease in reduction of area of longitudinally oriented specimens (about 3%), and a decrease in transverse Charpy V-notch energy absorption at +80 F of about 10 ft-lb; and (c) that an increase in nickel content from 4.0 to 8.0 percent would decrease the Charpy V-notch energy absorption at +80 F about 5 ft-lb and lower the transition temperature (increase the energy absorption 10 ft-lb and the shear-fracture appearance from about 44 to 98 percent at -80 F) for transversely oriented specimens.

3. All the steels exhibited essentially 100 percent Charpy V-notch shear-fracture appearance at a test temperature of +80 F. At -80 F, the shear-fracture appearance varied directly with the nickel content of the steels.

4. The equations also predict that variations in carbon content do not significantly influence Charpy V-notch shear-fracture appearance; that variations in sulfur content do not significantly

influence yield and tensile strength, percent elongation, or Charpy V-notch shear-fracture appearance; that variations in nickel content do not influence tensile properties; and that variations in phosphorus content have no influence on tensile or impact properties.

Recommendations and Future Work

Studies are in progress at the Applied Research Laboratory to provide additional background information considered necessary to develop a base-metal composition with the toughness, hardenability, temperability, and weldability required to produce satisfactory submarine-hull steel weldments with a yield strength of 130,000 to 150,000 psi. The results of the present investigation indicate that, in future studies of composition,

1. The carbon content should probably be kept as low as possible, consistent with the required strength level and hardenability, to provide optimum toughness and weldability.

2. The sulfur content should be kept as low as possible.

3. Phosphorus contents below 0.020 percent should be satisfactory.

4. One of the considerations for establishing the optimum nickel content should be the effect of variations in nickel content on the Charpy V-notch shelf energy and transition temperature.

References

1. Washington Summary, U. S. Steel Corporation, "Tougher Steels Sought for Submarines," October 23, 1962. (Originally published in Commerce Business Daily, October 1, 1962.)

2. J. V. Alger, R. M. Brown, S. J. Manganello, W. J. Murphy, and L. F. Porter, "Development of a 7½Ni-Cr-Mo Steel for Submarine-Hull Applications," Applied Research Laboratory Progress Report, Project (40.02-058)(5), December 28, 1962.

APPENDICES

A - Melting Procedure

B - Experimental Design and Statistical Analysis

Appendix A

Melting Procedure

Melting control was maintained in the present work by adhering to the following conditions:

1. The materials used were from single lots.

2. The electrolytic iron was melted under an argon shield to maintain a low nitrogen content.

3. At "melt-in" the argon shield was removed, excessive increases in bath temperatures were avoided, and the excess slag was removed.

4. The heats were deoxidized with 0.22 weight percent of 95 percent ferrosilicon.

5. The alloying additions were made in the following order: ferrophosphorus, ferrosulfide, electrolytic chromium, electrolytic nickel, pure molybdenum, electrolytic manganese, and ferrosilicon. Each alloy addition was stirred into the bath before the next addition was made.

6. The slag was removed and the carbon addition for alloy content was made.

Appendix A (Continued)

7. Pure aluminum shot was added, and the heat was then teemed into a 100-pound, 3- by 8- by 14-inch slab-ingot mold with a refractory hot top. An exothermic material was then added to the hot top.

Appendix B

Experimental Design and Statistical Analysis

As explained in the Introduction, the purpose of the experimental work was to investigate the effect of certain changes in chemical composition on the mechanical properties of Laboratory-melted Ni-Cr-Mo steels. On the basis of previous experimental evidence, it was believed that the elements to be varied and the composition levels of interest were those given in Table I of the body of this report. It was further believed that the mechanical properties of these steels were related to the elements investigated by second-order equations. Thus, after a thorough consideration of all the known types of experiment plans, a central composite rotatable second-order design was selected as the one best suited to the purpose. When four elements are to be investigated, this type of design consists of the following:

1. Sixteen heats, comprising a 2^4 factorial.
2. Eight star-point heats.
3. Seven center-point heats.

The design composition of the necessary 31 heats is given in Table B-1.

After the experimental work was completed, a number of second-order equations were fitted to the data. Each equation expressed one mechanical property as a function of the four elements investigated. (Since the ladle-analysis values were often substantially different from

Appendix B (Continued)

the aim values, regression analysis, not analysis of variance, was used to obtain these equations.) After dropping out the terms judged to be insignificant, the resulting equations are those tabulated in Table V of the body of this report. Also computed were 95 percent confidence limits on each regression coefficient, and these are also given in Table V.

Table B-1

Design Composition of the Heats—Percent
(Central Composite Rotatable Second-Order Design)

Heat	C	P	S	Ni	
1	0.12	0.006	0.006	5.2	
2	0.18	0.006	0.006	5.2	
3	0.12	0.014	0.006	5.2	
4	0.18	0.014	0.006	5.2	
5	0.12	0.006	0.014	5.2	
6	0.18	0.006	0.014	5.2	
7	0.12	0.014	0.014	5.2	
8	0.18	0.014	0.014	5.2	2^4 factorial
9	0.12	0.006	0.006	7.6	
10	0.18	0.006	0.006	7.6	
11	0.12	0.014	0.006	7.6	
12	0.18	0.014	0.006	7.6	
13	0.12	0.006	0.014	7.6	
14	0.18	0.006	0.014	7.6	
15	0.12	0.014	0.014	7.6	
16	0.18	0.014	0.014	7.6	
17	0.09	0.010	0.010	6.4	
18	0.21	0.010	0.010	6.4	
19	0.15	0.002	0.010	6.4	
20	0.15	0.018	0.010	6.4	star points
21	0.15	0.010	0.002	6.4	
22	0.15	0.010	0.018	6.4	
23	0.15	0.010	0.010	4.0	
24	0.15	0.010	0.010	8.8	
25	0.15	0.010	0.010	6.4	
26	0.15	0.010	0.010	6.4	
27	0.15	0.010	0.010	6.4	center points
28	0.15	0.010	0.010	6.4	
29	0.15	0.010	0.010	6.4	
30	0.15	0.010	0.010	6.4	
31	0.15	0.010	0.010	6.4	

NOTE: For the aim levels of the other elements (held as constant as possible), see Table I in the body of the report.

Table I

Nominal Composition Levels Investigated—Percent

C	P	S	Ni
0.09	0.002	0.002	4.0
0.12	0.006	0.006	5.2
0.15	0.010	0.010	6.4
0.18	0.014	0.014	7.6
0.21	0.018	0.018	8.8

NOTE: The following elements were held constant within the indicated composition range:

Mn	Si	Cr	Mo	Al*	N
0.22/0.25	0.19/0.25	0.77/0.80	0.97/1.00	0.025/0.040	0.004/0.009

*Acid soluble.

Table II

Chemical Composition of the Steels Investigated-Percent
(Check Analyses)

Steel	Heat No.*	C	Mn	P	S	Si	Ni	Cr	Mo	V	Al**	N
A	N7274	0.16	0.25	0.009	0.008	0.22	6.38	0.77	0.99	<0.005	0.030	0.007
B	N7289	0.16	0.24	0.010	0.009	0.22	6.43	0.78	0.99	<0.005	0.027	0.008
C	N7290	0.11	0.24	0.015	0.006	0.22	7.55	0.78	0.98	<0.005	0.028	0.008
D	N7291	0.15	0.24	0.005	0.009	0.21	6.35	0.78	0.98	<0.005	0.028	0.006
E	N7292	0.12	0.23	0.008	0.006	0.21	7.66	0.78	1.00	<0.005	0.031	0.008
H	N7293	0.18	0.23	0.017	0.007	0.19	5.12	0.78	0.99	<0.005	0.027	0.009
J	N7294	0.17	0.23	0.007	0.007	0.21	5.08	0.77	0.97	<0.005	0.025	0.009
K	N7295	0.16	0.23	0.009	0.016	0.21	6.37	0.78	0.99	<0.005	0.031	0.008
L	N7296	0.19	0.24	0.009	0.009	0.24	6.42	0.80	0.99	<0.005	0.032	0.008
M	N7297	0.15	0.23	0.011	0.009	0.23	6.38	0.78	0.98	<0.005	0.032	0.009
N	N7298	0.18	0.24	0.007	0.006	0.21	7.63	0.79	0.99	<0.005	0.039	0.009
P	N7299	0.16	0.23	0.007	0.008	0.23	6.40	0.78	1.00	<0.005	0.040	0.007
S	N7300	0.16	0.22	0.009	0.009	0.25	6.40	0.77	0.98	<0.005	0.038	0.007
T	N7301	0.16	0.23	0.009	0.004	0.22	6.42	0.78	0.98	<0.005	0.036	0.008
U	N7302	0.12	0.23	0.005	0.014	0.23	5.07	0.77	0.97	<0.005	0.037	0.007
W	N7303	0.19	0.24	0.013	0.007	0.22	7.67	0.78	0.98	<0.005	0.040	0.006
X	N7304	0.12	0.24	0.005	0.007	0.23	5.07	0.78	0.98	<0.005	0.038	0.006
Y	N7305	0.14	0.24	0.007	0.014	0.22	7.53	0.78	0.99	<0.005	0.038	0.006
Z	N7306	0.16	0.23	0.012	0.010	0.21	3.93	0.77	0.98	<0.005	0.037	0.007
AA	N7307	0.13	0.24	0.011	0.012	0.22	5.02	0.78	0.97	<0.005	0.030	0.008
BB	N7308	0.20	0.24	0.006	0.014	0.22	5.15	0.77	0.98	<0.005	0.027	0.008
CC	N7309	0.19	0.24	0.004	0.011	0.21	7.50	0.78	0.99	<0.005	0.032	0.007
DD	N7310	0.17	0.24	0.007	0.007	0.22	6.38	0.78	0.98	<0.005	0.028	0.008
EE	N7311	0.10	0.24	0.007	0.008	0.25	6.49	0.78	0.99	<0.005	0.030	0.008
HH	N7312	0.20	0.24	0.012	0.015	0.22	7.72	0.77	0.99	<0.005	0.030	0.006
JJ	N7313	0.14	0.23	0.012	0.005	0.22	5.20	0.77	0.98	<0.005	0.030	0.004
KK	N7314	0.17	0.23	0.018	0.008	0.22	6.40	0.78	0.99	<0.005	0.030	0.005
LL	N7315	0.14	0.23	0.012	0.014	0.24	7.72	0.80	0.99	<0.005	0.029	0.006
MM	N7316	0.17	0.23	0.009	0.010	0.22	8.83	0.79	0.99	<0.005	0.032	0.007
NN	N7317	0.17	0.23	0.008	0.009	0.23	6.46	0.79	0.99	<0.005	0.029	0.008
PP	N7318	0.18	0.24	0.011	0.013	0.24	5.15	0.78	0.98	<0.005	0.030	0.008

* 100-pound Laboratory air-induction-melted heats.
** Acid soluble.

(40.18-001)(2)

Table III

Longitudinal Mechanical Properties of the Steels Investigated*

	Tensile Properties**				Charpy V-Notch Impact Properties***					
	Yield Strength (0.2% Offset), ksi	Tensile Strength, ksi	Elongation in 1 Inch, %	Reduction of Area, %	Energy Absorbed, ft-lb		Shear Fracture, %		Lateral Expansion, mils	
Steel					+80 F	-80 F	+80 F	-80 F	+80 F	-80 F
A	158	174	17.5	63.6	39	33	100	90	28	21
B	161	175	18.0	63.1	41	35	100	93	28	21
C	153	173	20.0	68.0	52	49	100	98	37	30
D	156	174	17.5	64.2	44	38	100	80	29	23
E	153	170	18.0	68.1	57	48	100	95	38	29
H	163	179	17.5	64.4	45	31	100	60	31	19
J	163	177	20.0	65.2	43	35	100	65	30	23
K	159	176	18.0	58.4	28	26	100	65	19	16
L	165	184	17.0	59.8	34	28	100	85	22	17
M	158	174	18.5	62.1	40	31	100	65	27	19
N	161	181	18.5	61.8	43	34	100	80	28	21
P	158	175	19.5	63.2	43	35	100	75	29	22
S	159	175	17.5	64.1	45	38	100	80	30	24
T	157	172	19.0	66.6	57	49	100	90	41	30
U	153	167	18.0	64.1	40	22	100	40	28	17
W	160	180	18.0	62.8	42	36	100	95	28	21
X	156	169	17.5	66.0	62	38	100	50	42	25
Y	155	171	17.5	61.6	38	35	100	85	26	23
Z	159	171	18.0	63.8	48	23	95	35	32	15

(Continued)

Table III (Continued)

Longitudinal Mechanical Properties of the Steels Investigated*

Steel	Tensile Properties** Yield Strength (0.2% Offset), ksi	Tensile Strength, ksi	Elongation in 1 Inch, %	Reduction of Area, %	Charpy V-Notch Impact Properties*** Energy Absorbed, ft-lb +80 F	Energy Absorbed, ft-lb -80 F	Shear Fracture, % +80 F	Shear Fracture, % -80 F	Lateral Expansion, mils +80 F	Lateral Expansion, mils -80 F
AA	156	170	18.5	64.0	40	27	100	45	29	18
BB	166	180	18.0	61.6	32	26	100	55	22	17
CC	161	181	17.0	59.3	27	25	100	90	19	16
DD	159	175	18.0	63.8	37	34	100	75	24	21
EE	152	165	18.5	61.3	45	33	100	60	32	22
HH	159	178	16.5	53.0	27	25	100	85	20	16
JJ	151	166	18.5	66.6	59	32	100	55	41	23
KK	158	174	18.0	64.2	40	33	100	70	27	20
LL	155	170	19.0	63.0	33	30	100	85	22	19
MM	159	179	18.0	64.1	38	35	100	95	25	21
NN	162	179	17.0	63.7	43	36	100	80	29	23
PP	165	180	18.0	62.4	33	25	100	65	22	17

* One-half-inch-thick plates cross-rolled (longitudinal to transverse rolling ratio of 1½ to 1), austenitized for 1 hour at 1475 F, water-quenched, tempered for 1 hour at 1025 F, and water-quenched.

** Average of duplicate tension tests with 0.252-inch-diameter specimens.

*** Average of triplicate Charpy V-notch impact tests.

Table IV

Transverse Mechanical Properties of the Steels Investigated*

	Tensile Properties**				Charpy V-Notch Impact Properties***					
					Energy Absorbed, ft-lb		Shear Fracture, %		Lateral Expansion, mils	
Steel	Yield Strength (0.2% Offset), ksi	Tensile Strength, ksi	Elongation in 1 Inch, %	Reduction of Area, %	+80 F	-80 F	+80 F	-80 F	+80 F	-80 F
A	162	179	18.5	64.6	43	38	100	80	29	22
B	161	175	19.0	63.9	46	39	100	95	31	23
C	153	168	19.0	68.5	63	57	100	98	42	34
D	158	174	17.5	62.7	46	39	100	93	31	22
E	152	170	21.0	68.9	61	57	100	98	40	34
H	165	179	18.0	64.3	47	34	100	60	31	20
J	164	178	17.5	64.2	53	40	100	70	34	23
K	161	176	17.5	59.9	33	26	100	65	21	17
L	167	184	16.5	61.8	38	30	100	90	24	19
M	159	174	18.5	64.4	46	37	100	80	29	22
N	163	181	19.0	64.2	44	38	100	85	29	23
P	159	176	19.0	64.6	46	39	100	80	29	23
S	159	175	17.0	63.1	45	38	100	80	28	21
T	159	175	19.0	67.0	66	58	100	90	45	32
U	154	168	18.0	63.6	42	28	100	45	30	18
W	160	180	17.5	64.4	46	41	100	95	30	23
X	157	170	19.0	65.6	68	47	100	65	46	28
Y	154	171	19.5	65.6	41	36	100	90	28	22
Z	159	171	18.0	64.7	51	23	95	35	33	14

(Continued)

Table IV (Continued)

Transverse Mechanical Properties of the Steels Investigated*

Steel	Tensile Properties** Yield Strength (0.2% Offset), ksi	Tensile Strength, ksi	Elongation in 1 Inch, %	Reduction of Area, %	Charpy V-Notch Impact Properties*** Energy Absorbed, ft-lb +80 F	Energy Absorbed, ft-lb -80 F	Shear Fracture, % +80 F	Shear Fracture, % -80 F	Lateral Expansion, mils +80 F	Lateral Expansion, mils -80 F
AA	157	170	17.5	63.9	43	28	100	40	30	18
BB	167	179	18.5	62.7	36	29	100	60	23	17
CC	162	182	18.5	60.6	31	27	100	80	20	17
DD	161	176	17.0	62.4	44	31	100	65	29	19
EE	151	165	19.0	65.6	53	39	100	65	37	25
HH	160	179	17.5	60.2	34	31	100	100	24	20
JJ	151	166	19.5	66.2	63	35	100	45	45	22
KK	159	175	18.0	65.4	43	41	100	80	29	23
LL	157	171	19.0	64.9	40	36	100	95	27	23
MM	159	179	17.5	62.8	41	36	100	90	25	21
NN	163	179	17.5	64.2	45	37	100	80	31	23
PP	167	182	18.0	60.4	36	26	100	65	23	17

* One-half-inch-thick plates cross-rolled (longitudinal to transverse rolling ratio of 1½ to 1), austenitized for 1 hour at 1475 F, water-quenched, tempered for 1 hour at 1025 F, and water-quenched.

** Average of duplicate tension tests with 0.252-inch-diameter specimens.

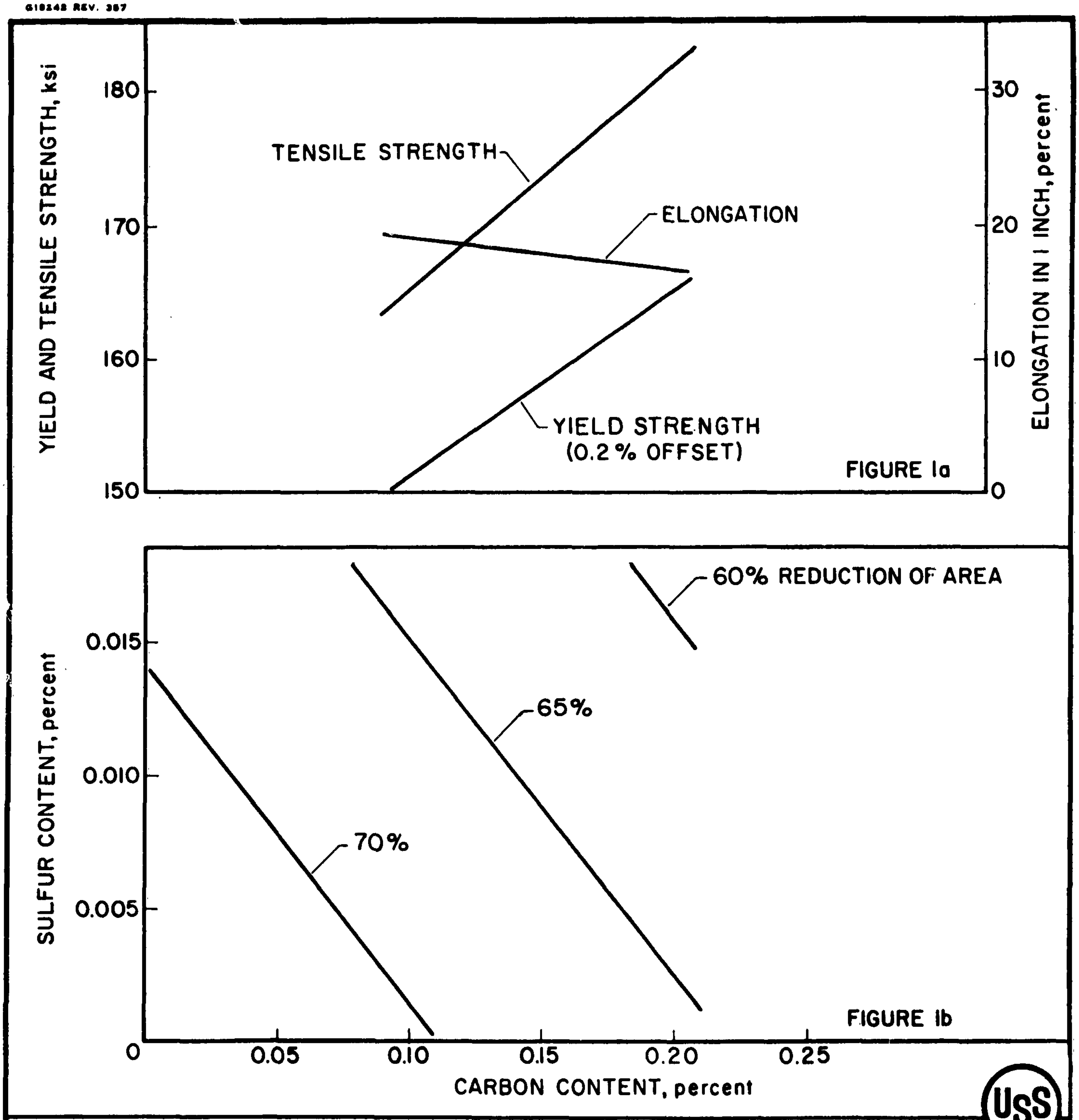
*** Average of triplicate Charpy V-notch impact tests.

Table V

Equations for Predicting the Effect of Composition on the Mechanical Properties of Laboratory Ni-Cr-Mo Steels*

Longitudinal Properties		Transverse Properties	
Yield Strength in ksi			
1)	$139 + \left[(126 \pm 30) \times \%C\right]$	10)	$137 + \left[(141 \pm 35) \times \%C\right]$
Tensile Strength in ksi			
2)	$159 + \left[(107 \pm 79) \times \%C\right]$	11)	$148 + \left[(169 \pm 32) \times \%C\right]$
Elongation in Percent			
3)	$20 - \left[(12 \pm 11) \times \%C\right]$	12)	$21 - \left[(18 \pm 12) \times \%C\right]$
Reduction of Area in Percent			
4)	$76 - \left[(47 \pm 28) \times \%C\right] - \left[(533 \pm 229) \times \%S\right]$	13)	$75 - \left[(45 \pm 18) \times \%C\right] - \left[(363 \pm 150) \times \%S\right]$
Charpy V-Notch Energy Absorption at +80 F in ft-lb			
5)	$93 - \left[(144 \pm 61) \times \%C\right] - \left[(1911 \pm 502) \times \%S\right] - \left[(1.62 \pm 1.41) \times \%Ni\right]$	14)	$100 - \left[(168 \pm 65) \times \%C\right] - \left[(2033 \pm 535) \times \%S\right] - \left[(1.34 \pm 1.51) \times \%Ni\right]$
Charpy V-Notch Energy Absorption at -80 F in ft-lb			
6)	$43 - \left[(76 \pm 58) \times \%C\right] - \left[(1404 \pm 478) \times \%S\right] + \left[(2.44 \pm 1.35) \times \%Ni\right]$	15)	$52 - \left[(116 \pm 75) \times \%C\right] - \left[(1671 \pm 622) \times \%S\right] + \left[(2.91 \pm 1.75) \times \%Ni\right]$
Charpy V-Notch Lateral Expansion at +80 F in mils			
7)	$65 - \left[(108 \pm 43) \times \%C\right] - \left[(1284 \pm 351) \times \%S\right] - \left[(1.21 \pm 0.99) \times \%Ni\right]$	16)	$71 - \left[(132 \pm 48) \times \%C\right] - \left[(1338 \pm 400) \times \%S\right] - \left[(1.06 \pm 1.13) \times \%Ni\right]$
Charpy V-Notch Lateral Expansion at -80 F in mils			
8)	$31 - \left[(62 \pm 33) \times \%C\right] - \left[(765 \pm 275) \times \%S\right] + \left[(1.01 \pm 0.77) \times \%Ni\right]$	17)	$31 - \left[(80 \pm 39) \times \%C\right] - \left[(794 \pm 320) \times \%S\right] + \left[(1.70 \pm 0.90) \times \%Ni\right]$
Charpy V-Notch Shear-Fracture Appearance at -80 F in Percent			
9)	$-11 + \left[(13.34 \pm 3.14) \times \%Ni\right]$	18)	$-10 + \left[(13.46 \pm 3.43) \times \%Ni\right]$

*One-half-inch-thick plates cross-rolled (longitudinal to transverse rolling ratio of 1 1/2 to 1), austenitized for 1 hour at 1475 F, water-quenched, tempered for 1 hour at 1025 F, and water-quenched.

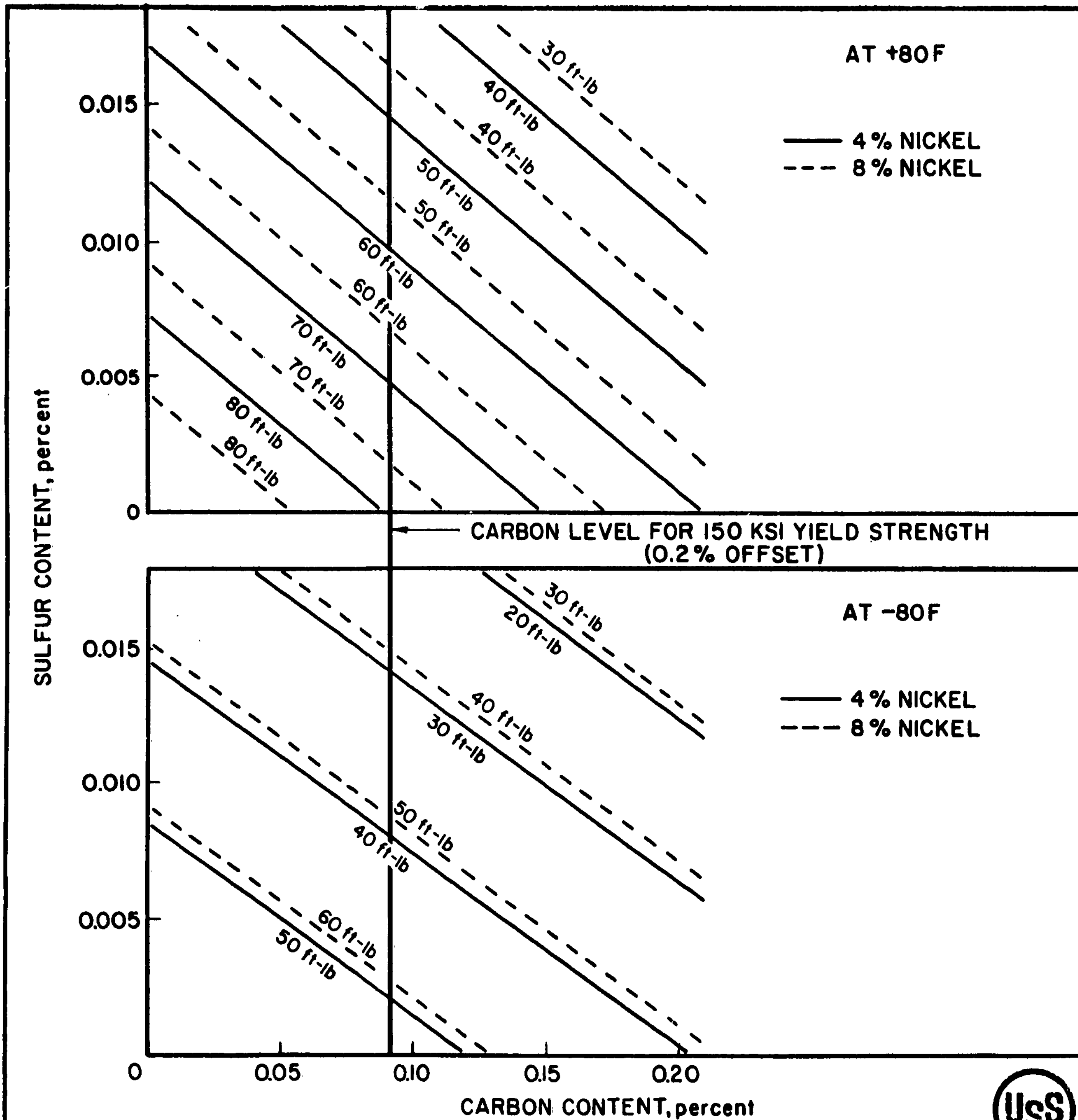


PREDICTED EFFECT OF CARBON AND SULFUR ON TRANSVERSE TENSILE PROPERTIES OF LABORATORY-MELTED Ni-Cr-Mo STEELS WATER-QUENCHED AND TEMPERED AT 1025 F

DRAWN BY K.V.S.	CHK'D BY D.S.D.	APPROVED BY J.H.G.	UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA.	FIGURE NO. 1
DRAWING No. ARL 18-52		PROJECT No. 40.18-001 (2)		
		DATE 5-28-63		

1025 CLEARPRINT PPL. CO. PGH. PA.

G-18242 REV. 357



PREDICTED EFFECT OF CARBON, SULFUR, AND NICKEL ON TRANSVERSE CHARPY V-NOTCH ENERGY ABSORPTION OF LABORATORY-MELTED Ni-Cr-Mo STEELS WATER QUENCHED AND TEMPERED AT 1025 F

DRAWN BY K.V.S.	CHK'D BY D.S.D.	APPROVED BY J.H.G.	UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA.	FIGURE NO. 2
DRAWING No. ARL 18-53		PROJECT No. 40.18-001(2) DATE 5-28-63		

1025 CLEARPRINT PPL. CO. PGH. PA.