

UNCLASSIFIED

AD **4 5 63 2 2**

DEFENSE DOCUMENTATION CENTER

FOR

SCIENTIFIC AND TECHNICAL INFORMATION

CAMERON STATION ALEXANDRIA, VIRGINIA



UNCLASSIFIED

NOTICE: When government or other drawings, specifications or other data are used for any purpose other than in connection with a definitely related government procurement operation, the U. S. Government thereby incurs no responsibility, nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use or sell any patented invention that may in any way be related thereto.

CATALOGED BY DDC

AS AD No. 45632

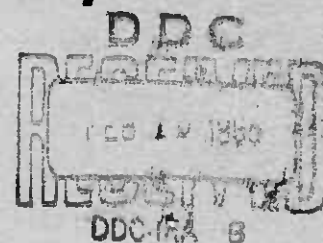
4 5 6 3 2 2



Technical Report

Effect of Tempering and Stress-Relieving
Treatments on the Mechanical Properties
of HY-80 and 5Ni-Cr-Mo-V
Production Steels

Applied Research Laboratory
United States Steel
Monroeville, Pennsylvania



December 1, 1964 Project No. 40.018-001(35)

NObs-88540 SR007-01-01 Task 853 S-11104-4

U. S. GOVERNMENT AGENCIES MAY OBTAIN
COPIES OF THIS REPORT DIRECTLY FROM DDC.
OTHER QUALIFIED DDC USERS SHALL REQUEST
THROUGH CHIEF, BUREAU OF SHIPS (CODE 210L)

EFFECT OF TEMPERING AND STRESS-RELIEVING TREATMENTS ON THE MECHANICAL
PROPERTIES OF HY-80 AND 5NI-CR-MO-V PRODUCTION STEELS

(40.018-001) (35) (a-ORD-NP-3) (S-11104-4)

By S. J. Manganello, L. F. Porter, J. P. Paulina, and R. J. Sitko

Approved by J. H. Gross, Division Chief

Abstract

Although most plates for submarine hulls are not normally stress-relieved, highly deformed hull plates are stress-relieved and plates for other applications may require stress relieving. Therefore, a study was initiated to determine the effect of stress relieving for times up to 125 hours in the temperature range 950 to 1050 F on the properties of quenched and tempered plates of the 5Ni-Cr-Mo-V experimental HY-130/150 steel. In addition, the effect of tempering for similar times and temperatures on the properties of quenched plates was determined. For comparison, similar studies were conducted on an open-hearth and on an electric-furnace HY-80 steel.

The tempering study showed that the 5Ni-Cr-Mo-V steel was more resistant to softening during long-time tempering than the HY-80 steels and that its Charpy V-notch energy absorption in the yield-strength range 130 to 150 ksi was higher than those of the HY-80 steels. However, the 5Ni-Cr-Mo-V steel was more susceptible to temper embrittlement than the HY-80 steels.

The stress-relieving study showed that the yield strength of quenched and tempered HY-80 steels (about 90 ksi) was not significantly changed by stress relieving the steels for times up to 125 hours at temperatures of 950 to 1050 F. The yield strength of quenched and tempered 5Ni-Cr-Mo-V steel (about 145 ksi) was not significantly affected by similar stress-relieving treatments except that stress relieving at the highest temperature (1050 F) and longest time (125 hours) did lower the yield strength about 25 ksi.

The transition temperature of the HY-80 and the 5Ni-Cr-Mo-V steels was raised by the stress-relieving treatments, particularly by the 125-hour treatment followed by slow cooling. However, the transition temperature of the HY-80 steels was not raised enough to affect the energy absorption at 0 F, whereas the transition temperature of the 5Ni-Cr-Mo-V steel was raised enough to lower the energy absorption at 0 F.

The stress-relief embrittlement of the 5Ni-Cr-Mo-V steel does not appear to be a serious problem except in very heavy plates that would be stress-relieved many times, a practice that is not common. Studies are now in progress to determine whether minor composition changes can reduce the susceptibility of the 5Ni-Cr-Mo-V steel to temper embrittlement.

Introduction

Recent Applied Research Laboratory studies^{1,2)*} have indicated that a 5Ni-Cr-Mo-V steel, in 1/2- through 4-inch-thick plates, is promising as an HY-130/150 submarine-hull steel. Although submarine hulls are not stress-relieved, highly deformed subassemblies may be stress-relieved and other hull applications may require stress relieving. Therefore, a study was initiated to determine the effects of stress relieving for times up to 125 hours in the temperature range 950 to 1050 F on the mechanical properties of water-quenched and blower-cooled 1/2-inch-thick plates** of an electric-furnace heat of the 5Ni-Cr-Mo-V steel. For comparison, a similar study was conducted on 1/2-inch-thick plates of both open-hearth (0.18% C) and electric-furnace (0.14% C) HY-80 steel. Simultaneously, studies were conducted on the effect of long-time tempering treatments on the properties of the three steels. The present report describes the results of these studies.

Materials and Experimental Work

Cross-rolled 1/2-inch-thick plates of three production steels of the compositions shown in Table I were evaluated. Steel A is an open-hearth HY-80 steel, Steel B, an electric-furnace HY-80 steel, and Steel C, an electric-furnace 5Ni-Cr-Mo-V steel. Parent plates of each steel were sectioned into 5- by 8-inch plate samples (up to 38 plate samples per steel) for heat-treatment studies.

*See References.

**Blower cooling 1/2-inch-thick plates simulates water quenching 4-inch-thick plates.

Tempering Studies

To determine the effect of tempering variables on the three steels, twelve 1/2-inch-thick plate samples of each steel were austenitized for 2 hours at 1650 F (Steels A and B) or at 1500 F (Steel C) and blower-cooled to simulate the cooling rate at the midthickness of a water-quenched 4-inch-thick plate.³⁾ Individual plate samples were then tempered for 5, 25, and 125 hours at 950, 1000, and 1050 F and slow-cooled (in Sil-O-Cel). In addition, six 1/2-inch-thick plate samples of each steel were austenitized for 30 minutes at the temperatures described above and water-quenched. Individual plate samples were then tempered for 25 hours at 950, 1000, and 1050 F and either water-quenched or slow-cooled (in Sil-O-Cel).*

Stress-Relieving Studies

To determine the effect of stress-relieving variables on the three steels in the quenched and tempered condition, thirteen 1/2-inch-thick plate samples of each steel were austenitized for 2 hours at 1650 F (Steels A and B) or at 1500 F (Steel C), blower-cooled, tempered for 2 hours at 1250 F** (Steels A and B) or at 1050 F** (Steel C), and blower-cooled. One plate sample of each steel was not stress-relieved. The remainder of the plate samples were individually stress-relieved for 5, 25, and 125 hours at 950,

*Only three plate samples of Steel A were water-quenched after austenitizing; these plates were then tempered and slow-cooled.

**These tempering temperatures were selected so that the yield strength of the HY-80 steels would be about 90 ksi and that of the 5Ni-Cr-Mo-V steel would be about 140 ksi.

1000, and 1050 F and slow-cooled (in Sil-O-Cel). The long stress-relief times (25 and 125 hours) and the very slow cooling rate after stress relief were selected so that the most severe embrittlement would result, even though such severe conditions are unlikely to occur in practice. In addition, seven 1/2-inch-thick plate samples of each steel were austenitized for 30 minutes at the temperatures described above, water-quenched, tempered for 30 minutes at 1275 F* (Steels A and B) or at 1080 F* (Steel C), and water-quenched. One plate sample of each steel was not stress-relieved. The remainder of the plate samples were individually stress-relieved for 25 hours at 950, 1000, and 1050 F and either water-quenched or slow-cooled (in Sil-O-Cel).

Mechanical Tests

Two longitudinal 0.252-inch-diameter tension-test specimens and ten to twelve longitudinal Charpy V-notch impact-test specimens were machined from each heat-treated 1/2-inch-thick plate sample. The tension-test specimens were tested at room temperature, and duplicate or triplicate impact-test specimens were tested in the range -320 to 180 F.

Metallographic Studies

Representative specimens of each steel and condition were examined by means of light and electron microscopy. Photomicrographs were prepared to illustrate the structure of selected samples.

*These tempering temperatures were selected so that the yield strength of the HY-80 steels would be about 90 ksi and the yield strength of the 5Ni-Cr-Mo-V steel would be about 140 ksi.

Results and Discussion

Mechanical Properties

Tempering Studies. The mechanical properties obtained from studies in which 1/2-inch-thick water-quenched and 1/2-inch-thick blower-cooled plate samples of the three production steels were subjected to (1) variations in tempering temperature in the range 950 to 1050 F, (2) variations in tempering time in the range 5 to 125 hours, and/or (3) two different cooling rates (water quenching and slow cooling) after tempering for 25 hours are given in Appendix Tables A through F. The salient results are summarized in Table II and Figure 1.

Figure 1 shows that the yield strength of Steel A decreased significantly as the tempering time was increased from 5 to 125 hours at the three tempering temperatures investigated. Correspondingly, the energy absorption increased as the yield strength decreased except at the 1000 F tempering temperature for 125 hours where it decreased slightly and at the 1050 F tempering temperature for 25 and 125 hours where the increase was less than the proportionate yield-strength decrease. This behavior indicates a small susceptibility of open-hearth HY-80 steel to temper embrittlement.

The results for Steel B were generally similar to those for Steel A except that corresponding yield strengths were slightly lower and energy absorptions at 0 F were slightly higher for Steel B than for Steel A. The differences are probably related to the lower carbon content of Steel B.

The increase in energy absorption with decreased yield strength for Steel B was consistent for all tempering temperatures and times, which indicates that the electric-furnace HY-80 steel was essentially free from susceptibility to temper embrittlement.

The results for the 5Ni-Cr-Mo-V steel indicate that it is much more resistant to softening than HY-80 steel when both steels are tempered in the range 950 to 1050 F. Except when tempered at 1000 F or 1050 F for 125 hours, the 5Ni-Cr-Mo-V steel exhibited yield strengths exceeding 135 ksi. In addition, on a yield-strength-toughness basis, the energy absorption of the 5Ni-Cr-Mo-V steel was significantly better than that of HY-80 steel. However, the 5Ni-Cr-Mo-V steel did exhibit a greater susceptibility to temper embrittlement than HY-80 steel. When the 5Ni-Cr-Mo-V steel was tempered at 950 F for 125 hours, at 1000 F for 25 or 125 hours, or at 1050 F for 25 hours, the energy absorption decreased markedly even though the yield strength remained constant or decreased slightly. The greatest susceptibility of the 5Ni-Cr-Mo-V steel occurred when it was tempered at 950 F or 1000 F, which is below the minimum recommended tempering temperature of 1050 F. In addition, the tempering treatments employed were intended to simulate the most severe conditions that might be encountered—extremely long tempering times for very heavy plates that would be furnace-cooled from the tempering temperature. Thus thinner plates, which would cool more rapidly even if air-cooled, or thicker plates, which could be readily quenched from the

tempering temperature, would exhibit far less temper embrittlement even when tempered for long times. Thus, the observed susceptibility of the 5Ni-Cr-Mo-V steel to temper embrittlement under the severe conditions investigated is not considered a serious deterrent to its use in submarine hulls.

Stress-Relieving Study. The mechanical properties obtained from studies in which 1/2-inch-thick water-quenched and tempered and 1/2-inch-thick blower-cooled and tempered plate samples were subjected to (1) variations in stress-relieving temperature in the range 950 to 1050 F, (2) variations in stress-relieving time in the range 5 to 125 hours, and/or (3) two different cooling rates (water quenching and slow cooling) after stress relieving for 25 hours are given in Appendix Tables G through L. The salient results are summarized in Table III and are plotted in Figures 2 through 6. As shown in Table III, the yield strength of the blower-cooled and tempered plates of the HY-80 steels varied, after stress relieving, from 87 to 93 ksi for Steel A and from 83 to 91 ksi for Steel B. Thus, the yield strength was insignificantly affected by variations in stress-relieving temperature or time. Tempering Steel C for times up to 125 hours at 950 F, 1000 F, and 1050 F did not significantly affect the yield strength except at 1050 F for 125 hours. This particular combination resulted in a 25 ksi decrease in the yield strength.

The energy-absorption values at 0 F for the HY-80 steels were not significantly affected by variations in stress-relieving conditions because

all HY-80 specimens (at an average yield strength of 90 ksi) exhibited 100 percent shear fractures when tested at 0 F. However, the energy-absorption values at -160 F (Figures 2 and 3) were significantly reduced, and the 50 percent shear-fracture-appearance transition temperatures (FATT) and 15-mil lateral-expansion transition temperatures of the HY-80 steels (Table III) were significantly increased by increases in stress-relieving time at stress-relieving temperatures of 950 F, 1000 F, and 1050 F. Slow cooling after stress relieving for 25 hours (as compared with water quenching) also slightly increased the FATT and the 15-mil lateral-expansion transition temperatures of the HY-80 steels, Appendix Tables H and J.

The energy-absorption values at 0 F for the 5Ni-Cr-Mo-V steel were significantly reduced by increasing the time at a given stress-relieving temperature (Table III). For example, the blower-cooled and tempered (non-stress-relieved) plates that absorbed 81 ft-lb at 0 F (at a yield strength of 143 ksi), absorbed only 14, 18, and 46 ft-lb at 0 F when stress-relieved for 125 hours at 950, 1000, and 1050 F, respectively (at yield strengths of 143, 136, and 118 ksi, respectively). Figure 5 shows that the 0 F test temperature was below the impact-shelf region (less than 100% shear fracture) for the 5Ni-Cr-Mo-V steel plates stress-relieved for long times. Thus, the energy absorptions of the 5Ni-Cr-Mo-V steel were lowered by the aforementioned stress-relieving treatments because the treatments increased the transition temperature so that impact tests at 0 F were within the transition-

temperature range. The impact-energy curves for the 5Ni-Cr-Mo-V steel plates stress-relieved for 125 hours at 950 F or at 1000 F (Figure 5) were shifted markedly downward and to the right. Reference to the 50 percent shear-fracture-appearance and 15-mil lateral-expansion transition temperatures (Table III) shows that the FATT was raised as much as 270 F and the 15-mil lateral-expansion transition temperature was raised as much as 275 F by the 125-hour stress relief.

Figure 6 shows that the notch toughness of the 5Ni-Cr-Mo-V steel was generally impaired by slow cooling after stress relieving for 25 hours compared with water quenching after stress relieving. The water-quenched and tempered plates, Figure 6A, were embrittled slightly more than the blower-cooled and tempered plates, Figure 6B, when stress-relieved at 1000 F for 25 hours and water-quenched or slow-cooled after stress relieving. For the cooling rates studied, the water-quenched and tempered plates of the 5Ni-Cr-Mo-V steels were most severely embrittled when they were stress-relieved at 950 F (followed by water quenching), Figure 6C, whereas the blower-cooled and tempered plates were most severely embrittled when they were stress-relieved at 1000 F (followed by slow cooling), Figure 6D.

The foregoing data indicate that the notch toughness of the 5Ni-Cr-Mo-V steel is markedly impaired when the steel is stress-relieved at about 1000 F for times greater than about 5 hours. This impairment is probably a manifestation of temper embrittlement. The HY-80 steels were also susceptible

to temper embrittlement but to a lesser extent, probably because of the lower alloy content of the HY-80 steels and of the higher tempering temperatures (1250 and 1275 F) and lower strength of the HY-80 steels compared with those of the 5Ni-Cr-Mo-V steel.

The conditions selected in the tempering study for investigating the effects of stress relieving on the properties of the 5Ni-Cr-Mo-V steel were extreme. With stress-relieving times up to 5 hours, the embrittlement is insignificant even with slow cooling after stress relieving. With stress-relieving times up to 25 hours, the embrittlement is only moderate. Thus, only very heavy plates that require many stress-relieving treatments during fabrication and that are cooled very slowly after stress relieving would be seriously embrittled.

Metallographic Studies

The microstructures of the blower-cooled and tempered and of the blower-cooled, tempered, and stress-relieved (for 125 hours at 1000 F) specimens of the electric-furnace HY-80 steel (Steel B) and the electric-furnace 5Ni-Cr-Mo-V steel (Steel C) are shown in Figures 7 and 8 (HY-80 steel) and Figures 9 and 10 (5Ni-Cr-Mo-V steel).

As mentioned previously, the HY-80 steel did not embrittle nearly as greatly as did the 5Ni-Cr-Mo-V steel after stress relieving for 125 hours at 1000 F. Comparison of the microstructure of the non-stress-relieved specimen of the HY-80 steel (Figure 7) with that of the corresponding

specimen stress-relieved for 125 hours at 1000 F (Figure 8) indicates that there was little difference between the microstructures of the two specimens. Both specimens exhibited typical tempered microstructures (for steels tempered at 1250 F) of ferrite carbide aggregate wherein the carbides are coalesced and the ferrite matrix has an open appearance.

The non-stress-relieved specimen of the 5Ni-Cr-Mo-V steel exhibited a tempered microstructure, Figure 9, somewhat different from that of the corresponding specimen of HY-80 steel, Figure 7, largely because the 5Ni-Cr-Mo-V steel was tempered at 1050 F, whereas the HY-80 steel was tempered at 1250 F. The non-stress-relieved 5Ni-Cr-Mo-V steel exhibited fewer large carbide particles than the corresponding HY-80 steel and, in addition, exhibited a large amount of a fine needle-like precipitate. This fine precipitate, which may be vanadium carbide, is probably responsible for the resistance of the 5Ni-Cr-Mo-V steel to softening during tempering. Stress relieving the tempered 5Ni-Cr-Mo-V steel for 125 hours at 1000 F decreased the amount of the needle-like precipitate and increased the number of the larger carbide particles, many of which are concentrated in the grain boundaries, Figure 10.

The microstructures of the (1) water-quenched and tempered, (2) water-quenched, tempered, and stress-relieved (for 25 hours at 1000 F)*, and

*Stress-relieving times longer than 25 hours were not investigated for the plate samples that were water-quenched after austenitizing.

(3) blower-cooled, tempered, and stress-relieved (for 25 hours at 1000 F) specimens of the electric-furnace HY-80 steel (Steel B) are shown in Figures 11, 12, and 13; and the microstructures of the corresponding specimens of the electric-furnace 5Ni-Cr-Mo-V steel (Steel C) are shown in Figures 14, 15, and 16. As mentioned previously, the water-quenched and tempered plates of Steels A, B, and C appeared to be somewhat more susceptible to temper embrittlement than the blower-cooled and tempered plates.

The photomicrographs of the non-stress-relieved specimens of the HY-80 steel (Figure 11 for the water-quenched plates and Figure 7 for the blower-cooled plates) depict typical tempered structures; however, Figures 11B and 7C show that the water-quenched plates exhibited more fine needle-like precipitates than did the blower-cooled plates, and that the blower-cooled plates exhibited a greater amount of coalesced carbide particles. Comparison of the microstructure of a water-quenched and tempered (non-stress-relieved) specimen of HY-80 steel (Figure 11) with that of a corresponding specimen stress-relieved for 25 hours at 1000 F (Figure 12) shows that stress relieving resulted in additional coalescence of the carbide particles; however, some evidence of the fine needle-like precipitate remained. The microstructure of a blower-cooled and tempered (non-stress-relieved) specimen of HY-80 steel (Figure 7) and of a corresponding specimen stress-relieved for 25 hours at 1000 F (Figure 13) was generally similar.

The photomicrographs of the non-stress-relieved specimens of the 5Ni-Cr-Mo-V steel (Figure 14 for the water-quenched plates and Figure 9 for the blower-cooled plates) depict typical tempered structures; however, Figures 14B and 9B show that the water-quenched plates exhibited a greater amount of fine carbide particles than did the blower-cooled plates. Comparison of the microstructure of a water-quenched and tempered (non-stress-relieved) specimen of 5Ni-Cr-Mo-V steel (Figure 14) with that of a corresponding specimen stress-relieved for 25 hours at 1000 F (Figure 15) shows that stress relieving resulted in a large amount of semicontinuous grain-boundary carbides. Comparison of the microstructure of a blower-cooled and tempered (non-stress-relieved) specimen of 5Ni-Cr-Mo-V steel (Figure 9) with that of a corresponding specimen stress-relieved for 25 hours at 1000 F (Figure 16) shows that in this case, stress relieving resulted in an even greater amount of semicontinuous grain-boundary carbides; however, some evidence of the fine needle-like precipitate remained.

The metallographic studies show that the 5Ni-Cr-Mo-V steel contains more fine carbides than the HY-80 steels. This is a result of the lower tempering temperatures employed for the 5Ni-Cr-Mo-V steel and of the resistance to tempering afforded by the presence of vanadium in the 5Ni-Cr-Mo-V steel. At least part of the embrittlement occurring in the 5Ni-Cr-Mo-V steel as a result of stress relieving and of slow cooling from stress-relieving temperatures is associated with the formation of a semicontinuous film of

grain-boundary carbides. There is no appreciable tendency for grain-boundary carbides to form in the HY-80 steels.

Summary

The present study was conducted to determine the effects of variations in tempering and stress-relieving treatments on the mechanical properties of an open-hearth HY-80 steel, an electric-furnace HY-80 steel, and an electric-furnace 5Ni-Cr-Mo-V steel. Austenitized and water-quenched 1/2-inch-thick plates and austenitized and blower-cooled 1/2-inch-thick plates (both tempered and untempered plates) were subjected to tempering treatments (untempered plates) or stress-relieving treatments (tempered plates) for times up to 125 hours at temperatures in the range 950 to 1050 F and either water-quenched or slow-cooled. The results may be summarized as follows:

Tempering Study

1. The yield strength of the HY-80 steels was more significantly reduced by an increase in tempering temperature and/or tempering time than was the yield strength of the 5Ni-Cr-Mo-V steel. The notch toughness of the three steels, particularly that of the HY-80 steels, generally increased as the yield strength decreased.

2. Although the 5Ni-Cr-Mo-V steel was more susceptible to temper embrittlement than the HY-80 steels, the 5Ni-Cr-Mo-V steel exhibited notch toughness that was generally superior to that of the HY-80 steels in the yield-strength range 130 to 150 ksi.

Stress-Relieving Study

1. The yield strength of the HY-80 steels (about 90 ksi) was insignificantly affected by variations in stress-relieving temperature or time, but the yield strength of the 5Ni-Cr-Mo-V steel (about 145 ksi) was slightly to moderately reduced when the blower-cooled and tempered plates were stress-relieved for 125 hours at 1000 F or 1050 F.

2. The energy-absorption values at 0 F for the HY-80 steels were not significantly affected by variations in stress-relieving conditions; however, the energy-absorption values at -160 F were significantly reduced and the 50 percent shear-fracture-appearance transition temperatures and the 15-mil lateral-expansion-transition temperatures of the HY-80 steels were significantly increased as the stress-relieving time was increased up to 125 hours for stress-relieving temperatures of 950, 1000, and 1050 F. Slow cooling after stress relieving (as compared with water quenching) also impaired the notch toughness of the HY-80 steels.

3. The energy-absorption values at 0 F for the 5Ni-Cr-Mo-V steel were significantly reduced by increasing the stress-relieving time at a given stress-relieving temperature or by slow cooling after stress relieving at temperatures of 1000 or 1050 F; this reduction in notch toughness was associated with an increase in the transition temperature—as measured either by the 50 percent shear-fracture appearance or by the 15-mil lateral-expansion transition temperatures.

4. The impairment of notch toughness caused by slow cooling after stress relieving was somewhat more severe for the water-quenched and tempered 1/2-inch-thick plates of the 5Ni-Cr-Mo-V steel than for the blower-cooled and tempered 1/2-inch-thick plates (simulated 4-inch-thick plate).

5. Metallographic studies indicate that the formation of a semi-continuous grain-boundary network during stress-relieving treatments and during slow cooling from stress-relieving temperatures is at least partly responsible for the embrittlement of the 5Ni-Cr-Mo-V steel.

The results indicate that the 5Ni-Cr-Mo-V steel is susceptible to embrittlement when stress-relieved for very long times and cooled slowly after stress relieving. However, the embrittlement does not appear to be a serious problem because the embrittling conditions are not commonly encountered.

Recommendations and Future Work

Studies are currently in progress to determine whether the temper embrittlement observed in the 5Ni-Cr-Mo-V steel is caused by the residual elements (P, S, O, and N), by the relatively high manganese content, and/or by the vanadium content of the steel.

References

1. S. J. Manganello and L. F. Porter, "Evaluation of the Hardenability, Temperability, and Mechanical Properties of Ten 5Ni-Cr-Mo Steels," Applied Research Laboratory Progress Report, Project No. 40.18-001(9), (S-11109-1), September 20, 1963.
2. S. J. Manganello and L. F. Porter, "Base-Metal Evaluation of a Production Electric-Furnace 5Ni-Cr-Mo-V Heat," Applied Research Laboratory Progress Report, Project No. 40.018-001(21), (S-11104-3), April 1, 1964.
3. S. J. Manganello, L. F. Porter, and R. J. Sitko, "Simulation of the Cooling of a Water-Quenched 4-Inch-Thick Plate," Applied Research Laboratory Progress Report, Project No. 40.18-001(8), (S-11105), September 18, 1963.

APPENDIX

-18-

UNITED STATES STEEL

Table A

Effect of Long-Time Tempering on the Longitudinal Tensile Properties of HY-80 Steel (Heat No. 72P305)

Tempering Condition	Yield Strength (0.2% Offset), ksi		Tensile Strength, ksi		Elongation in 1 Inch, %		Reduction of Area, %		Yield-Tensile Ratio	
	WQ*	8C*	WQ	8C	WQ	8C	WQ	8C	WQ	8C
950 F (25 hr) WQ**	—	137	—	158	—	19.0	—	65.5	—	0.87
950 F (25 hr) SC**	148	144	160	157	18.0	19.0	65.8	65.9	0.93	0.92
1000 F (25 hr) WQ	—	127	—	139	—	20.5	—	69.7	—	0.91
1000 F (25 hr) SC	125	123	139	136	20.5	20.0	71.7	71.2	0.90	0.90
1050 F (25 hr) WQ	—	105	—	120	—	22.5	—	73.8	—	0.88
1050 F (25 hr) SC	116	110	131	125	21.5	22.0	73.0	72.4	0.89	0.88

1/2-Inch-Thick Plates Austenitized for 2 Hours at 1650 F and 8 slower-cooled (8C)

Tempering Condition	Yield Strength (0.2% Offset), ksi		Tensile Strength, ksi		Elongation in 1 Inch, %		Reduction of Area, %		Yield-Tensile Ratio	
	WQ	8C	WQ	8C	WQ	8C	WQ	8C	WQ	8C
950 F (5 hr) SC	156	143	169	155	18.5	19.5	64.3	65.9	0.92	0.92
(25 hr)	144	123	157	136	19.0	20.0	65.9	71.2	0.92	0.90
(125 hr)	122	108	139	123	20.0	22.0	71.1	71.6	0.88	0.88
1000 F (5 hr) SC	143	123	155	136	19.5	20.0	65.9	71.2	0.92	0.90
(25 hr)	123	108	136	123	20.0	22.0	71.2	71.6	0.90	0.88
(125 hr)	108	99	123	112	22.0	24.5	71.6	74.6	0.88	0.88
1050 F (5 hr) SC	122	110	141	125	20.5	22.0	70.5	72.4	0.87	0.88
(25 hr)	110	99	125	112	22.0	24.5	72.4	74.6	0.88	0.88
(125 hr)	99	—	112	—	24.5	—	74.6	—	—	—

*WQ means water-quenched after a 30-minute austenitizing treatment at 1650 F; 8C means slower-cooled after a 2-hour austenitizing treatment at 1650 F (1/2-inch-thick plate samples).

**WQ means water-quenched after tempering; SC means slower-cooled (in sil-O-Cel) after tempering.

Table 8

Effect of Long-Time Tempering on the Longitudinal Charpy V-Notch Impact Properties of HY-80 Steel (Heat No. 72P305)

Tempering Condition	Energy Absorbed, ft-lb						Shear Fracture, %						Lateral Expansion, mils						FATT, +		Hardness, R _C			
	+80 F			-80 F			+80 F			-80 F			+80 F			0 F			F		WQ		BC	
	WQ*	BC*	WQ	WQ	BC	WQ	WQ	BC	WQ	WQ	BC	WQ	WQ	BC	WQ	WQ	BC	WQ	WQ	BC	WQ	WQ	BC	
950 F (25 hr) WQ**	—	65	—	61	—	30	—	100	—	100	—	25	—	38	—	33	—	9	—	—	40	—	38.5	
950 F (25 hr) SC**	63	57	61	53	33	34	100	100	100	100	50	35	36	27	35	22	14	8	—	80	—	37.5	39.0	
1000 F (25 hr) WQ	—	87	—	82	—	82	—	100	—	100	—	100	—	55	—	51	—	47	—	—	145	—	33.5	
1000 F (25 hr) SC	94	89	95	88	88	84	100	100	100	100	100	100	100	54	59	53	57	52	—	140	155	33.0	32.5	
1050 F (25 hr) WQ	—	104	—	112	—	108	—	100	—	100	—	100	—	71	—	64	—	66	—	—	155	—	27.0	
1050 F (25 hr) SC	97	89	94	91	89	92	100	100	100	100	100	100	100	60	58	56	55	53	53	100	120	32.0	31.5	

1/2-Inch-Thick Plate Austenitized for 2 Hours at 1650 F and Blower-Cooled (BC)

Tempering Condition	Energy Absorbed, ft-lb						Shear Fracture, %						Lateral Expansion, mils						FATT, + F	Hardness, RC																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																			
	+80 F			0 F			+80 F			0 F			+80 F			0 F																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																							
	-80 F	-80 F	-80 F	0 F	0 F	0 F	+80 F	+80 F	+80 F	0 F	0 F	0 F	-80 F	-80 F	-80 F																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																								
950 F (5 hr) SC (25 hr) (125 hr)	46	25	20	100	35	20	23	9	3																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														

+Fracture-appearance (50% shear) transition temperature.

*WQ means water-quenched after a 30-minute austenitizing treatment at 1650 F; BC means blower-cooled after a 2-hour austenitizing treatment at 1650 F (1/2-inch-thick plate samples).

**WQ means water-quenched after tempering; SC means slow-cooled (in Sil-O-Cel) after tempering.

Table C

Effect of Long-Time Tempering on the Longitudinal Tensile Properties of HY-80 Steel (Heat No. X51289)

Tempering Condition	Yield Strength (0.2% Offset), ksi		Tensile Strength, ksi		Elongation in 1 Inch, %		Reduction of Area, %		Yield-Tensile Ratio	
	WQ*	3C*	WQ	8C	WQ	8C	WQ	8C	WQ	8C
950 F (25 hr) WQ**	149	138	159	157	18.5	20.0	67.7	65.8	0.94	0.88
950 F (25 hr) SC**	149	136	158	154	19.0	20.0	67.4	67.1	0.94	0.88
1000 F (25 hr) WQ	122	133	135	147	21.0	20.0	73.2	68.5	0.90	0.90
1000 F (25 hr) SC	124	121	130	134	21.5	20.5	74.0	70.8	0.95	0.90
1050 F (25 hr) WQ	109	104	122	121	22.0	20.5	76.9	73.1	0.89	0.86
1050 F (25 hr) SC	117	105	126	119	22.5	23.0	76.5	72.8	0.93	0.88

1/2-Inch-Thick Plates Austenitized for 2 Hours at 1650 F and Blower-Cooled (8C)

Tempering Condition	Yield Strength (0.2% Offset), ksi		Tensile Strength, ksi		Elongation in 1 Inch, %		Reduction of Area, %		Yield-Tensile Ratio	
	WQ*	3C*	WQ	8C	WQ	8C	WQ	8C	WQ	8C
950 F (5 hr) SC	131		153		19.5		66.1		0.86	
(25 hr)	136		154		20.0		67.1		0.88	
(125 hr)	130		154		20.0		68.5		0.84	
1000 F (5 hr) SC	128		146		19.0		67.5		0.88	
(25 hr)	121		134		20.5		70.8		0.90	
(125 hr)	106		119		22.5		73.7		0.89	
1050 F (5 hr) SC	119		134		21.0		69.6		0.89	
(25 hr)	105		119		23.0		72.8		0.88	
(125 hr)	92		106		24.0		76.6		0.87	

*WQ means water-quenched after a 30-minute austenitizing treatment at 1650 F; BC means blower-cooled after a 2-hour austenitizing treatment at 1650 F (1/2-inch-thick plate samples).

**WQ means water-quenched after tempering; SC means slow-cooled (in Sil-O-Cel) after tempering.

Table D

Effect of Long-Time Tempering on the Longitudinal Charpy V-Notch Impact Properties of HY-80 Steel (Heat No. X51289)

Tempering Condition	Energy Absorbed, ft-lb				Shear Fracture, %				Lateral Expansion, mils				FATT, °		Hardness,						
	+80 F		0 F		+80 F		0 F		+80 F		0 F		F		R _C						
	WQ*	BC*	WQ	BC	WQ	BC	WQ	BC	WQ	BC	WQ	BC	WQ	BC	WQ	BC					
950 F (25 hr) WQ**	79	68	76	45	28	100	98	100	60	75	15	42	37	41	19	32	11	-115	-10	38.5	37.5
950 F (25 hr) SC**	74	74	72	70	54	100	100	100	55	65	35	48	44	38	29	22	16	-100	-10	38.0	37.5
1000 F (25 hr) WQ	112	85	109	86	108	100	100	100	100	100	55	62	51	58	52	59	30	-205	-85	34.5	35.5
1000 F (25 hr) SC	119	109	118	103	107	100	100	100	100	100	80	67	68	71	61	57	45	-190	-120	34.5	34.0
1050 F (25 hr) WQ	134	118	139	121	131	100	100	100	100	100	100	77	73	77	75	73	72	-240	-155	29.5	28.5
1050 F (25 hr) SC	127	123	135	123	125	100	100	100	100	100	100	72	77	69	75	71	73	190	-170	29.0	28.0

1/2-Inch-Thick Plate Austenitized for 2 Hours at 1650 F and Blower-Cooled (BC)

Tempering Condition	Energy Absorbed, ft-lb			Shear Fracture, %			Lateral Expansion, mils			FATT, + F	Hardness, RC
	+80 F	0 F	-80 F	+80 F	0 F	-80 F	+80 F	0 F	-80 F		
950 F (5 hr) SC (25 hr) (125 hr)	69	42	25	93	50	15	36	19	3	+ 5	37.0
	74	70	31	100	55	35	44	29	16	- 10	37.5
	88	79	48	100	93	55	50	45	23	- 85	35.0
1000 F (5 hr) SC (25 hr) (125 hr)	82	50	30	100	70	30	50	49	12	- 30	35.5
	109	103	84	100	100	80	68	61	45	-120	34.0
	119	121	105	100	100	100	74	77	68	-135	28.5
1050 F (5 hr) SC (25 hr) (125 hr)	94	99	47	100	100	45	59	63	28	- 65	33.0
	123	123	125	100	100	100	77	75	73	-170	28.0
	149	146	131	100	100	93	87	86	75	-120	29.0

+Fracture-appearance (50% shear) transition temperature.

*WQ means water-quenched after a 30-minute austenitizing treatment at 1650 F; BC means blow-cooled after a 2-hour austenitizing treatment at 1650 F (1/2-inch-thick plate samples).

****WQ** means water-quenched after tempering; **SC** means slow-cooled (in Sil-O-Cel) after tempering.

Table E

Effect of Long-Time Tempering on the Longitudinal Tensile Properties of 5Ni-Cr-Mo-V Steel (Heat No. X53185)

Tempering Condition	Yield Strength (0.2% Offset), ksi		Tensile Strength, ksi		Elongation in 1 Inch, %		Reduction of Area, %		Yield-Tensile Ratio	
	WQ*	BC*	WQ	BC	WQ	BC	WQ	BC	WQ	BC
950 F (25 hr) WQ**	153	141	162	160	17.5	19.5	69.8	71.8	0.94	0.88
950 F (25 hr) SC	155	141	164	159	17.5	18.5	70.4	68.1	0.94	0.89
1000 F (25 hr) WQ	147	145	153	156	19.5	19.0	72.3	71.2	0.96	0.93
1000 F (25 hr) SC	152	143	157	155	19.5	20.0	71.4	71.0	0.97	0.92
1050 F (25 hr) WQ	134	128	139	140	19.5	19.5	73.4	72.7	0.96	0.91
1050 F (25 hr) SC	142	137	146	147	20.0	19.0	72.1	69.4	0.97	0.93

1/2-Inch-Thick Plates Austenitized for 2 Hours at 1500 F and Blower-Cooled (BC)

Tempering Condition	Yield Strength (0.2% Offset), ksi		Tensile Strength, ksi		Elongation in 1 Inch, %		Reduction of Area, %		Yield-Tensile Ratio	
	WQ*	BC*	WQ	BC	WQ	BC	WQ	BC	WQ	BC
950 F (5 hr) SC	136		158		18.5		66.2		0.86	
(25 hr)	141		159		18.5		68.1		0.89	
(125 hr)	141		157		19.5		69.8		0.90	
1000 F (5 hr) SC	144		158		19.0		68.7		0.91	
(25 hr)	143		155		20.0		71.0		0.92	
(125 hr)	129		139		19.5		70.0		0.93	
1050 F (5 hr) SC	144		158		19.0		70.8		0.91	
(25 hr)	137		147		19.0		69.4		0.93	
(125 hr)	112		122		21.0		72.9		0.92	

*WQ means water-quenched after a 30-minute austenitizing treatment at 1500 F; BC means blower-cooled after a 2-hour austenitizing treatment at 1500 F (1/2-inch-thick plate samples).

**WQ means water-quenched after tempering; SC means slow-cooled (in Sil-O-Cel) after tempering.

Table F

Effect of Long-Time Tempering on the Longitudinal Charpy V-Notch Impact Properties of 5Ni-Cr-Mo-V Steel (Heat No. X53185)

Tempering Condition	Energy Absorbed, ft-lb			Shear Fracture, %			Lateral Expansion, mils						FATT, +		Hardness, RC	
	-80 F			0 F			+80 F		0 F		-80 F		F		RC	
	WQ*	BC*	WQ	WQ	BC	WQ	WQ	BC	WQ	BC	WQ	BC	WQ	BC	WQ	BC
950 F (25 hr) WQ**	98	104	95	105	64	89	100	100	100	100	65	100	59	60	52	32
950 F (25 hr) SC**	99	106	92	92	60	56	100	100	100	100	45	50	58	61	50	27
1000 F (25 hr) WQ	96	96	93	98	67	67	100	100	93	100	55	60	60	58	52	33
1000 F (25 hr) SC	78	94	53	58	27	29	70	90	50	55	25	20	46	59	28	13
1050 F (25 hr) WQ	123	127	125	120	82	119	100	100	100	100	70	100	75	75	73	71
1050 F (25 hr) SC	65	98	45	73	30	41	60	90	50	65	25	45	43	61	27	41
															15	19
															0	-115
															0	-170
															0	-65
															34.0	34.5
															35.5	35.0
															35.5	32.5
															35.0	29.5
															35.0	34.0
															34.5	32.5

1/2-Inch-Thick Plate Austenitized for 2 Hours at 1500 F and Blower-Cooled (BC)

*Fracture-appearance (50% shear) transition temperature.

*WQ means water-quenched after a 30-minute austenitizing treatment at 1500 F; 8C means blower-cooled after a 2-hour austenitizing treatment at 1500 F (1/2-inch-thick plate samples).

**WQ means water-quenched after tempering; SC means slow-cooled (in Sil-O-Cel) after tempering.

Table G

Effect of Long-Time Stress-Relieving on the Longitudinal Tensile Properties of Quenched and Tempered HY-80 Steel (Heat No. 72P305)

Stress-Relieving Condition	Yield Strength (0.2% Offset), ksi		Tensile Strength, ksi		Elongation in 1 Inch, %		Reduction of Area, %		Yield-Tensile Ratio	
	WQ*	SC**	WQ	BC	WQ	BC	WQ	BC	WQ	BC
Not Stress-Relieved	95	92	111	110	27.0	27.0	77.0	74.3	0.86	0.83
950 F (25 hr) WQ**	96	87	114	107	27.0	27.5	76.2	74.1	0.85	0.81
950 F (25 hr) SC**	95	90	111	109	27.0	28.5	76.6	74.2	0.85	0.83
1000 F (25 hr) WQ	94	85	113	104	27.0	28.5	74.6	73.9	0.83	0.81
1000 F (25 hr) SC	92	88	108	107	27.0	28.0	76.5	74.8	0.85	0.82
1050 F (25 hr) WQ	92	83	110	103	27.0	28.5	76.2	75.8	0.84	0.80
1050 F (25 hr) SC	96	88	113	106	26.0	28.0	72.5	74.3	0.85	0.83

1/2-Inch-Thick Plates Austenitized for 2 Hours at 1650 F, Blower-Cooled, Tempered for 2 Hours at 1250 F, and Blower-Cooled (BC)

Stress-Relieving Condition	Yield Strength (0.2% Offset), ksi		Tensile Strength, ksi		Elongation in 1 Inch, %		Reduction of Area, %		Yield-Tensile Ratio	
	WQ*	SC**	WQ	BC	WQ	BC	WQ	BC	WQ	BC
950 F (5 hr) SC	93		111		27.0		74.6		0.84	
(25 hr)	90		109		28.5		74.2		0.83	
(125 hr)	89		107		28.5		74.6		0.83	
1000 F (5 hr) SC	87		105		28.0		74.4		0.83	
(25 hr)	88		107		28.0		74.8		0.82	
(125 hr)	88		105		28.0		73.2		0.84	
1050 F (5 hr) SC	91		109		28.5		74.8		0.83	
(25 hr)	88		106		28.0		74.3		0.83	
(125 hr)	88		105		28.0		73.4		0.84	

*WQ means water-quenched after a 30-minute austenitizing treatment at 1650 F and a 30-minute tempering treatment at 1275 F; BC means blower-cooled after a 2-hour austenitizing treatment at 1650 F and a 2-hour tempering treatment at 1250 F (1/2-inch-thick plate samples).

**WQ means water-quenched after stress-relieving; SC means slow-cooled (in Sil-O-Cel) after stress-relieving.

Table H

Effect of Long-Time Stress-Relieving on the Longitudinal Charpy V-Notch Impact Properties of Quenched and Tempered HY-80 Steel (Heat No. 72P305)

Stress-Relieving Condition	Energy Absorbed, ft-lb			Shear Fracture, %			Lateral Expansion, mils						FATT, +		Hardness, RC	
	-80 F			-160 F			0 F			-80 F			-160 F		F	
	WQ*	BC*	WQ	BC	WQ	BC	WQ	BC	WQ	BC	WQ	BC	WQ	BC	WQ	BC
Not Stress-Relieved	135	117	127	107	103	105	100	100	100	100	81	76	72	68	70	22.0 21.0
950 F (25 hr) WQ**	125	123	112	117	63	70	100	100	98	100	50	65	78	79	72	22.0 20.0
950 F (25 hr) SC**	130	115	127	101	54	60	100	100	100	100	40	50	82	75	81	21.5 21.0
1000 F (25 hr) WQ	118	131	108	109	68	67	100	100	100	100	85	75	72	82	69	23.5 20.0
1000 F (25 hr) SC	129	125	124	111	59	52	100	100	100	100	40	65	81	80	78	22.5 19.5
1050 F (25 hr) WQ	126	124	118	112	73	78	100	100	100	100	55	65	81	77	68	22.0 19.5
1050 F (25 hr) SC	112	113	101	98	46	52	100	100	100	98	40	50	71	75	66	23.5 21.5

1/2-Inch-Thick Plates Austenitized for 2 Hours at 1650 F, Blower-Cooled, Tempered for 2 Hours at 1250 F, and Blower-Cooled (BC)

Stress-Relieving Condition	Energy Absorbed, ft-lb			Shear Fracture, %			Lateral Expansion, mils						FATT, +		Hardness, RC	
	-80 F			-160 F			0 F			-80 F			-160 F		F	
	WQ*	BC*	WQ	BC	WQ	BC	WQ	BC	WQ	BC	WQ	BC	WQ	BC	WQ	BC
950 F (5 hr) SC	121	113	90				100	100	100		74	70	50		-215	21.5
(25 hr)	115	101	60				100	100	50		75	66	42		-150	21.0
(125 hr)	117	92	40				100	93	40		76	62	23		-150	20.0
1000 F (5 hr) SC	117	108	65				100	100	65		76	71	43		-190	21.0
(25 hr)	125	111	52				100	100	65		80	75	34		-170	19.5
(125 hr)	99	88	34				100	80	35		70	56	18		-125	20.5
1050 F (5 hr) SC	117	114	61				100	100	55		74	69	39		-180	21.0
(25 hr)	113	98	52				100	98	50		75	67	39		-155	21.5
(125 hr)	105	72	39				100	80	30		72	51	18		-135	21.0

*Fracture-appearance (50% shear) transition temperature.

**WQ means water-quenched after a 30-minute austenitizing treatment at 1650 F and a 30-minute tempering treatment at 1275 F; SC means blower-cooled after a 2-hour austenitizing treatment at 1650 F and a 2-hour tempering treatment at 1250 F (1/2-inch-thick plate samples).

**WQ means water-quenched after stress-relieving; SC means slow-cooled (in Sil-O-Cel) after stress-relieving.

Table I

Effect of Long-Time Stress-Relieving on the Longitudinal Tensile Properties
of Quenched and Tempered HY-80 Steel (Heat No. X51289)

Stress-Relieving Condition	Yield Strength (0.2% Offset), ksi		Tensile Strength, ksi		Elongation in 1 Inch, %		Reduction of Area, %		Yield-Tensile Ratio	
	WQ*	BC*	WQ	BC	WQ	BC	WQ	BC	WQ	BC
Not Stress-Relieved	98	89	112	107	27.5	28.0	77.8	76.2	0.87	0.83
950 F (25 hr) WQ**	93	86	110	105	27.0	29.0	77.9	76.2	0.83	0.82
950 F (25 hr) SC**	97	89	112	106	27.0	27.5	77.8	76.4	0.87	0.84
1000 F (25 hr) WQ	91	83	108	101	26.5	27.5	78.3	75.0	0.84	0.82
1000 F (25 hr) SC	97	86	112	104	27.0	28.0	77.3	75.6	0.86	0.83
1050 F (25 hr) WQ	92	85	110	104	27.0	28.0	78.6	75.8	0.84	0.82
1050 F (25 hr) SC	97	83	112	100	27.0	28.0	77.3	74.4	0.86	0.83

1/2-Inch-Thick Plates Austenitized for 2 Hours at 1650 F, Blower-Cooled, Tempered
for 2 Hours at 1250 F, and Blower-Cooled (BC)

Stress-Relieving Condition	Yield Strength (0.2% Offset), ksi		Tensile Strength, ksi		Elongation in 1 Inch, %		Reduction of Area, %		Yield-Tensile Ratio	
	WQ*	BC*	WQ	BC	WQ	BC	WQ	BC	WQ	BC
950 F (5 hr) SC	91		108		28.0		76.4		0.84	
(25 hr)	89		106		27.5		76.4		0.84	
(125 hr)	86		103		28.5		75.8		0.83	
1000 F (5 hr) SC	87		104		28.0		76.8		0.84	
(25 hr)	86		104		28.0		75.6		0.83	
(125 hr)	84		102		27.0		73.0		0.83	
1050 F (5 hr) SC	89		105		27.0		74.9		0.84	
(25 hr)	83		100		28.0		74.4		0.83	
(125 hr)	84		101		27.0		73.7		0.83	

*WQ means water-quenched after a 30-minute austenitizing treatment at 1650 F and a 30-minute tempering treatment at 1275 F; BC means blower-cooled after a 2-hour austenitizing treatment at 1650 F and a 2-hour tempering treatment at 1250 F (1/2-inch-thick plate samples).

**WQ means water-quenched after stress-relieving; SC means slow-cooled (in Sil-O-Cel) after stress-relieving.

Table J
Effect of Long-Time Stress-Relieving on the Longitudinal Charpy V-Notch Impact Properties
of Quenched and Tempered HY-80 Steel (Heat No. X51289)

Stress-Relieving Condition	Energy Absorbed, ft-lb			Shear Fracture, %			Lateral Expansion, mils						FATT, +		Hardness, RC	
	-80 F			-160 F			0 F			-80 F			F		WQ	
	WQ*	BC*	WQ	WQ	BC	WQ	WQ	BC	WQ	WQ	BC	WQ	WQ	BC	WQ	BC
Not Stress-Relieved	158	142	138	138	135	66	100	100	100	100	100	45	90	85	79	82
950 F (25 hr) WQ**	160	150	148	129	124	76	100	100	100	100	100	93	45	86	90	84
950 F (25 hr) SC**	165	149	148	133	138	61	100	100	100	100	100	45	92	86	85	82
1000 F (25 hr) WQ	156	148	144	135	138	62	100	100	100	100	100	55	85	88	83	80
1000 F (25 hr) SC	163	155	148	145	110	37	100	100	100	100	100	65	35	92	89	82
1050 F (25 hr) WQ	160	155	150	148	117	98	100	100	100	100	100	90	70	89	89	86
1050 F (25 hr) SC	157	144	135	120	93	61	100	100	100	85	55	55	87	89	80	75

1/2-Inch-Thick Plates Austenitized for 2 Hours at 1650 F, Blower-Cooled, Tempered
for 2 Hours at 1250 F, and Blower-Cooled (BC)

Stress-Relieving Condition	Energy Absorbed, ft-lb			Shear Fracture, %			Lateral Expansion, mils			FATT, + F	Hardness, RC
	-80 F -160 F			0 F -80 F -160 F			0 F -80 F -160 F				
	0 F	-80 F	-160 F	0 F	-80 F	-160 F	0 F	-80 F	-160 F		
950 F (5 hr) SC (25 hr) (125 hr)	148	137	82	100	100	60	87	84	50	-170	21.0
	149	133	61	100	100	45	86	82	42	-160	19.5
	155	113	36	100	95	50	88	74	33	-165	18.5
1000 F (5 hr) SC (25 hr) (125 hr)	151	136	68	100	100	50	88	84	43	-155	19.5
	155	145	37	100	100	35	89	87	23	-125	19.0
	143	85	31	100	55	35	87	49	19	-100	20.0
1050 F (5 hr) SC (25 hr) (125 hr)	146	139	96	100	100	60	89	84	46	-185	19.5
	144	120	61	100	85	55	89	75	43	-175	20.0
	133	83	42	100	80	40	85	55	25	-135	19.5

+Fracture-appearance (50% shear) transition temperature.

*WQ means water-quenched after a 30-minute austenitizing treatment at 1650 F and a 30-minute tempering treatment at 1275 F; BC means blower-cooled after a 2-hour austenitizing treatment at 1650 F and a 2-hour tempering treatment at 1250 F (1/2-inch-thick plate samples).

**WQ means water-quenched after stress-relieving; SC means slow-cooled (in Sil-O-Cel) after stress-relieving.

Table K
Effect of Long-Time Stress-Relieving on the Longitudinal Tensile Properties of
Quenched and Tempered 5Ni-Cr-Mo-V Steel (Heat No. X53185)

Stress-Relieving Condition	Yield Strength (0.2% Offset), ksi		Tensile Strength, ksi		Elongation in 1 Inch, %		Reduction of Area, %		Yield-Tensile Ratio	
	WQ*	8C*	WQ	8C	WQ	8C	WQ	8C	WQ	8C
Not Stress-Relieved	150	143	155	161	21.0	21.5	69.8	67.1	0.90	0.89
950 F (25 hr) WQ**	156	141	162	159	21.5	22.0	69.9	66.4	0.96	0.89
950 F (25 hr) SC**	155	143	161	158	20.0	23.0	65.5	68.8	0.96	0.90
1000 F (25 hr) WQ	150	143	156	158	21.0	21.5	68.2	67.8	0.96	0.90
1000 F (25 hr) SC	153	143	157	155	20.5	21.5	64.6	64.2	0.97	0.92
1050 F (25 hr) WQ	141	135	146	148	22.0	22.0	69.4	69.7	0.97	0.91
1050 F (25 hr) SC	144	139	147	147	22.0	21.5	68.6	67.3	0.98	0.94

1/2-Inch-Thick Plates Austenitized for 2 Hours at 1500 F, Blower-Cooled, Tempered
for 2 Hours at 1050 F, and Blower-Cooled (8C)

Stress-Relieving Condition	Yield Strength (0.2% Offset), ksi		Tensile Strength, ksi		Elongation in 1 Inch, %		Reduction of Area, %		Yield-Tensile Ratio	
	WQ*	8C*	WQ	8C	WQ	8C	WQ	8C	WQ	8C
950 F (5 hr) SC	145		161		22.0		68.6		0.90	
(25 hr)	143		158		23.0		68.8		0.90	
(125 hr)	143		158		21.5		64.9		0.91	
1000 F (5 hr) SC	146		161		22.0		68.4		0.91	
(25 hr)	143		155		21.5		64.2		0.92	
(125 hr)	136		145		22.0		66.8		0.93	
1050 F (5 hr) SC	144		158		21.0		62.9		0.91	
(25 hr)	139		147		21.5		67.3		0.94	
(125 hr)	118		128		24.0		69.1		0.92	

*WQ means water-quenched after a 30-minute austenitizing treatment at 1500 F and a 30-minute tempering treatment at 1080 F; 8C means blower-cooled after a 2-hour austenitizing treatment at 1500 F and a 2-hour tempering treatment at 1050 F (1/2-inch-thick plate samples).

**WQ means water-quenched after stress-relieving; 8C means slow-cooled (in Sil-O-Cool) after stress-relieving.

Table I

Effect of Long-Time Stress-Relieving on the Longitudinal Charpy V-Notch Impact Properties of Quenched and Tempered 5Ni-Cr-Mo-V Steel (Heat No. X53185)

Stress-Relieving Condition	Energy Absorbed, ft-lb				Shear Fracture, %				Lateral Expansion, mils				FATT, +		Hardness, RC	
	0 F		-80 F		0 F		-80 F		0 F		-80 F		F		RC	
	WQ*	BC*	WQ	BC	WQ	BC	WQ	BC	WQ	BC	WQ	BC	WQ	BC	WQ	BC
Not Stress-Relieved	84	81	62	66	44	37	100	100	100	100	75	50	50	49	48	31
950 F (25 hr) WQ**	49	63	39	51	15	22	90	100	65	70	30	35	23	36	16	28
950 F (25 hr) SC**	43	62	25	41	15	20	60	90	40	55	30	30	19	34	9	18
1000 F (25 hr) WQ	50	76	29	47	—	29	70	100	30	70	—	50	27	41	14	26
1000 F (25 hr) SC	34	43	23	29	7	17	60	65	35	40	20	30	19	21	9	12
1050 F (25 hr) WQ	71	84	49	65	30	36	100	100	80	90	30	60	44	51	28	39
1050 F (25 hr) SC	31	44	20	30	8	15	55	70	35	50	20	30	17	25	6	12

1/2-Inch-Thick Plates Austenitized for 2 Hours at 1500 F, Blower-Cooled, Tempered for 2 Hours at 1050 F, and Blower-Cooled (BC)

Stress-Relieving Condition	Energy Absorbed, ft-lb				Shear Fracture, %				Lateral Expansion, mils				FATT, +		Hardness, RC	
	0 F		-80 F		0 F		-80 F		0 F		-80 F		F		RC	
	WQ*	BC*	WQ	BC	WQ	BC	WQ	BC	WQ	BC	WQ	BC	WQ	BC	WQ	BC
950 F (5 hr) SC	69	43	28	—	100	65	35	—	46	20	7	—	-115	—	36.0	—
(25 hr)	62	41	20	—	90	55	30	—	34	18	4	—	-90	—	36.5	—
(125 hr)	14	7	3	—	40	30	15	—	5	4	0	—	+80	—	36.0	—
1000 F (5 hr) SC	73	45	25	—	100	65	30	—	41	20	5	—	-105	—	36.5	—
(25 hr)	43	29	17	—	65	40	30	—	21	12	0	—	-40	—	35.5	—
(125 hr)	18	9	5	—	40	25	10	—	6	3	0	—	+110	—	34.0	—
1050 F (5 hr) SC	65	38	25	—	85	65	30	—	39	16	8	—	-110	—	36.5	—
(25 hr)	44	30	15	—	70	50	30	—	25	12	4	—	-80	—	33.5	—
(125 hr)	46	28	19	—	50	40	30	—	30	14	3	—	0	—	28.5	—

+Fracture-appearance (50% shear) transition temperature.

*WQ means water-quenched after a 30-minute austenitizing treatment at 1500 F and a 30-minute tempering treatment at 1080 F; BC means blower-cooled after a 2-hour austenitizing treatment at 1500 F and a 2-hour tempering treatment at 1050 F (1/2-inch-thick plate samples).

**WQ means water-quenched after stress-relieving; SC means slow-cooled (in Sil-O-Cel) after stress-relieving.

Table I
Chemical Composition of Steels Investigated--Percent
(Check Analyses)

Steel	Type Steel	Heat No.	Plate No.	C	Mn	P	S	Si	Ni	Cr	Mo	V	Al*	N**
A	HY-80 (Open Hearth)	72P305	089952-1	0.18	0.30	0.018	0.013	0.20	2.99	1.68	0.41	<0.01	0.022	0.007
B	HY-80 (Electric Furnace)	X51289	038334A1(1)	0.14	0.28	0.009	0.012	0.25	2.96	1.58	0.52	<0.01	0.071	0.014
C	5Ni-Cr-Mo-V (Electric Furnace)	X53185	0234802A3	0.095	0.74	0.005	0.005	0.27	4.96	0.62	0.55	0.067	0.018	0.010

*Acid soluble.

**Kjeldahl determination.

(40.018-001) (35)

UNITED STATES STEEL

Table II
Effect of Tempering Temperature and Time on the Longitudinal Mechanical Properties of
Quenched HY-80 and 5Ni-Cr-Mo-V Steel Plates

Steel	Type Steel	Tempering Time, hr	Yield Strength After Tempering, ksi			Charpy V-Notch Energy Absorption at 0 F After Tempering, ft-lb			Fracture-Appearance Transition Temperature (50% Shear) After Tempering, F			15-Mil Lateral Expansion Transition Temperature After Tempering, F		
			950 F	1000 F	1050 F	950 F	1000 F	1050 F	950 F	1000 F	1050 F	950 F	1000 F	1050 F
			950 F	1000 F	1050 F	950 F	1000 F	1050 F	950 F	1000 F	1050 F	950 F	1000 F	1050 F
A	HY-80 (Open-Hearth)	5	156	143	122	25	66	86	+ 40	- 85	-140	+ 40	- 90	-165
		25	144	123	110	53	88	91	- 55	-155	-120	- 35	-150	-180
		125	122	108	99	87	83	101	-105	-145	- 85	-120	-130	-110
B	HY-80 (Electric-Furnace)	5	131	128	119	42	50	99	+ 5	- 30	- 65	- 15	- 70	-135
		25	136	121	105	70	103	123	- 10	-120	-170	- 85	-165	-205
		125	130	106	92	79	121	146	- 85	-135	-120	-115	-170	-190
C	5Ni-Cr-Mo-V (Electric-Furnace)	5	136	144	144	86	98	100	- 80	-110	- 90	-135	195	-160
		25	141	143	137	92	58	73	- 80	- 10	- 65	-165	- 45	-110
		125	141	129	112	44	65	106	0	0	- 80	- 80	- 90	-175

NOTE: Plates (1/2-inch-thick) were austenitized for 2 hours at 1650 F (HY-80 steels) or at 1500 F (5Ni-Cr-Mo-V steel), blower-cooled to simulate the cooling rate at the center of a water-quenched 4-inch-thick plate, tempered for the indicated times at the indicated temperatures, and slow-cooled (in Sil-O-Cel).

Table III

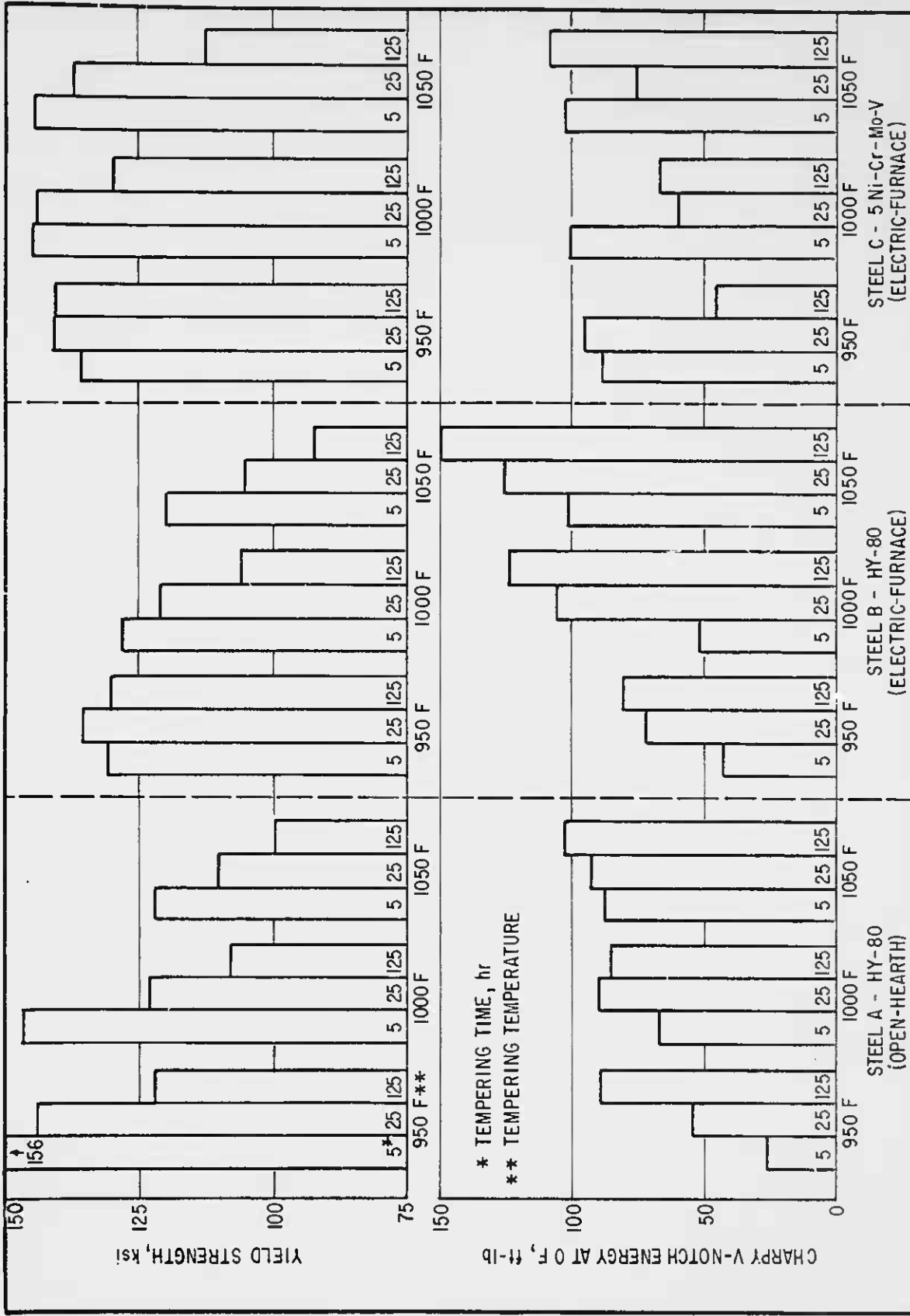
Effect of Stress-Relieving Temperature and Time on the Longitudinal Mechanical Properties of Quenched and Tempered HY-80 and 5Ni-Cr-Mo-V Steel Plates

Steel	Type Steel	Stress-Relieving Time, hr	Yield Strength After Stress Relieving, ksi			Charpy V-Notch Energy Absorption at 0 F After Stress Relieving, ft-lb			Fracture-Appearance Transition Temperature (50% Shear) After Stress Relieving, F			15-Mil Lateral Expansion Transition Temperature After Stress Relieving, F		
			950 F	1000 F	1050 F	950 F	1000 F	1050 F	950 F	1000 F	1050 F	950 F	1000 F	1050 F
A	HY-80 (Open-Hearth)	0	92	92	92	117	117	117	-260	-260	-260	-295	-295	-295
		5	93	87	91	121	117	117	-215	-190	-180	-230	-245	-250
		25	90	88	88	115	125	113	-150	-170	-155	-210	-195	-205
		125	89	88	88	117	99	105	-150	-125	-135	-185	-170	-170
B	HY-80 (Electric-Furnace)	0	89	89	89	142	142	142	-150	-150	-150	-255	-255	-255
		5	91	87	89	148	151	146	-170	-155	-185	-255	-210	-250
		25	89	86	83	149	155	144	-160	-125	-175	-210	-195	-205
		125	86	84	84	155	143	133	-165	-100	-135	-185	-170	-175
C	5Ni-Cr-Mo-V (Electric-Furnace)	0	143	143	143	81	81	81	-160	-160	-160	-155	-155	-155
		5	145	146	144	69	73	65	-115	-105	-110	-100	-95	-80
		25	143	143	139	62	43	44	-90	-40	-80	-90	-50	-55
		125	143	136	118	14	18	46	+80	+110	0	+120	+115	-70

NOTE: Plates (1/2-inch-thick) were austenitized for 2 hours at 1650 F (HY-80 steels) or at 1500 F (5Ni-Cr-Mo-V steel), blower-cooled to simulate the cooling rate at the center of a water-quenched 4-inch-thick plate, tempered for 2 hours at 1250 F (HY-80 steels) or at 1050 F (5Ni-Cr-Mo-V steel), blower-cooled, stress-relieved for the indicated times at the indicated temperatures, and slow-cooled (in Sil-O-Cel).

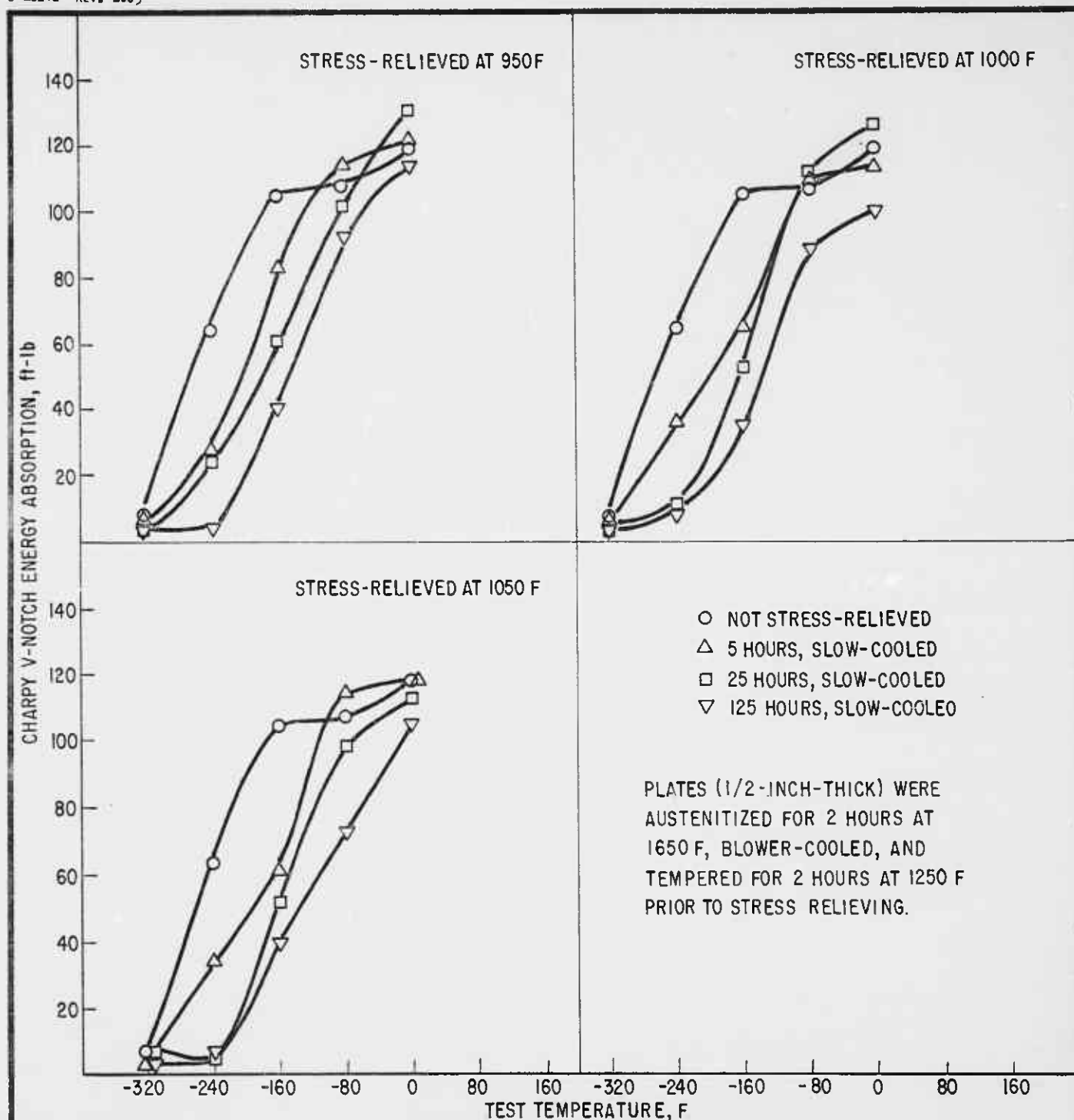
(40.018-001) (35)

UNITED STATES STEEL



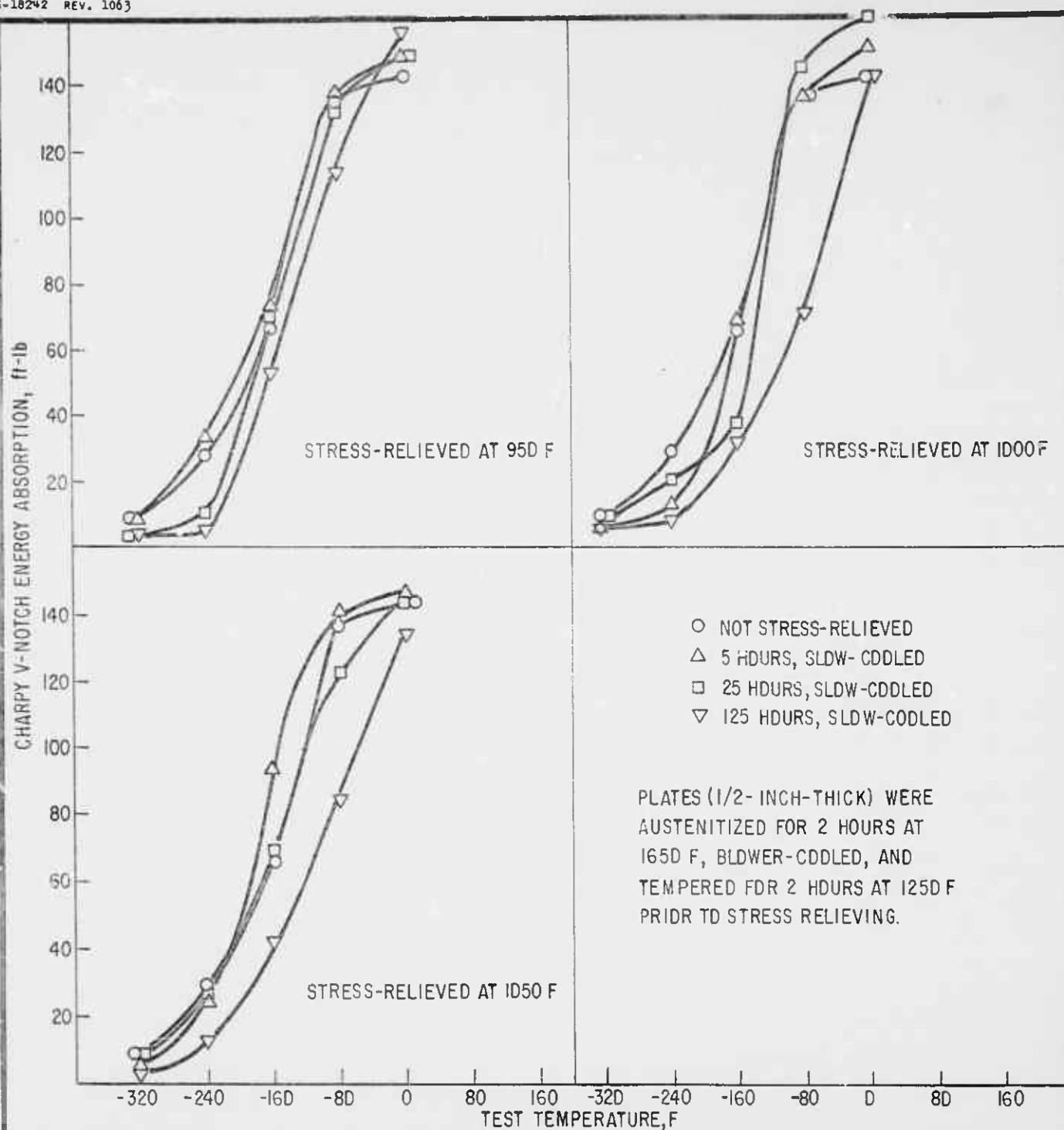
EFFECT OF TEMPERING TEMPERATURE AND TIME ON THE MECHANICAL PROPERTIES OF SIMULATED 4-INCH-THICK WATER-QUENCHED PLATES OF HY-80 AND 5 Ni-Cr-Mo-V STEELS

DRAWN BY M. M.		CHK'D BY J. H. G.		APPROVED BY J. H. G.	
DRAWING NO. ARL 18-448		PROJECT NO. 40.018-001 (35)		DATE 10/28/64	
UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA.				FIGURE NO. 1	



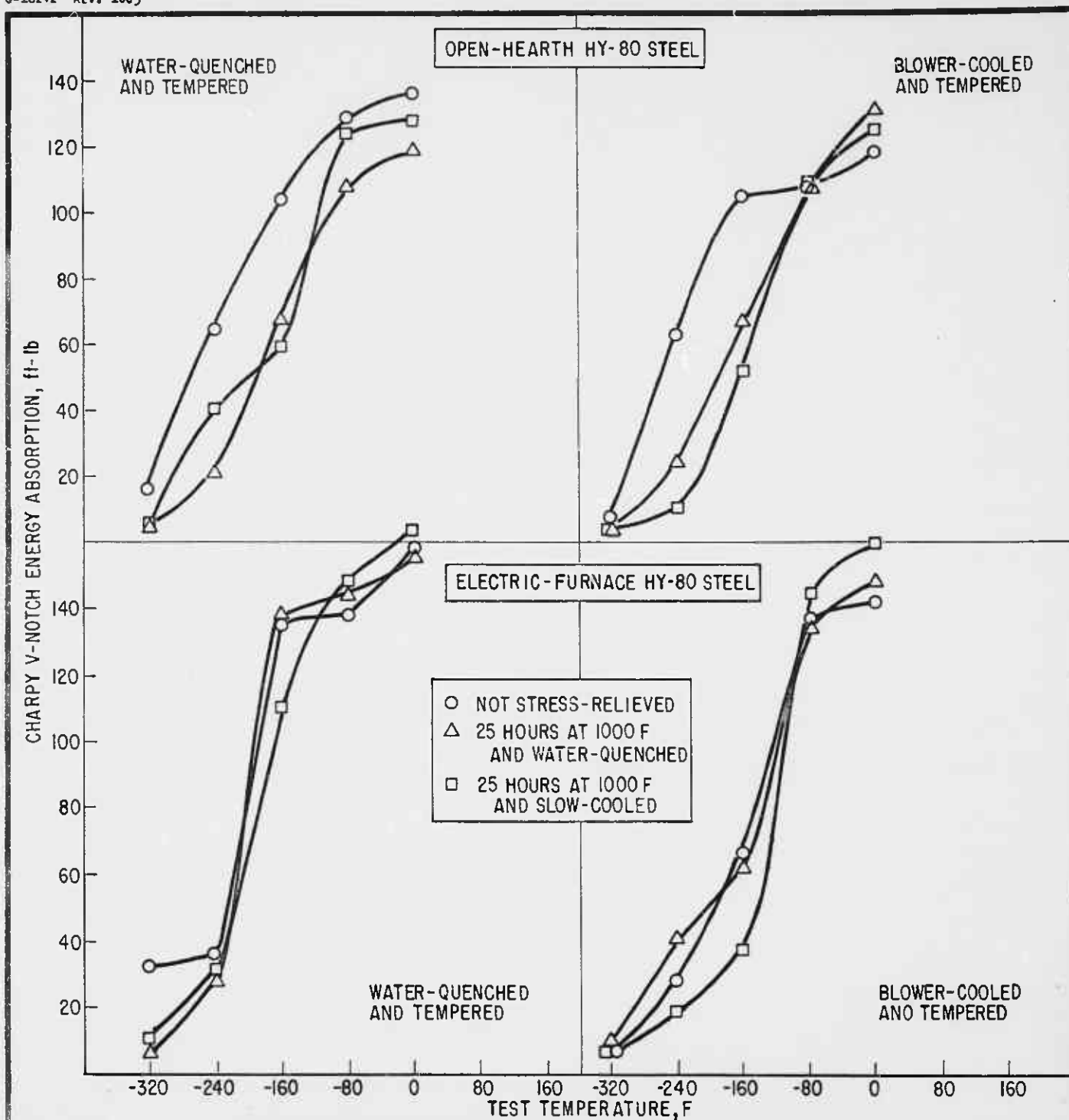
EFFECT OF STRESS-RELIEVING TEMPERATURE AND TIME ON THE ENERGY ABSORPTION OF OPEN-HEARTH HY-80 STEEL (HEAT NO. 72P305)

DRAWN BY M.M.	CHK'D BY S.J.M.	APPROVED BY J.H.G.	UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA.	FIGURE NO. 2
DRAWING No ARL 18-449		PROJECT No 40.018-001 (35)		
		DATE 10/30/64		



EFFECT OF STRESS-RELIEVING TEMPERATURE AND TIME ON THE ENERGY ABSORPTION
 OF ELECTRIC-FURNACE HY-80 STEEL (HEAT NO. X51289)

DRAWN BY M.M.	CHK'D BY S.J.M.	APPROVED BY J.H.G.	UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA.	FIGURE NO. 3
DRAWING No.		PROJECT No.		
ARL 18-450		40.018-001 (35) DATE 11/2/64		



EFFECT OF COOLING RATE AFTER STRESS RELIEVING ON THE ENERGY ABSORPTION OF HY-80 STEELS

DRAWN BY
M.M.

CHK'D BY
S. J. M.

APPROVED BY
J. H. G.

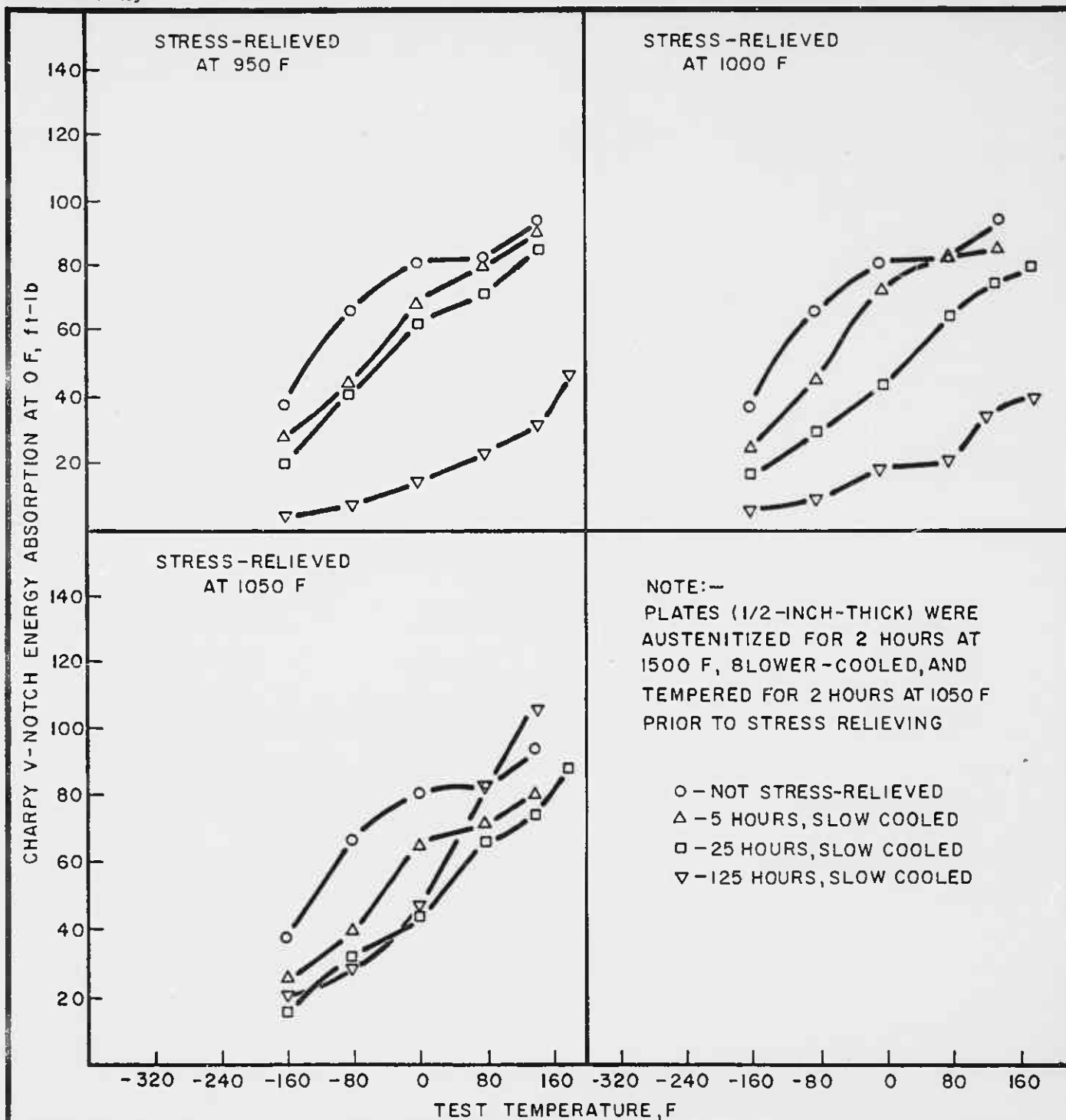
DRAWING No.
ARL 18-451

PROJECT No.
40.018-001 (35)

DATE
10/30/64

UNITED STATES STEEL CORPORATION
APPLIED RESEARCH
PITTSBURGH, PA.

FIGURE
NO.
4

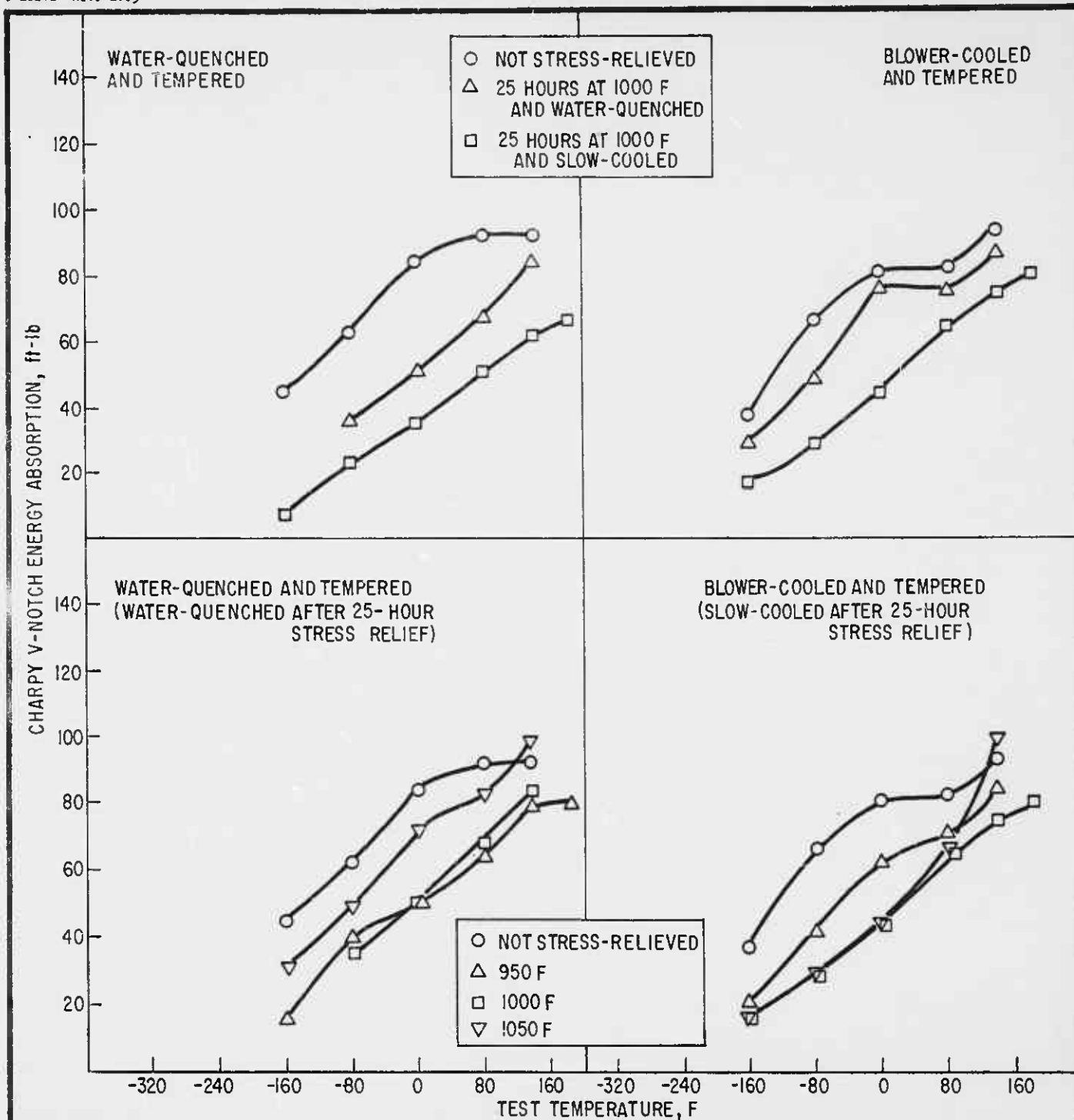


EFFECT OF STRESS-RELIEVING TEMPERATURE AND TIME ON THE ENERGY ABSORPTION OF ELECTRIC-FURNACE 5Ni-Cr-Mo-V STEEL (HEAT NO. X53185)

DRAWN BY G. A. Z.	CHK'D BY S. J. M.	APPROVED BY J. H. G.
DRAWING No. ARL 18-452		PROJECT No. 40.018-001(35)
		DATE 10-28-64

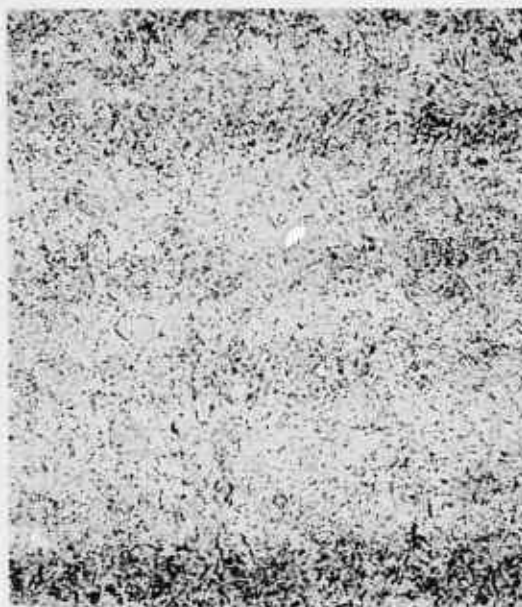
UNITED STATES STEEL CORPORATION
APPLIED RESEARCH
PITTSBURGH, PA.

FIGURE NO.
5

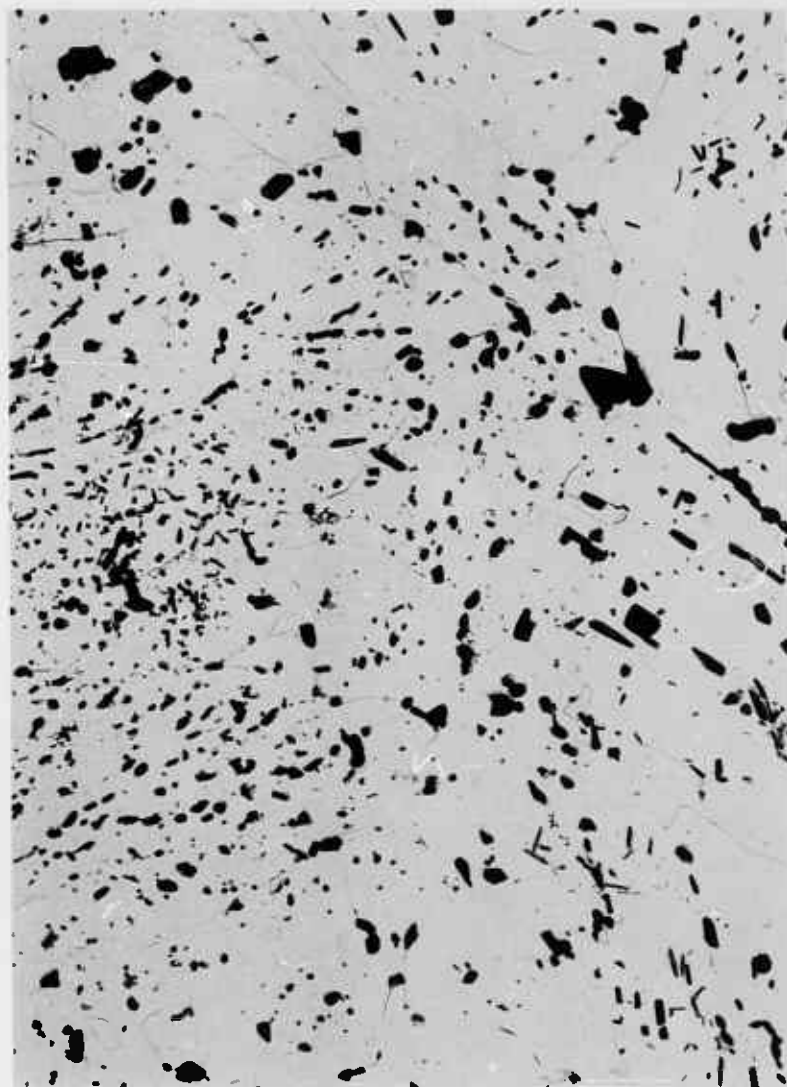


EFFECT OF COOLING RATE AFTER STRESS RELIEVING AND OF STRESS-RELIEVING TEMPERATURE ON THE ENERGY ABSORPTION OF ELECTRIC FURNACE 5 Ni-Cr-Mo-V STEEL

DRAWN BY M.M.	CHK'D BY S.J.M.	APPROVED BY J.H.G.	UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA.	FIGURE NO. 6
DRAWING No. ARL 18-453		PROJECT No. 40.018-001(35)		
		DATE 10/29/64		



A. Light photomicrograph.
X500.



B. Extraction photomicrograph. X12,000.

Figure 7. Electric-furnace HY-80 steel. Blower-cooled plate sample, not stress-relieved. Super pic

18-213A-1
18E-223A-2
18E-223A-1

1

(40.018-001) (35)

UNITED STATES STEEL



B. Extraction photomicrograph. X12,000.



C. Electron photomicrograph. X12,000.

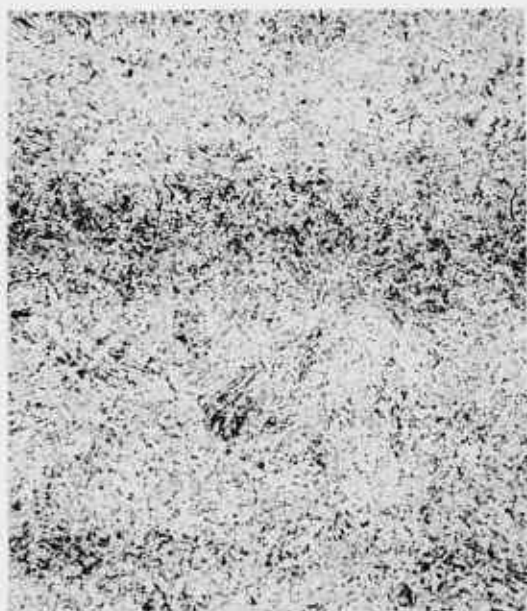
Electric-furnace HY-80 steel. Blower-cooled and tempered 1/2-inch-thick plate sample, not stress-relieved. Super picral etch.

(40.018-001) (35)

UNITED STATES STEEL

2

Figure 7A, B, C



A. Light photomicrograph.
X500.



B. Extraction photomicrograph. X12,000.

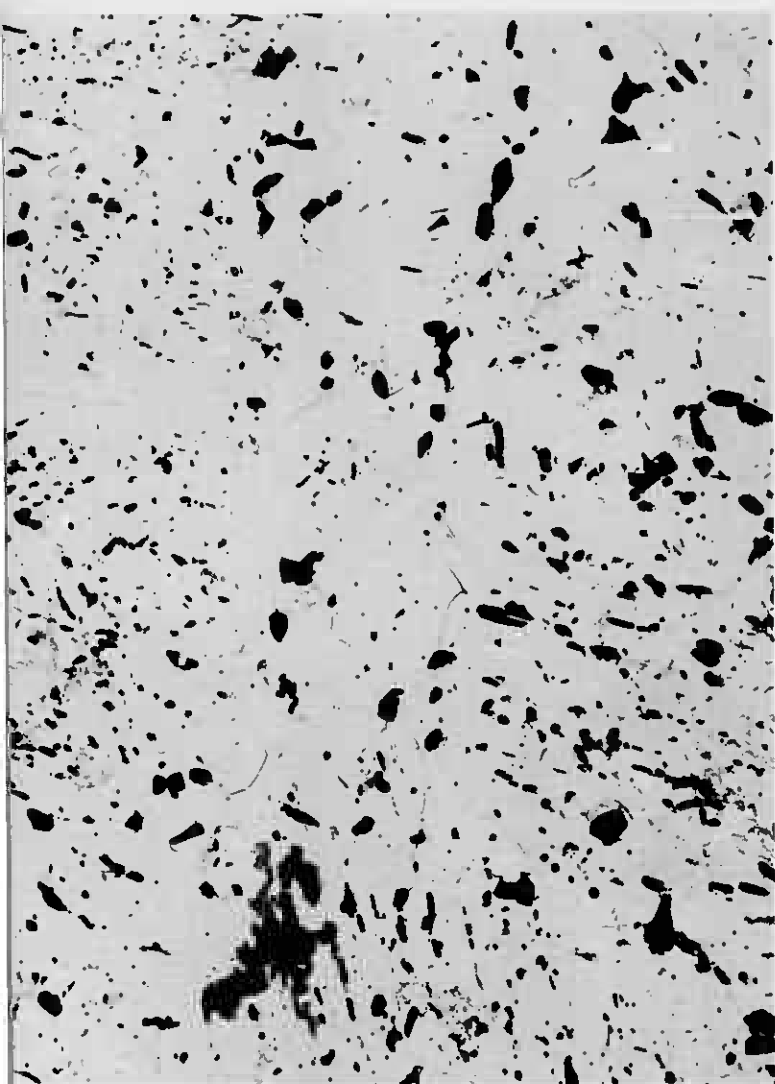
Figure 8. Electric-furnace HY-80 steel. Blower-cooled and plate sample. Stress-relieved for 125 hours at Super picral etch.

18-214A-1
18E-224A-1
18E-224A-2

1

(40.018-001)(35)

UNITED STATES STEEL



B. Extraction photomicrograph. X12,000.



C. Electron photomicrograph. X12,000.

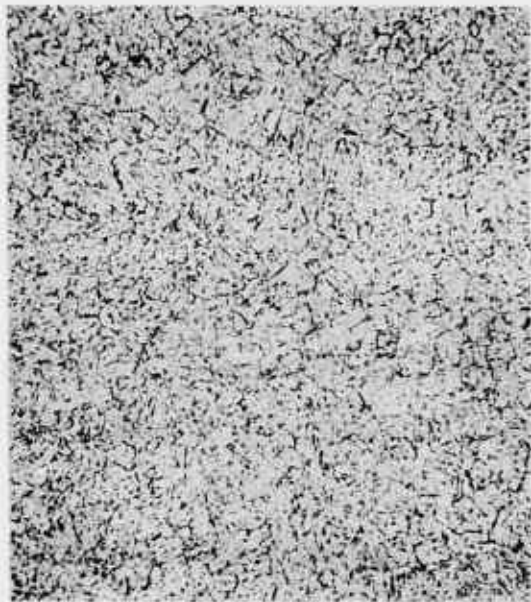
Electric-furnace HY-80 steel. Blower-cooled and tempered 1/2-inch-thick plate sample. Stress-relieved for 125 hours at 1000 F and slow-cooled. Super picral etch.

2

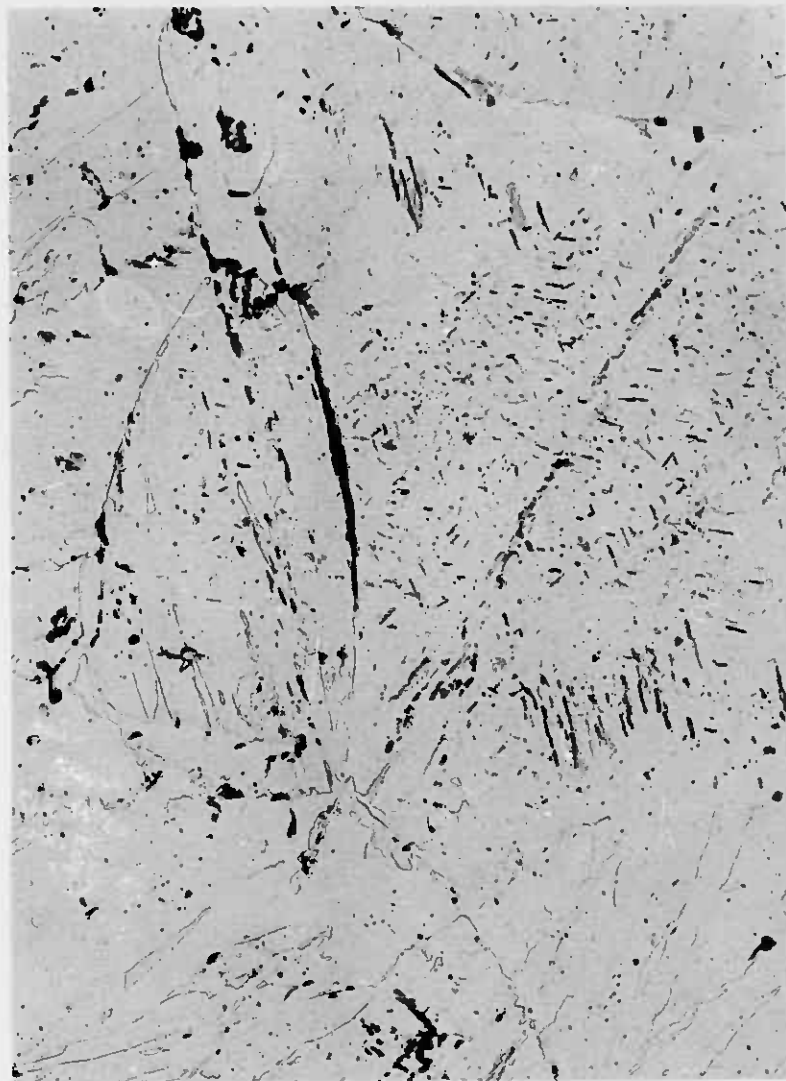
(40.018-001) (35)

Figure 8A, B, C

UNITED STATES STEEL



A. Light photomicrograph.
X500.



B. Extraction photomicrograph. X12,000.

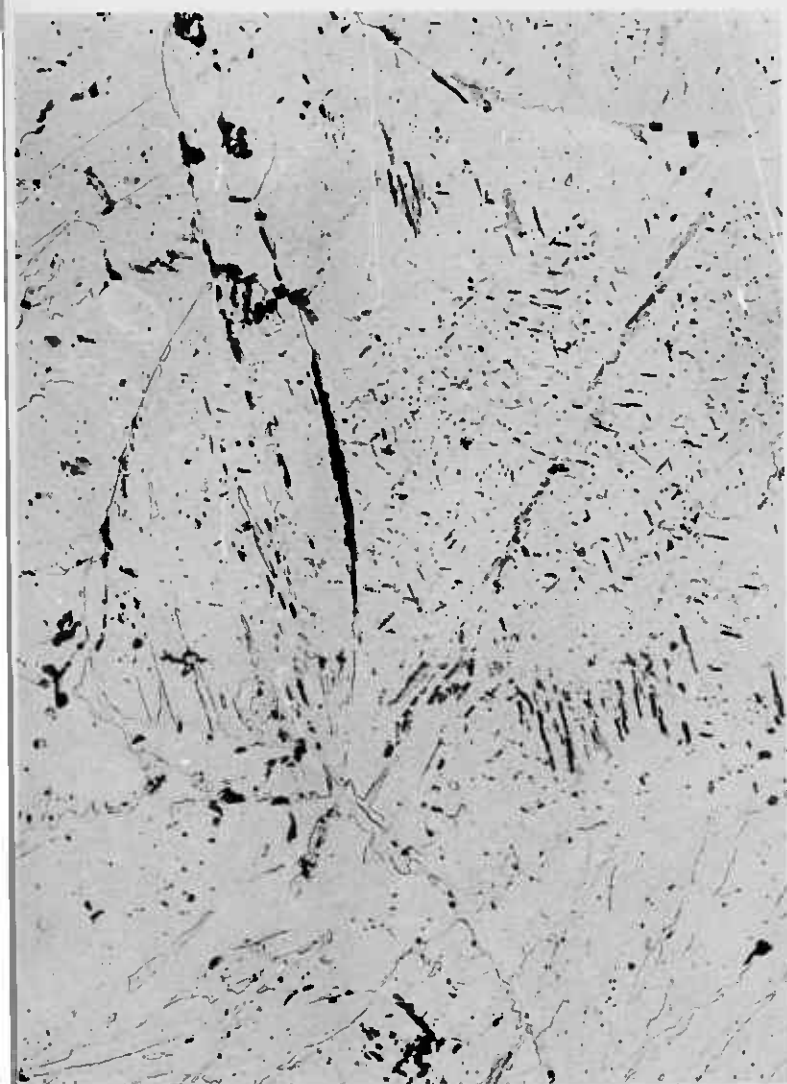
Figure 9. Electric-furnace 5Ni-Cr-Mo-V steel. Blower-cool
plate sample, not stress-relieved. Super picral

1

18-215A-1
18E-225A-1
18E-225A-2

(40.018-001) (35)

UNITED STATES STEEL



B. Extraction photomicrograph. X12,000.



C. Electron photomicrograph. X12,000.

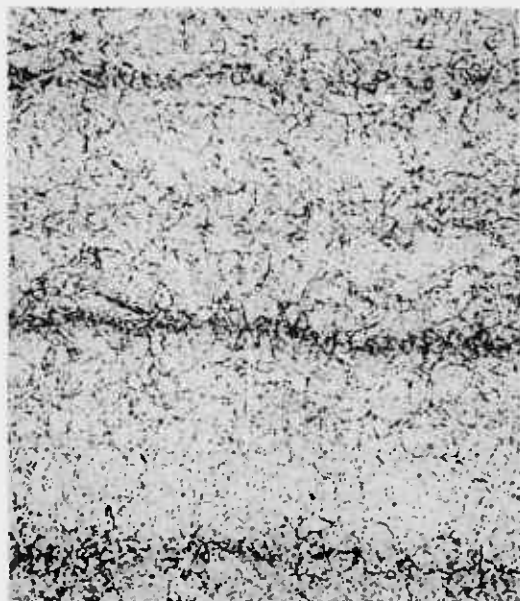
Electric-furnace 5Ni-Cr-Mo-V steel. Blower-cooled and tempered 1/2-inch-thick plate sample, not stress-relieved. Super picral etch.

(40.018-001)(35)

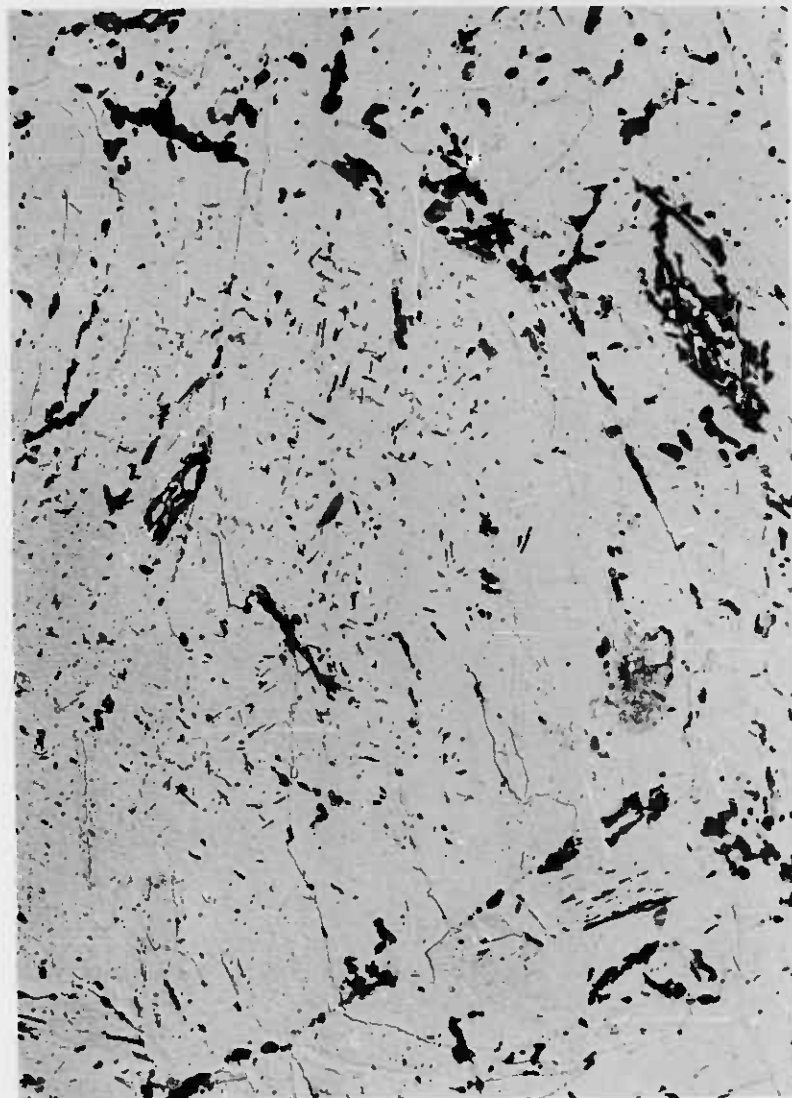
UNITED STATES STEEL

2

Figure 9A, B, C



A. Light photomicrograph.
X500.



B. Extraction photomicrograph. X12,000.

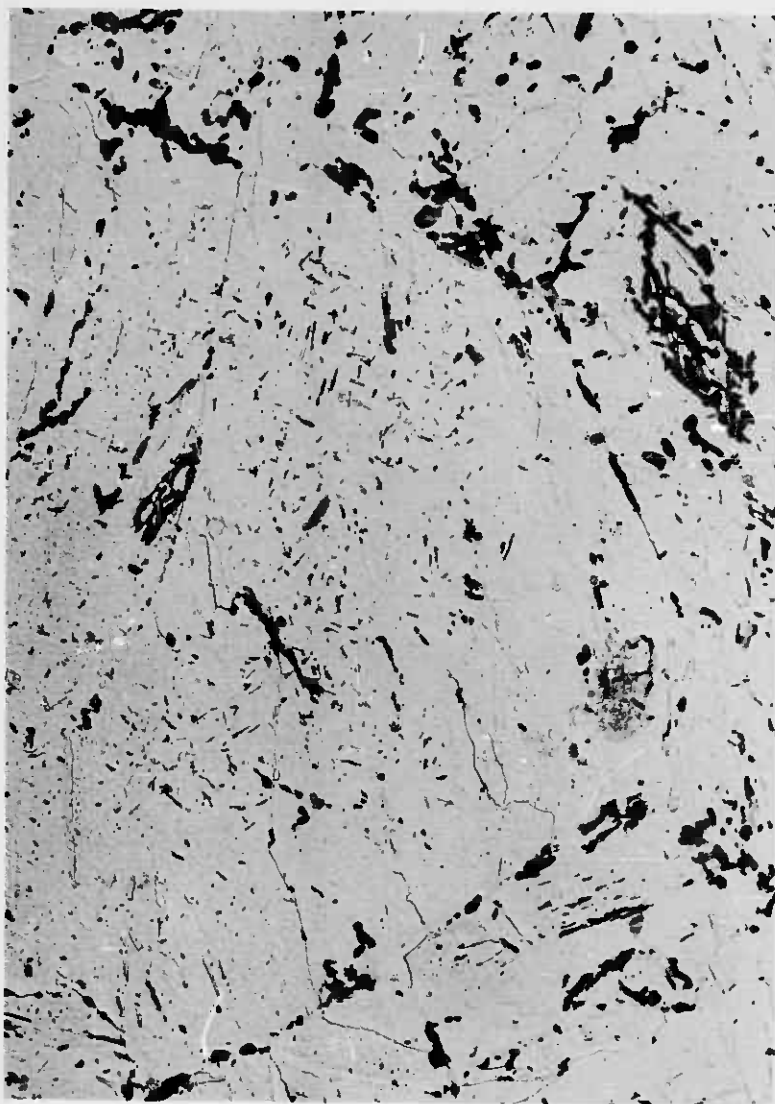
Figure 10. Electric-furnace 5Ni-Cr-Mo-V steel. Blower-cool plate sample. Stress-relieved for 125 hours at picral etch.

18-216A-1
18E-226A-1
18E-226A-2

1

(40.018-001) (35)

UNITED STATES STEEL



B. Extraction photomicrograph. X12,000.



C. Electron photomicrograph. X12,000.

0. Electric-furnace 5Ni-Cr-Mo-V steel. Blower-cooled and tempered 1/2-inch-thick plate sample. Stress-relieved for 125 hour at 1000 F and slow-cooled. Superpicral etch.

(40.018-001) (35)

UNITED STATES STEEL

2

Figure 10A, B, C



A. Light photomicrograph.
X500.



B. Electron photomicrograph. X12,000.

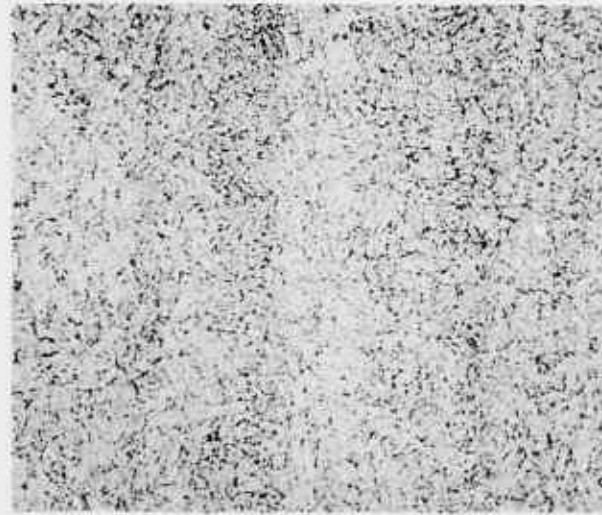
Figure 11. Electric-furnace HY-80 steel. Water-quenched and tempered 1/2-inch-thick plate sample, not stress-relieved. Super picral etch.

18-217A-1
18E-227A-1

(40.018-001) (35)

Figure 11A, B

UNITED STATES STEEL



A. Light photomicrograph.
X500.



B. Electron photomicrograph. X12,000.

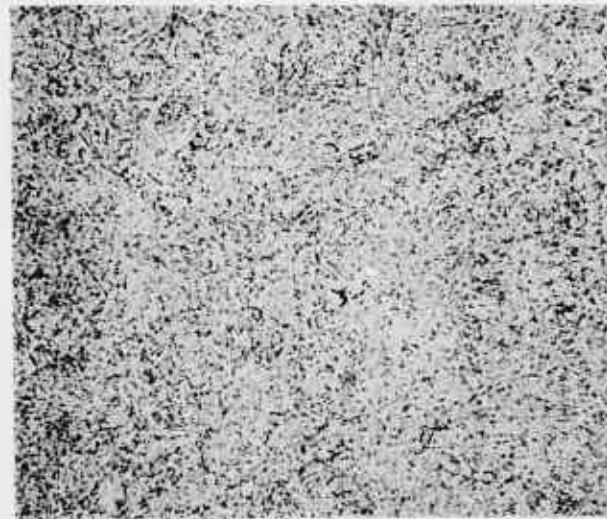
Figure 12. Electric-furnace HY-80 steel. Water-quenched and tempered 1/2-inch-thick plate sample. Stress-relieved for 25 hours at 1000 F and slow-cooled. Super picral etch.

18-218A-1
18E-228A-1

(40.018-001)(35)

Figure 12A, B

UNITED STATES STEEL



A. Light photomicrograph.
X500.



B. Electron photomicrograph. X12,000.

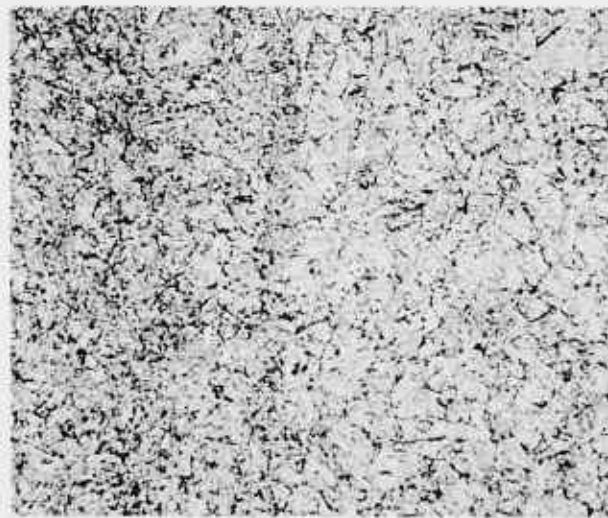
Figure 13. Electric-furnace HY-80 steel. Blower-cooled and tempered 1/2-inch-thick plate sample. Stress-relieved for 25 hours at 1000 F and slow-cooled. Super picral etch.

18-219A-1
18E-229A-1

(40.018-001) (35)

Figure 13A, B

UNITED STATES STEEL



A. Light photomicrograph.
X500.



B. Electron photomicrograph. X12,000.

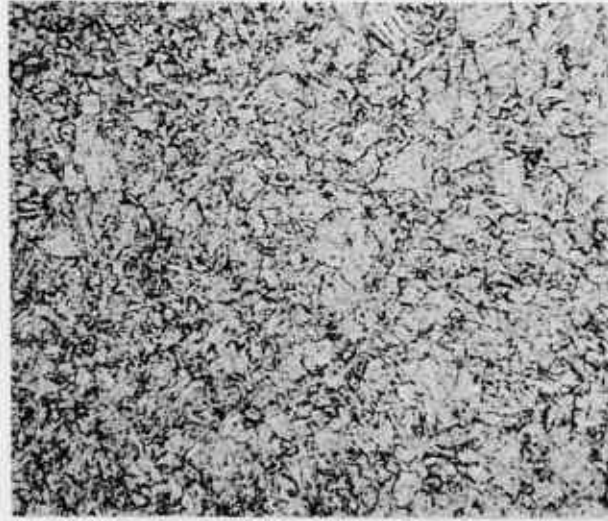
Figure 14. Electric-furnace 5Ni-Cr-Mo-V steel. Water-quenched and tempered 1/2-inch-thick plate sample, not stress-relieved. Super picral etch.

18-220A-1
18E-230A-1

(40.018-001) (35)

Figure 14A, B

UNITED STATES STEEL



A. Light photomicrograph.
X500.



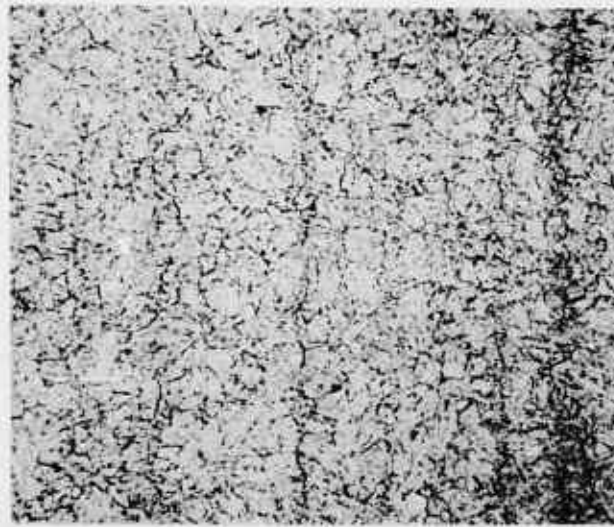
B. Electron photomicrograph. X12,000.

Figure 15. Electric-furnace 5Ni-Cr-Mo-V steel. Water-quenched and tempered 1/2-inch-thick plate sample. Stress-relieved for 25 hours at 1000 F and slow-cooled. Super picral etch.

18-221A-1
18E-231A-1

(40.018-001) (35)

Figure 15A, B



A. Light photomicrograph.
X500.



B. Electron photomicrograph. X12,000.

Figure 16. Electric-furnace 5Ni-Cr-Mo-V steel. Blower-cooled and tempered 1/2-inch-thick plate sample. Stress-relieved for 25 hours at 1000 F and slow-cooled. Super picral etch.

18-222A-1
18E-232A-1

(40.018-001) (35)

Figure 16A, B

UNITED STATES STEEL