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THE EFFECTS OF TEMPERED NONMARTENSITIC PRODUCTS ON THE NOTCH TOUGHNESS AND MECHANICAL PROPERTIES OF AN HY-80 STEEL

by

A. R. Willner and M. L. Salive

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ABSTRACT

This report discusses the effects of nonmartensitic products and mechanical properties on the nil-ductility-transition (NDT) temperature and transverse Charpy V-notch absorption level, for a selected HY-80 steel. Proeutectoid ferrite was found to have the most detrimental effect on the transverse Charpy maximum energy level. Large prior austenitic grain size, irrespective of microstructure, increases the NDT temperature by approximately 100 F. It is recommended that the present HY-80 specification be amended to require two chemistry ranges, one for thin and one for thick plates.

ADMINISTRATIVE INFORMATION

This work was initiated under Bureau of Ships sponsorship (BuShips letters A11/NS-011.083 (343) serial 343-211 of 26 May 1959 and R-7-0101 serial 634B-430 of 26 July 1960) and completed under the Model Basin Fundamental Research Program as Problem 735-184, Task 0401, Fundamental Research Project S-R001 01 01.

INTRODUCTION

This is the fifth in a series of preliminary reports[1-4*] on a program (see Figure 1) established to obtain metallurgical information concerning the effects of nonmartensitic products, chemical composition and impurities on the notch toughness and weldability of high strength steels.[5]

This report discusses the effects of nonmartensitic products and mechanical properties on the nil-ductility-transition (NDT) temperature, and transverse Charpy V-notch (C_V) maximum energy absorption level for a selected HY-80 steel. These data will be used by the Model Basin to evaluate the mechanical properties of HY-80 steel used in model construction and to correlate the response of HY-80 steels used in prototype construction.

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*References are listed on page 53.

BACKGROUND

In selecting a quenched and tempered structural steel, the general rule is to choose one that will quench to 100 percent martensite without retention of austenite that can later transform to nonmartensitic products upon tempering. However, one of the main requisites for development of the HY-80 steel was that the steel composition selected must harden to a minimum of 80 percent martensite after being quenched in still water.[6]

Previously reported hardenability calculations[4] showed that (1) commercially produced HY-80 steel plates 3 in. or more thick usually contain less than 80 percent martensite and (2) the reported longitudinal Charpy V-notch energies at -120 F decreased with increasing nonmartensitic products. A number of conflicting reports have been published, however, on the effects of nonmartensitic products on the notch toughness of tempered steels.[7-11] In general, these investigations concerned steels with carbon contents above 0.3 percent whereas, at the time of this investigation, HY-80 steel had a mill "ordered" carbon range from 0.14 to 0.23 percent.

Low carbon martensitic steels have been shown to have an overall Charpy V-notch toughness superiority over higher carbon steels with the same alloy content.[12] When NDT temperatures were investigated for the same steel series[13] (43XX series), however, it was shown that the lowest NDT temperatures for the strength levels investigated (90 to 240 ksi) were obtained for steels with a carbon content varying between 0.35 to 0.38 percent. Steels with a carbon content of 0.2 percent or less exhibited higher Charpy V-notch maximum shelf energies; however, neither of the cited investigations[12-13] studied the effects of tempered nonmartensitic products on notch toughness.

A previously reported work[14] on the effects of heat treatment on the microstructure and longitudinal Charpy V-notch temperature-energy relationship of rich-chemistry HY-80 steels was performed on 1- to $1^1/2$-in. thick HY-80 plate air cooled to simulate the microstructure of a water-quenched 8-in. thick section. This report[14] showed neither the effects of grain size nor the effects of given percentages of a nonmartensitic product on the mechanical properties; the effects of directionality and strength level on Charpy V-notch maximum shelf energies or on transition temperatures were not taken into consideration. The effects of directionality on the Charpy V-notch properties were fully discussed in References 1 and 2 and are commented upon in this report under the section dealing with materials and procedures.

Test procedures and means of correlating Charpy V-notch energy absorption values to resistance to shear tearing have been developed by the Naval Research Laboratory (NRL).[15] This work indicates that a Charpy V-notch shelf energy value of 40 to 50 ft-lb marks a point of transition in tearing resistance. It can be concluded from the NRL report[15] that materials of the strength levels presently being used in ship construction should have at operating temperature a Charpy V-notch maximum energy shelf of at least 40 to 50 ft-lb in the weakest direction in order to resist low-energy shearing. Therefore, the Charpy V-notch shelf of 40 to 50 ft-lb will be used in this report to evaluate the effects of nonmartensitic products, grain size, and strength level on the notch shear toughness of HY-80 steel. The brittle behavior or flat break temperature (NDT) will be determined by the drop weight test.

MATERIALS AND PROCEDURES

MATERIAL

For the present study, the Model Basin selected a 5/8-in. thick HY-80 plate (E103), similar in chemical composition to the 1/2-in. plate (HC) used in the initial studies;[1] see Table 1. Both of these plates were cross rolled approximately 7 percent but, as shown in Table 1, the inclusion count was higher for the 5/8-in. plate. However, as shown in Figure 2, the major difference between these two plates is their transverse maximum Charpy V-notch values. The upper and lower curves respectively represent specimens taken from the 1/2-in. HC plate and the 5/8-in. E103 plate. A similar spread in maximum Charpy values is also found in the longitudinal direction of commercially produced HY-80 steel.[16, 17] Therefore, the HC and E103 plates can be considered as representing, respectively, the upper and lower shear toughness bounds of commercially produced HY-80 steel.

TEST SPECIMENS

ASTM drop-weight specimens, Type P3, 5/8 x 2 x 5 in.[18] were used to study the effects of various heat treatments on the NDT temperature. Crack starter beads were placed on these drop-weight bars prior to heat treatment in accordance with procedures established in Reference 2.

All test specimens representing the 5/8-in. HY-80 plate E103 were obtained from the broken drop-weight bars after testing.

To prevent extraneous defects from masking the results of the variables being studied, the tensile specimens were machined parallel to the major direction of plate roll and the Charpy V-notch specimens from the transverse direction so that, if banding or nonmetallic inclusions were present within the test specimen, they would be distributed as dispersed particles and not act as crack arresters.

Threaded subsize 0.252-in.-diameter tensile specimens and standard Charpy V-notch specimens (notched perpendicular to the rolled surface through the thickness of the plate) were machined and tested in accordance with Federal standards.[19, 20]

Standard cylindrical compression specimens 0.5 in. in diameter and 2 in. long were machined from the 5/8-in. E103 plate in accordance with ASTM standards.[21]

MECHANICAL TEST PROCEDURES

In determining the drop-weight NDT temperature, the test procedures as outlined by the ASTM Standards[18] were used. The drop-weight specimens were tested over a range of temperatures with a 123-lb hammer falling from a height of 2 ft. A 0.075-in. stop arrangement in the bottom center of the jig limited the deflection of the specimen. A drop-weight specimen was considered broken when a crack emanating from the crack-starter bead propagated across the surface and down one side of the specimen. To determine the NDT temperature, a temperature increment of 20 F was used to bracket NDT.

Mechanical property load-strain curves were recorded using averaging microformer-type compressometers and extensometers. A 120,000-lb capacity Baldwin-Southwark hydraulic testing machine was used for all compression and tension testing; the machine calibrated within ± 0.5 percent.

A Baldwin subpress was used to avoid any eccentric loading in compression. Universal joint-threaded gripping devices were employed in tension testing. A strain magnification of 500 to 1 and a strain rate of 0.0025 in/in/min were used throughout this investigation.

Charpy V-notch impact specimens were tested in a Tinius-Olsen pendulum-type impact tester with 268 ft-lb capacity and a striking velocity of 16.85 ft/sec. Prior to testing, the machine was calibrated in accordance with ASTM standards.[22] Federal standard procedures[19, 20] were used for testing both the tensile and the Charpy V-notch specimens.

HEAT TREATMENT

All drop-weight specimens were heat treated in accordance with the steps shown in Figure 3. All austenitizing, isothermal treatments, and tempering were performed in neutral salt bath furnaces with temperatures controlled to within ± 5 F. Figure 4 was used to develop the isothermal holding times necessary to obtain a given percentage of nonmartensitic product. A check as to the actual percentage of transformation obtained was made for all treatments involving isothermal studies. Metallographic analysis of the untempered, as-quenched microstructures indicated that quenching was complete and that specimen size had no effect.

METALLOGRAPHY

Metallographic procedures for preparation of specimens have been discussed in the previously cited reports.[1, 3] However, for examination of microstructure and determination of percentages of isothermal products, three consecutive etching solutions were used. After each etch, the specimen was washed in alcohol and then dried. These solutions and their intended purpose are as follows:

1. An etch of saturated picric acid in alcohol plus two drops of sephiran chloride per 100 cc of solution was used for revealing ferritic grain boundaries.

2. An etch of 1 percent nital was used for revealing ferritic microstructures.

3. An etch of 20 percent sodium meta-bisulfite in water plus two drops of aerosol per 500 cc of solution was used for distinguishing isothermal products from martensite.

TEST RESULTS

The test results for each given heat-treating parameter investigated are summarized in Tables 2 through 5 and depicted in Figures 5 through 20. In addition, Charpy V-notch temperature transition curves for each of the nonmartensitic products investigated are available in the Appendix.

Since, as shown in Figure 2, the E103 HY-80 plate has a different Charpy curve than the HC HY-80 steel used in the previous investigation, a portion of this previous study had to be repeated in order to obtain a baseline for determining the relative effects of nonmartensitic products on the notch toughness of HY-80 steel.

MICROSTRUCTURE

The resultant microstructures for each of the heat treatments studied are compared in Figures 5, 6, and 7.

EFFECTS OF FINE AUSTENITIC GRAIN SIZE AND NONMARTENSITIC PRODUCTS ON THE MECHANICAL PROPERTIES

Effects of Tempering Temperature

Figure 8 is a plot of mechanical tensile properties and NDT temperature versus tempering temperature of HY-80 (E103) heat treated to a fine grain structure, ASTM 9, and isothermally treated to contain various percentages of nonmartensitic products.

Up to the tempering temperature of 1000 F, bainite lowers the ultimate and yield strengths and increases the NDT temperature. Above 1000 F, the mechanical and NDT properties of the partially bainitic and the martensitic structures coincide. The mechanical tensile property results agree with the previous analysis made on commercial HY-80 steel production which indicated that the tempering temperature used by the producers were independent of nonmartensitic products.[4] Increasing the tempering temperature above 1150 F increases the NDT temperature for the fully martensitic structure as well as for the structure containing bainite; however, the NDT temperatures were well within the acceptable range for HY-80 plate.

As shown in Figure 8, various percentages of proeutectoid ferrite lower the mechanical properties more for a given tempering temperature than does bainite. Surprisingly, the greater the ferrite content the lower the NDT temperature; this is probably due to the lower strength, higher toughness ferrite. It should be understood that commercially produced HY-80 steel plates over 1 1/2 in. thick have an average Grossman's D_{I-50M}* hardenability factor of 6 in.,[4] which is representative of an "S" type of time-temperature-transformation (TTT) curve; see Figure 4. The initiation of the 1200 F proeutectoid ferrite nose is at 100 sec; however, as shown in the lower corner of Figure 4, over 2500-sec holding time is required to produce a microstructure containing 20 percent ferrite. Increasing or decreasing the transformation temperature within the ferritic range markedly increases the required initiation time as shown in Figure 4. It should be understood that HY-80 steel with a D_{I-50M} of 2.7 in. or less will have a "C" type of TTT curve (see Figure 4), which will be conducive to ferrite formation when heat treating low chemistry plates over 1 in. thick. "C" type TTT curves can also be produced with HY-80 steels having D_{I-50M} greater than 2.7 in. if the carbon content is high and chromium (Cr) and molybdenum (Mo) content are on the lean side. Increasing percentages of carbon will extend the initiation of transformation time, but only increasing percentages of Cr and Mo will change the nose of TTT curve for HY-80 steels.

Effects of Strength Level on Toughness

Figures 9 and 10 show the effects of strength level on the NDT temperature and Charpy V-notch properties for the HY-80 steel plate E103; for comparative purposes, the transverse maximum Charpy energy has been included.

Figure 9 indicates that various percentages of bainite have a slight effect on the NDT temperature for a given strength level. The minimum NDT temperature for the HY-80 steel containing bainite is reached

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*Grossman's factors for calculating D_{I-50M} are based on a 50 percent martensitic structure at the center of a round bar after an ideal quench.

between 90- and 100-ksi yield strength. The highest NDT is reached around 140-ksi yield strength and then the NDT decreases with increasing strength levels. Surprisingly, with yield strengths below 80 ksi, there is an increase in NDT temperature.

As shown in Figure 9, the transverse Charpy V-notch energy absorption and lateral expansion of specimens broken at the NDT temperature indicate a uniform correlation at the various strength levels. In other words, at the NDT temperature, the transverse Charpy energies and lateral expansion of the HY-80 steel containing bainite appear to fall within a predictable range, i.e., 20 to 30 ft-lb and 15 to 25 mils lateral expansion for yield strengths 120 ksi and below; for yield strengths above 120 ksi, the transverse Charpy values at the NDT temperature fall at about 20 ft-lb and 8 mils lateral expansion. Surprisingly, there is no correlation between Charpy V-notch fibrous fracture appearance at the NDT temperature and the yield strength of the material.

The transverse Charpy V-notch maximum energies decrease with increasing strength levels. However, there is no dramatic separation due to bainite in the maximum energy to yield strength correlation. The 40 ft-lb Charpy shelf is reached between 110- to 120-ksi yield strength.

There is a correlation between increasing percentages of ferrite, the NDT temperature, and strength level as shown in Figure 9; however, there is no simple correlation between transverse Charpy V-notch properties at the NDT temperature as was found for the martensitic and bainitic structures.

Figure 10 is similar to Figure 9 except that ultimate tensile strength rather than yield strength is the basis of correlation. The same correlations are found in Figure 10 as were found in Figure 9 and, therefore, they will not be discussed further.

Effects of Strength Level and Fibrous Fracture Appearance on Charpy V-Notch Properties

It has been shown previously that the Charpy V-notch energy absorbed can be predicted from the yield strength for a given Charpy fibrous fracture transition appearance of a fully quenched HY-80 steel.[1]

Maximum energies were obtained at 212 F, whereas the Charpy V-notch 100 percent fibrous fracture is defined as that point on a Charpy V-notch fracture transition curve that will just show an all-fibrous fracture appearance. The Charpy V-notch energies and temperatures for a specific fibrous condition were obtained from the Charpy property curves of the Appendix and are depicted in Figures 11 and 12 as a function of the strength level.

The maximum energy curves depicted in Figure 11 are the same as the upper curves shown in Figures 9 and 10. The maximum energy curves for the material containing various percentages of bainite follow the fully martensitic curve. However, the curves which represent those Charpy specimens containing ferrite fall well below the curves for bainite and martensite specimens.

The 40 ft-lb energy at 32 F is considered the lower bound for shear tearing resistance in steels exhibiting 100 percent Charpy V-notch fibrous fracture appearance. It can be seen from Figure 11 that the 40 ft-lb transverse Charpy level at 100 percent fibrous fracture for specimens containing various percentages of tempered bainite fall between the 110- and 120-ksi yield-strength level, whereas for specimens containing ferrite, the 40 ft-lb energy is reached at about 90-ksi yield strength. As seen in Figure 12, the 100 percent Charpy V-notch fibrous fracture energy for these strength levels falls at or below 32 F. As shown in Figure 11, the energy level transition is greatly influenced by strength level as well as by microstructure; however, as shown in Figure 12, the 100 percent fibrous fracture transition temperature is not significantly affected until the 120-ksi yield-strength level is approached.

It can be seen from Table 3 that below 115-ksi yield strength, Charpy specimens with 100 or 80 percent fibrous fracture appearance meet the 40 ft-lb energy level at 32 F or lower. However, the Charpy energy level at 50 and 30 percent fibrous fracture appearance did not meet the 40 ft-lb level for any given yield strength.

EFFECTS OF LARGE AUSTENITIC GRAIN SIZE AND NONMARTENSITIC PRODUCTS ON THE MECHANICAL PROPERTIES

The effects of strength level on fully quenched and tempered steels which were austenitized to produce a variety of grain sizes have been reported for the HC HY-80 steel plate.[1] The results indicated that the Charpy V-notch transition temperatures increased with increasing austenitizing and decreasing tempering temperatures. It was also shown that increasing grain size did not lower the Charpy V-notch maximum energy shelf.

Effects of Tempering Temperatures

In order to study the effects of grain size and nonmartensitic products on the notch toughness, energy absorption, and transition temperatures, the drop-weight specimens were austenitized at 2000 F, transferred to a 1640 F salt bath, and then isothermally held at the temperature of interest. The prior austenitic grain size was found to be approximately ASTM 3.5. Although the holding times at the isothermal temperatures were the same as used for the fine grain studies, the percentage of transformation products was considerably less. This is attributed to the fact that large grain size shifts the initiation of transformation to longer times.[23]

The mechanical and NDT temperatures are plotted in Figure 13 as a function of tempering temperature. Similar mechanical tensile properties are found for coarse- and fine-grain structures (compare Figures 13 and 8). It should be remembered in comparing these two figures that the coarse-grain structures contained less isothermal products than did the fine-grain structures.

The NDT temperature shown in Figure 13 is approximately 100 F higher for the coarse-grain structures than for the fine-grain structures. This difference holds regardless of the type of nonmartensitic structure investigated.

Effects of Strength Level on Toughness

Figures 14 and 15 show, respectively, the effects of strength level on the NDT temperature and on the transverse Charpy properties at the NDT temperatures for the coarse-grain structures, ASTM 3.5. For comparative purposes, the maximum Charpy V-notch energy levels for various strengths are included on these figures.

The HY-80 steel plate E103 with an ASTM grain size of 3.5 has an NDT temperature ranging from -140 to -30 F for yield strengths between 80 to 100 ksi. The most detrimental effect on the NDT temperature appears to be produced by 17 percent bainite; 9 percent proeutectoid ferrite has an adverse effect on the NDT, but not to the same degree as the 17 percent bainite. However, it is doubtful that normal commercially produced HY-80 steel will be cooled at such a slow rate as to produce any proeutectoid ferrite during heat treating or welding.

The transverse Charpy V-notch values at the NDT temperature are 25 to 35 ft-lb and 5 to 25 mils lateral expansion. Again, the Charpy V-notch fibrous fracture appearance does not show any relationship for predicting the NDT temperature.

Effects of Strength Level and Fibrous Fracture Appearance on Charpy V-Notch Properties

Figures 16 and 17 show the correlation between transverse Charpy V-notch energy absorbed and fibrous fracture transition temperatures for these large-grained structures at given percentages of fibrous fracture appearance at various strength levels.

Table 6 shows the transverse Charpy V-notch energy absorption and the temperature at which 100 percent fibrous fracture appearance occurs for 80- and 100-ksi yield strengths. It should be remembered when reviewing this table that the isothermal holding time required to obtain the nonmartensitic products is exceptionally long. In production heat treatment, the 2000 F austenitizing treatment would not be used. When welding, temperatures of 2000 F and above will be obtained; however, the cooling rate between 2000 F and the start of martensite transformation temperature (Ms) are such that the temperature lag required to obtain nonmartensitic products will not occur.

Table 6 shows that HY-80 having a large grain size (ASTM 3.5) and nonmartensitic products will have transverse Charpy energies in excess of 40 ft-lb. The specimens containing 17 percent bainite have a 100 percent Charpy V-notch fibrous fracture transition temperature over 100 F. The transition temperature for the specimens containing 9 percent ferrite is sensitive to yield-strength level; i.e., the transition temperatures are increased ten-fold when going from 80- to 100-ksi yield strength.

Since the shear transition of HY-80 steel is evaluated at 32 F, Table 7 was compiled from Figures 16 and 17 to show the relationship between yield strength and transverse Charpy energy values occurring at 32 F for the 100 percent fibrous appearance. This table shows that except for the structure containing 17 percent bainite, the Charpy values at 32 F for the yield strength shown (80 to 113 ksi) are well above the 40 ft-lb minimum.

YIELDING CHARACTERISTICS

Since the stress-strain curves of HY-80 steel are of interest for design purposes to predict buckling or instability ranges,[4] Figures 18 and 19 depict the effects of grain size, various isothermal treatments, and tempering temperature on the tensile yielding characteristics of HY-80 steel.

These figures show that the stress-strain curves between 80- and 100-ksi yield strength have a discontinuous type of yielding characteristic. That is, the stress-strain curves have either upper and lower yield points, a plateau, or a semi-plateau yielding characteristic. It is interesting to note in Figure 18 that for the fine grain HY-80 steel isothermally treated to contain 25 percent ferrite and tempered at 1250 F, there are two types of stress-strain curves, the curvilinear and the discontinuous.

Effects of Continuous Cooling

Since variations in cooling rates can produce a multiplicity of microstructures, a limited study was made to evaluate the effects of nonmartensitic products formed by three different cooling rates.

All specimens were austenitized (1640 F) at the same time. One series of specimens was removed from the furnace and water quenched, the second series was air cooled, and the third series was left in the furnace and allowed to cool with the door open. All specimens were tempered at 1150 F for 1 hr. The following cooling rates were obtained between 1350 and 800 F:

Water quenched	5×10^3 F/min
Air cooled	35.1 F/min
Slow cooled	9.5 F/min

Microstructure

The resultant microstructure for each of these cooling rates may be compared in Figures 5 and 20. Figure 5b shows the tempered martensitic appearance of the water-quenched steel, and Figures 20a and 20b show the microstructure for the tempered air-cooled and slow-cooled specimens which consisted of upper and lower bainites.

Mechanical and Notch Toughness Properties

The mechanical and notch toughness properties obtained from the HY-80 specimens which were water quenched, air cooled, and slow cooled are given in Table 8. The water-quenched specimens have the highest yield strength but the others also meet the 80-ksi yield strength minimum requirements. All have acceptable NDT temperatures and acceptable Charpy maximum energy shelves.

DISCUSSION

It was shown in a previous report[4] that HY-80 steel produced in accordance with MIL-S-16216E and F was to a lower hardenability than that made under MIL-S-16216D. If this historical trend continues, the producers may start to make HY-80 steel under MIL-S-16216G to still lower hardenabilities. Since the longitudinal Charpy values are only representative of the NDT temperature and not the maximum shear energy, difficulties could arise because the nonmartensitic product may become predominately ferrite with the associated reduction in shear tearing resistance.

Figure 11 indicates the detrimental effect that ferrite can have on the maximum and 100 percent fibrous fracture shear energy level. Additional difficulty can occur in the heat-affected zone of a thick plate made to a low hardenability where a small percentage of ferrite and large grain size could affect the shear tearing resistance of the zone having an incremental yield strength over 100 ksi. This is borne out by previous experimental work[24] on the effects of lowering the hardenability of heavy gage plates.

The 80 percent martensitic requirement specified in MIL-S-16216G should be adhered to. In fact, to ensure that HY-80 steel has a pearlitic hardenability greater than its bainitic hardenability, the two chemistry ranges, one for thin and one for thick plates, previously specified in MIL-S-16216D should be made a requirement of the current specification.

The HY-80 E103 plate heat treated to a fine grain structure and containing isothermal bainites in the ranges studied will meet the minimum mechanical property and notch toughness requirements of MIL-S-16216G.

If temperatures are used in fabrication which will coarsen the grain size to ASTM 4 or less and the yield strength is raised above 120 ksi, shear tearing may occur, especially in the presence of nonmartensitic products. Plates 3 in. or more in thickness will probably contain bainite in excess of 20 percent.[4] It is doubtful that they would contain any proeutectoid ferrite. However, the present study has shown that bainite should not significantly affect the notch toughness. The heat-affected zone produced by welding thick plates made to a rich chemical analysis with the specified heat inputs of 55,000 j/in. or less[25] should not produce any significant amounts of bainite.[23] This does not preclude cracking in the heat-affected zone due to chemical composition; for example, having high sulphur content in the presence of high nickel content or having a high percentage of nonmetallic inclusions.

An analysis of the effect of nonmartensitic products on commercially produced plates has been completed and will be published. The present report will be used as a baseline for comparing the effects of nonmartensitic products on commercially produced heats.

CONCLUSIONS

The following conclusions can be derived from this study:

1. Up to 50 percent bainite (with the remainder martensite) in HY-80 steel has very little effect on the NDT temperature and the Charpy V-notch maximum energy properties.

2. Proeutectoid ferrite has a detrimental effect on the Charpy V-notch maximum energy level of HY-80 steel, especially with increasing strength level. At yield-strength levels of approximately 90 ksi, the maximum Charpy energy level met the 40 ft-lb requirement established herein as a criterion.

3. Large prior austenitic grain size has no effect on the maximum Charpy V-notch level for a given yield strength; however, the transverse Charpy V-notch fibrous fracture transition temperature is quite sensitive to yield-strength level and microstructure.

4. The NDT temperature for structures having large prior austenitic grain size are approximately 100 F higher than the NDT temperatures of fine-grained structures regardless of microstructure.

RECOMMENDATIONS

1. The 80 percent martensitic microstructure requirement of MIL-S-16216G should be kept in the specification.

2. The two chemistry ranges, one for thin and one for thick plates, previously specified in MIL-S-16216D should be made a part of the current HY-80 specification.

TABLE 1

Comparison of Chemical Composition and Inclusion Content of Two HY-80 Steel Plates Used in the Present and in a Previous DTMB Study

TABLE 1A

Chemical Composition, Percent

Alloying Element	DTMB Plate Designation	
	E103	HC
C	0.16	0.15
Mn	0.30	0.24
P	0.009	0.011
S	0.017	0.014
Si	0.25	0.14
Ni	2.78	2.85
Cr	1.52	1.44
Mo	0.36	0.45
Cu	0.058	0.03
Total Al	0.042	0.037
Acid Sol. Al	0.038	0.034
Ti	0.001	0.001
V	0.001	0.001
Pb	0.001	0.002
Sn	0.004	0.005
Mg	0.001	0.001
O_2	0.008	0.009
N_2	0.009	0.008
H_2	<.0001	<.0001

TABLE 1B

Inclusion Content[1]

Direction	DTMB Plot Designation	
	E103	HC
Transverse	0.5^{vd}-0-A	0.6^{vd}-0-B
Longitudinal	1.1^{vd}-0-C	2.0^{vd}-1.2^{5}-B

1. ASTM, E45-51, Method B

TABLE 2

Effects of Microstructure and Tempering Temperature on the Mechanical Properties and Notch Toughness of HY-80 Steel (DTMB Plate E103) Austenitized at 1640 F

Isothermal Treatment		Tempering	Microstructure	Specimen Direction	Tensile Properties					Notch Toughness Properties		
							Percent		Ratio		Charpy V-Notch Energy, Ft-lb	
Temperature degrees F	Time Seconds	Temperature degrees F	Percent		0.2 Percent Offset Yield Strength ksi	Ultimate Tensile Strength ksi	Elong in/in.	Red. in Area	Y.S./U.T.S. x 100	NDT Temperature deg F	at NDT	Maximum Energy
		80	100 M	Trans	148	200	14	45	74	-150	21	23
		400	100 M	Long	161	193	14	62	84			
				Trans	158	193	15	47	83	-165	22	25
		600	100 M	Long	160	186	16	61	86		33	48
				Trans						-130	24	24
		900	100 M	Long	152	165	18	66	92	-110		
				Trans	155	169	16	51	92	-110	21	25
		1000	100 M	Long	140	154	19	68	91	-120	48	86
				Trans						-110	26	32
		1100	100 M	Long								
				Trans	113	124	19	60	91	-170	25	42
		1150	100 M	Long	103	116	24	76	89	-220	46	133
				Trans	104	116	22	63	89	-210	29	56
		1250	100 M	Long	91	105	27	78	87	-255	45	139
				Trans						-255	24	56
		1270	100 M	Long	85	103	28	77	83	-240	54	151
				Trans						-240	29	65
		1300	100 M	Long	82	104	27	76	79			
				Trans						-190	38	62
		1330	100 M	Long	81	105	27	76	77			
				Trans						-190	37	58
875	152	400	25 B & 75 M	Long	151	193	17	56	79			
				Trans	152	193	14	40	79	-150	19	22
875	152	600	25 B & 75 M	Trans	151	184	13	46	82	- 90	16	22
875	152	1000	25 B & 75 M	Trans	138	155	17	52	89	- 90	20	27
875	152	1150	25 B & 75 M	Long	106	120	22	76	88			
				Trans	108	121	22	64	89	-220	26	48
875	152	1250	25 B & 75 M	Trans	82	102	26	67	80	-190	30	56
875	1600	400	50 B & 50 M	Long	139	186	16	56	75			
				Trans	143	187	14	47	76	-110	19	21
875	1600	600	50 B & 50 M	Trans	140	174	13	44	80	- 70	14	21
875	1600	1000	50 B & 50 M	Trans	132	148	15	45	89	- 70	24	28
875	1600	1150	50 B & 50 M	Long	100	114	24	75	88	-215	49	143
				Trans	101	116	22	63	87	-200	26	53
875	1600	1250	50 B & 50 M	Trans	80	103	26	65	78	-150	34	54
965	3600	1150	2X & 98 M	Long	108	121	22	75	89			
				Trans						-200	27	49

875	1600	1000	50 B & 50 M	Trans	132	148	15	45	69	- 70	24	28
875	1600	1150	50 B & 50 M	Long	100	114	24	75	88	-215	49	143
				Trans	101	116	22	63	87	-200	26	53
875	1600	1250	50 B & 50 M	Trans	80	103	26	65	78	-150	34	54
965	3600	1150	2X & 98 M	Long	108	121	22	75	69			
				Trans						-200	27	49
1200	3350	400	25 F & 75 M	Long		183	16	55				
				Trans		172	18	56		-190	20	19
1200	3350	600	25 F & 75 M	Trans	131	161	15	43	61	- 90	17	21
1200	3350	1000	25 F & 75 M	Trans	112	[illegible]	19	52	83	-130	23	29
1200	3350	1150	25 F & 75 M	Long	79	99	29	76	80			
				Trans	78	99	27	66	80	-240 ±20	9	65
1200	3350	1250	25 F & 75 M	Long	80	102	30	76	78			
				Trans	83/63	103	25	63/59	81/61	-250	18	48
1200	5500	1150	31 F & 69 M	Long	77	99	27	76	79			
				Trans	78	98	27	64	80	-280 ±20	14	60
1200	8500	400	36 F & 64 M	Long	94	155	16	42	61			
				Trans	104	162	15	40	64	-210	11	21
1200	8500	600	36 F & 64 M	Trans	111	149	15	45	74	-170	14	22
1200	8500	1000	36 F & 64 M	Long	81	103	29	74	79			
				Trans	106/85	130/106	20/25	53/64	82/80	-170	18	32
1200	8500	1100	36 F & 64 M	Long	82	103	25	76	80			
				Trans						-220	19	58
1200	8500	1150	36 F & 64 M	Long	84	103	28	77	82	-255	33	135
				Trans	81	103	27	66	79	-210	20	62
1200	8500	1250	36 F & 64 M	Long	75	97	31	74	77			
				Trans	78	97	29	62	80	-280 ±20	17	50

M = Martensite

B = Bainite

F = Ferrite

X = X Constituant

TABLE 3

Effects of Microstructure and Tempering Temperature on the Charpy V-Notch Impact Properties of HY-80 Steel (DTMB Plate E103) Austenitized at 1640 F

Isothermal Treatment		Tempering Temperature degrees F	Microstructure Percent	Specimen Direction	Tensile Properties		Ratio $\frac{YS}{TS} \times 100$	Maximum Energy		
Temperature degrees F	Time Seconds				Yield Strength ksi	Tensile Strength ksi		ft. lb.	Lateral Expansion, mils	Temper-ature degrees
		80	100 M	Trans	148	200	74	23	8	
		400	100 M	Trans	158	193	83	25	10	- 97
		600	100 M	Long	160	186	86	48	24	+ 6
				Trans				24	10	- 83
		900	100 M	Long	152	165	92			
				Trans	155	169	92	25	9	
		1000	100 M	Long	140	154	91	86	54	- 65
				Trans				32	20	- 27
		1100	100 M	Trans	113	124	91	42	33	- 62
		1150	100 M	Long	103	116	89	133	85	-130
				Trans	104	116	89	56	34	-120
		1250	100 M	Long	91	105	87	139	89	-166
				Trans				56	44	-100
		1270	100 M	Long	85	103	83	151	91	-121
				Trans				65	55	
		1300	100 M	Long	82	104	79			
				Trans				62	59	-120
		1330	100 M	Long	81	105	77			
				Trans				58	53	- 80
875	152	400	25 B & 75 M	Trans	152	193	79	22	8	
875	152	600	25 B & 75 M	Trans	151	184	82	22	9	+ 40
875	152	1000	25 B & 75 M	Trans	138	155	89	27	17	+ 37
875	152	1150	25 B & 75 M	Trans	108	121	89	48	39	- 97
875	152	1250	25 B & 75 M	Trans	82	102	80	56		
875	1600	400	50 B & 50 M	Trans	143	187	76	21	8	
875	1600	600	50 B & 50 M	Trans	140	174	80	21	8	
875	1600	1000	50 B & 50 M	Trans	132	148	89	28	16	+ 47
875	1600	1150	50 B & 50 M	Long	100	114	88	143	92	-124
				Trans	101	116	87	53	43	-100
875	1600	1250	50 B & 50 M	Long	80	103	78	54	47	
965		1150	2X & 98 M	Trans	108	89	49			
1200	3300	400	25 F & 75 M	Trans		172		19		
1200	3300	600	25 F & 75 M	Trans	131	161	81	21	11	+ 6
1200	3300	1000	25 F & 75 M	Trans	112	135	83	20	18	
1200	3300	1150	25 F & 75 M	Trans	78	99	80	68	60	-140
1200	3300	1200	25 F & 75 M	Trans	83/63	103	81/61	40	46	
1200	9900	1150	31 F & 69 M	Trans	78	98	80	60	54	-134
1200	8500	400	36 F & 64 M	Trans	104	165	64	21	8	
1200	8500	600	36 F & 64 M	Trans	111	140	74	22	12	- 30
1200	8500	1000	36 F & 64 M	Trans	106/85	130/106	82/80	32	22	- 18
1200	8500	1100	36 F & 64 M	Trans	82	103	80	58	53	- 90
1200	8500	1150	36 F & 64 M	Long	84	103	82	135	91	-144
				Trans	81	103	79	62	54	- 90
1200	8500	1200	36 F & 64 M	Trans	78	97	80	50	49	

Charpy V-Notch Impact Properties													
Percent Fibrous Fracture Appearance												At … er …ra …ea	
100 Percent			80 Percent			50 Percent			30 Percent				
…er- …re …es F	Energy ft. lb.	Lateral Expansion, mils	Temp degrees F	Energy ft. lb.	Lateral Expansion mils	Temp degrees F	Energy ft. lb.	Lateral Expansion mils	Temp degrees F	Energy ft. lb.	Lateral Expansion mils	Temp degrees F	Energy ft. l…
												-150	21
	24	7	-122	24	6	-162	22	5	-204	20	4	-165	22
	44	22	- 28	43	21	- 67	39	16	- 96	32	11		33
	24	8	- 97	24	8	-122	24	9	-150	23	10	-130	24
												-110	
						- 68	22	9	- 90	21	9	-110	21
	69	40	- 95	61	34	-130	43	22	-154	33	11	-120	48
	32	18	- 66	32	15	-114	25	12	-144	22	11	-110	26
	43	29	-110	39	25	-152	28	15	-188	24	13	-170	25
	118	71	-195	104	67	-206	55	61	-222	45	24	-220	46
	48	33	-145	45	30	-178	38	24	-222	27	15	-210	29
	108	79	-209	79	58	-226	66	43	-240	55	32	-255	45
	54	42	-126	51	39	-177	34	26	-225	25	15	-255	24
	131	84	-174	120	74	-218	82	30	-245	49	30	-240	54
	61		-140	51	40	-208	36	22	-231	31	18	-240	29
	56	44	-187	41	43	-212	32	34	-224	29	26	-190	38
	58	45	-154	55	41	-186	39	30				-190	37
												-150	19
	20	9	+ 3	19	9	- 33	19	9	- 65	18	8	- 90	18
	27	16	- 6	27	16	- 50	24	12	- 98	20	10	- 90	20
	44	32	-134	40	27	-180	28	18	-216	26	13	-220	26
												-190	30
												-110	19
	20	8		20	8	+ 6	19	8	- 14	19	7	- 70	14
	26	16	- 2	26	16	- 44	26	15	- 79	23	13	- 70	24
	123	76	-153	100	55	-186	60	37	-226	46	23	-215	49
	45	51	-128	40	26	-166	31	19	-200	27	15	-200	27
												-150	34
												-200	27
												-190	20
	21	11	- 21	21	10	- 60	18	8	- 92	16	6	- 90	17
	29	18	- 80	29	16	-116	24	14	-144	22	12	[illegible]	23
	47	19	-180	41	33	-214	30	22	-237	22	13	$-200^{\pm 20}$	9
												-250	18
	42	29	-174	37	25	-223	26	18	-261	18	14	$-200^{\pm 20}$	14
												-210	11
	22	11	- 74	22	10	-108	21	10	-146	16	8	-170	14
	31	19	- 85	30	18	-120	26	14	-152	21	10	-170	18
	49	40	-128	43	34	-167	32	34	-199	34	16	-220	19
	97	65	-150	83	54	-182	52	37	-209	37	21	-255	22
	98	48	-138	46	37	-200	27	20	-217	21	18	$-210^{\pm 20}$	24
												$-200^{\pm 20}$	17

TABLE 3

Effects of Microstructure and Tempering Temperature on the Charpy V-Notch Impact Properties of HY-80 Steel (DTMB Plate E103) Austenitized at 1640 F

								Ch…					
								Percent …					
…ering …rature …rees F	Microstructure Percent	Specimen Direction	Tensile Properties		Ratio YS/TS x 100	Maximum Energy		100 Percent			80 Percent		
			Yield Strength ksi	Tensile Strength ksi		ft. lb.	Lateral Expansion, mils	Temperature degrees F	Energy ft. lb.	Lateral Expansion, mils	Temp degrees F	Energy ft. lb.	Lateral Expansion, mils
80	100 M	Trans	148	200	74	23	8						
00	100 M	Trans	156	193	83	25	10	- 97	24	7	-122	24	6
00	100 M	Long	160	186	86	48	24	+ 6	44	22	- 28	43	21
		Trans				24	10	- 83	24	8	- 97	24	8
00	100 M	Long	152	165	92								
		Trans	155	169	92	25	9						
00	100 M	Long	140	154	91	86	54	- 65	69	40	- 95	61	34
		Trans				32	20	- 27	32	18	- 66	32	15
00	100 M	Trans	123	124	91	42	33	- 62	43	29	-110	39	25
50	100 M	Long	103	116	89	133	85	-130	118	71	-195	104	67
		Trans	104	116	89	56	34	-120	48	33	-145	45	30
50	100 M	Long	91	105	87	130	89	-166	108	79	-209	79	58
		Trans				56	44	-100	54	42	-126	51	39
00	100 M	Long	85	103	83	151	91	-121	131	84	-174	120	74
		Trans				65	55		61		-140	51	40
00	100 M	Long	82	104	79								
		Trans				62	39	-120	56	44	-187	41	43
00	100 M	Long	81	105	77								
		Trans				58	53	- 80	58	45	-154	55	41
00	25 B & 75 M	Trans	152	193	79	22	8						
00	25 B & 75 M	Trans	151	184	82	22	9	+ 40	20	9	+ 3	19	9
00	25 B & 75 M	Trans	138	155	89	27	17	+ 27	27	16	- 6	27	16
50	25 B & 75 M	Trans	108	121	89	48	39	- 97	44	32	-134	40	27
50	25 B & 75 M	Trans	82	102	80	56							
00	50 B & 50 M	Trans	143	187	76	21	8						
00	50 B & 50 M	Trans	140	174	80	21	8		20	8		20	8
00	50 B & 50 M	Trans	132	148	89	28	16	+ 47	26	16	- 2	26	16
50	50 B & 50 M	Long	100	114	88	143	92	-134	133	76	-153	100	55
		Trans	101	116	87	53	43	-100	45	52	-128	40	26
50	50 B & 50 M	Long	80	101	78	54	47						
50	12 & 88 M	Trans	108	89	40								
00	25 F & 75 M	Trans		172		19							
00	25 F & 75 M	Trans	131	161	81	21	11	+ 6	22	11	- 21	21	10
00	25 F & 75 M	Trans	113	135	83	20	18		20	18	- 80	20	16
50	25 F & 75 M	Trans	78	99	80	60	60	-140	47	19	-180	41	33
50	25 F & 75 M	Trans	83/63	103	81/62	48	46						
50	31 F & 69 M	Trans	78	98	80	60	54	-134	42	29	-174	37	25
00	36 F & 64 M	Trans	104	165	64	21	8						
00	36 F & 64 M	Trans	111	140	76	22	12	- 30	22	11	- 74	22	10
00	36 F & 64 M	Trans	106/86	130/106	82/80	32	22	- 18	31	19	- 85	30	18
00	36 F & 64 M	Trans	82	103	80	58	53	- 90	49	40	-128	43	34
50	36 F & 64 M	Long	84	103	82	135	92	-144	97	65	-128	83	54
		Trans	81	103	79	62	54	- 90	58	48	-128	46	37
50	36 F & 64 M	Trans	78	97	80	50	40						

Charpy V-Notch Impact Properties

...ral ...sion ...s	Fibrous Fracture Appearance: 50 Percent: Temp degrees F	50 Percent: Energy ft. lb.	50 Percent: Lateral Expansion mils	30 Percent: Temp degrees F	30 Percent: Energy ft. lb.	30 Percent: Lateral Expansion mils	At NDT: Temp degrees F	At NDT: Energy ft. lb.	At NDT: Lateral Expansion mils	At NDT: Percent Fiber
							-150	21	6	
	-162	22	5	-204	20	4	-165	22	5	48
	- 67	39	16	- 96	32	11		33	11	34
	-122	24	9	-150	23	10	-130	24	9	44
							-110			
	- 68	22	9	- 90	21	9	-110	21	9	23
	-130	43	22	-154	33	11	-120	48	27	59
	-114	25	12	-144	22	11	-110	26	12	53
	-152	28	15	-188	24	13	-170	25	14	38
	-206	55	61	-222	45	24	-220	46	25	31
	-178	38	24	-222	27	15	-210	29	17	35
	-226	65	43	-240	55	32	-255	45	25	19
	-177	34	26	-225	25	15	-255	24	12	22
	-218	82	30	-245	49	30	-240	54	34	34
	-208	36	22	-231	31	18	-240	29	17	21
	-212	32	34	-224	29	26	-190	38	29	74
	-186	39	30				-190	37	29	48
							-150	19	5	64
	- 33	19	9	- 65	18	8	- 90	18	8	20
	- 50	24	12	- 98	20	10	- 90	20	10	33
	-180	28	18	-216	26	13	-220	26	12	28
							-190	30	22	39
							-110	19	7	31
	+ 6	19	n	- 14	19	7	- 70	14	5	21
	- 44	26	15	- 79	23	13	- 70	24	14	35
	-186	60	37	-226	46	23	-215	49	27	35
	-166	31	19	-200	27	15	-200	27	15	30
							-150	34	27	42
							-200	27	15	40
							-190	20	7	30
	- 60	18	8	- 92	16	6	- 90	17	6	31
	-116	24	14	-144	22	12	-130	23	12	30
	-214	30	22	-237	22	12	$-200^{\pm 20}$	9	5	7
							-230	18	12	21
	-233	26	18	-261	18	14	$-200^{\pm 20}$	14	9	— 20
							-210	11	4	15
	-108	21	10	-146	16	8	-170	14	6	20
	-120	26	14	-152	21	10	-170	18	9	18
	-167	32	24	-190	24	16	-220	19	12	19
	-182	32	27	-209	37	21	-255	22	10	14
	-200	27	20	-217	21	15	$-210^{\pm 20}$	24	17	28
							$-200^{\pm 20}$	17	11	19

TABLE 4

Effects of Microstructure and Tempering Temperature on the Mechanical Properties and Notch Toughness of HY-80 Steel (DTMB Plate E103) Austenitized at 2000 F

Isothermal Treatment (A)					Longitudinal Tensile Properties					Notch Toughness Properties		
Temperature degrees F	Time (B) Seconds	Tempering Temperature degrees F	Microstructure Percent	Compressive Y.S. in ksi (0.2% Offset)	Y.S. ksi (0.2% Offset)	U. T. S. ksi	Percent Elongation	Percent Reduction Area	Y.S./U.T.S. x 100	NDT Temperature degrees F	Transverse Charpy V-Notch Energy, Ft.lb. At NDT	Transverse Charpy V-Notch Energy, Ft.lb. Maximum Energy
		400	100 M		152	187	14	59.2	81	- 50	24	41
		600	100 M	168	154	163	14	59.1	84	+ 15	24	28
		1000	100 M	145	138	153	17	64.1	90	+ 10	26	36
		1150	100 M	111	99	113	22.5	74.5	88	-115	35	60
		1250	100 M	97	75	96	25.5	76.6	78	-145	37	85
		1270	100 M	87	74	98	25.5	76.0	76	-155	31	77
		1300	100 M	88	82	102	25	75.6	80	-170	24	68
		1330	100 M	87	81	103	26	75.0	79	-160	30	69
875	152	400	3 B & 97 M	169	159	190	14	56.6	84	- 80	21	23
875	152	600	3 B & 97 M	170	158	185	15	60.7	85	- 30	19	23
875	152	1000	3 B & 97 M	150	139	151	18	66.0	92	- 10	29	39
875	152	1150	3 B & 97 M	129	109	122	22	73.0	89	-110	42	54
875	152	1250	3 B & 97 M	97	90	109	25	74.9	83	-150	32	64
875	1600	400	17 B & 83 M	146	128	173	17	59.0	74	- 30	22	30
875	1600	600	17 B & 83 M	145	129	166	17	57.9	78	+ 90	23	30
875	1600	1000	17 B & 83 M	123	112	130	21	67.9	86	+ 10	28	51
875	1600	1150	17 B & 83 M	117	108	123	21	67.8	88	- 10	34	55
875	1600	1250	17 B & 83 M	94	88	106	25	71.9	83	- 80	36	67
1200	3350	400	9 F & 97 M	142	118	165	12	24.8	72	- 70	14	14
1200	3350	600	9 F & 97 M	141	118	159	11	23.9	74	+ 40	12	16
1200	3350	1000	9 F & 97 M	138	119	141	16	45.3	84	- 50	19	29
1200	3350	1150	9 F & 97 M	108	98	115	22	67.8	85	- 70	37	48
1200	3350	1250	9 F & 97 M	88	79	102	28	72.3	78	-130	29	60

Notes:

A. Austenitized at 2000 F for 1 hour, transferred to 1625 F for 5 minutes, then isothermally treated as shown.

B. Time in Bath and then water quenched.

C. Tempered at temperature shown for 1 hour and then water quenched.

TABLE 5

Effects of Microstructure and Tempering Temperature on the Charpy V-Notch Impact Properties of HY-80 Steel (DTMB Plate E103) Austenitized at 2000 F

Isothermal Treatment[A]		Tempering[C] Temperature degrees F	Microstructure Percent	Longitudinal Tensile Properties		Ratio YS/TS x 100	Maximum Energy		1
Temperature degrees F	Time[B] Seconds			Yield Strength ksi	Tensile Strength ksi		ft lb	Lateral Expansion, mils	Temp degrees F
		400	100 M	152	187	81	41	12	+128
		600	100 M	154	183	84	28	13	+144
		1000	100 M	138	153	90	36	23	+ 96
		1150	100 M	95	113	88	60	46	+ 32
		1250	100 M	75	96	78	85	71	- 12
		1270	100 M	74	98	76	77	65	- 16
		1300	100 M	82	102	80	68	61	+212
		1330	100 M	81	103	79	69	59	+ 22
875	152	400	3 B & 97 M	159	190	84	23	11	+ 44
875	152	600	3 B & 97 M	158	185	85	23	11	+ 72
875	152	1000	3 B & 97 M	139	151	92	39	26	+ 88
875	152	1150	3 B & 97 M	109	122	89	54	44	+ 32
875	152	1250	3 B & 97 M	90	109	83	64	56	0
875	1600	400	17 B & 83 M	128	173	74	30	12	+212
875	1600	600	17 B & 83 M	129	166	78	30	16	+244
875	1600	1000	17 B & 83 M	112	130	86	51	36	+152
875	1600	1150	17 B & 83 M	108	123	88	55	47	+140
875	1600	1250	17 B & 83 M	88	106	83	67	60	+100
1200	3350	400	9 F & 91 M	118	165	72	13	6	+112
1200	3350	600	9 F & 91 M	118	159	74	16	7	+136
1200	3350	1000	9 F & 91 M	119	141	84	29	16	+ 52
1200	3350	1150	9 F & 91 M	98	115	85	48	40	+ 86
1200	3350	1250	9 F & 91 M	79	102	78	60	56	- 20

Notes:

A. Austenitized at 2000 F for 1 hour, transferred to 1625 F for 5 minutes, then isothermally treated as shown.

B. Time in Bath then water quenched.

C. Tempered at temperatures as shown for 1 hour and then water quenched.

Charpy V-Notch Impact Properties (Transverse)

Percent Fibrous Fracture Appearance										
100 Percent		80 Percent			50 Percent			30 Percent		
Energy ft lb	Lateral Expansion, mils	Temp degrees F	Energy ft lb	Lateral Expansion mils	Temp degrees F	Energy ft lb	Lateral Expansion mils	Temp degrees F	Energy ft lb	Lateral Expansion mils
37	12	- 32	32	12	- 16	28	11	- 36	26	10
28	13	+102	26	11	+64	25	9	+42	24	8
37	23	+ 74	37	22	+44	33	19	+16	27	15
60	44	- 16	54	40	- 78	43	29	-132	31	24
75	71	- 44	68	55	- 96	52	41	-132	41	30
72	58	- 36	70	54	- 66	60	45	-100	44	33
68	61	- 44	60	49	- 98	35	32	-130	27	21
64	56	- 18	63	43	-100	50	21	-158	30	19
22	9	- 20	22	9	- 52	22	7	- 64	21	6
22	10	- 12	21	6	- 54	18	5	- 64	17	5
34	23	+ 46	32	20	- 14	28	16	- 40	25	13
50	37	-114	41	24	-146	29	19	-150	26	19
64	52	-106	47	38	-138	33	27	-172	30	21
30	12	+108	27	12	- 6	24	9	- 40	22	7
39	19	+159	26	12	+114	23	11	+68	22	10
47	35	+107	44	34	- 53	34	28	+20	27	18
53	43	+ 94	51	40	+ 23	40	28	- 21	30	20
61	52	+ 44	58	48	- 25	48	39	- 78	38	25
15	6	- 17	15	5	- 40	15	5	- 60	15	5
16	6	+ 83	13	6	+ 64	12	6	+ 44	12	6
23	16	+ 2	22	15	- 26	21	12	- 54	19	11
46	38	- 4	43	34	- 74	27	21			
60	48	- 55	50	38	- 80	36	30	-154	29	29

ing Temperature on the
IY-80 Steel (DTMB Plate
2000 F

Longitudinal nsile Properties			Charpy V-Notch Impact Properties (Transverse)								
					Percent Fibrous Fracture Appe						
			Maximum Energy		100 Percent			80 Percent			5
ield ength ksi	Tensile Strength ksi	Ratio YS/TS x 100	ft lb	Lateral Expansion, mils	Temp degrees F	Energy ft lb	Lateral Expansion, mils	Temp degrees F	Energy ft lb	Lateral Expansion mils	Temp degrees F
152	187	81	41	12	+128	37	12	- 32	32	12	- 16
154	183	84	28	13	+144	28	13	+102	26	11	+64
138	153	90	36	23	+ 96	37	23	+74	37	22	+44
99	113	88	60	46	+ 32	60	44	- 16	54	40	- 78
75	96	78	85	71	- 12	75	71	- 44	68	55	- 96
74	98	76	77	65	- 16	72	58	- 36	70	54	- 66
82	102	80	68	61	+212	68	61	- 44	60	49	- 98
81	103	79	69	59	+ 22	64	56	- 18	63	43	-100
159	190	84	23	11	+ 44	22	9	- 20	22	9	- 52
158	185	85	23	11	+ 72	22	10	- 12	21	6	- 54
139	151	92	39	26	+ 88	34	23	+ 46	32	20	- 14
109	122	89	54	44	+ 32	50	37	-114	41	24	-146
90	109	83	64	56	0	64	52	-106	47	38	-138
128	173	74	30	12	+212	30	12	+108	27	12	- 6
129	166	78	30	16	+244	30	19	+159	26	12	+114
112	130	86	51	36	+152	47	35	+107	44	34	- 53
108	123	88	55	47	+140	53	43	+ 94	51	40	+ 23
88	106	83	67	60	+100	61	52	+ 44	58	48	- 25
118	165	72	13	6	+112	15	6	- 17	15	5	- 40
118	159	74	16	7	+136	16	6	+ 83	13	6	+ 64
119	141	84	29	16	+ 52	23	16	+ 2	22	15	- 26
98	115	85	48	40	+ 86	46	38	- 4	43	34	- 74
79	102	78	60	56	- 20	60	48	- 55	50	38	- 80

25 F for 5 minutes, then isothermally treated as shown.

en water quenched.

…pearance						At NDT			
50 Percent			30 Percent						
F	Energy ft lb	Lateral Expansion mils	Temp degrees F	Energy ft lb	Lateral Expansion mils	Temp degrees F	Energy ft lb	Percent Fiber	Lateral Expansion mils
	28	11	- 36	26	10	- 50	24	19	8
	25	9	+42	24	8	+15	24	11	7
	33	19	+16	27	15	+10	26	26	14
	43	29	-132	31	24	-115	35	36	26
	52	41	-132	41	30	-145	37	24	27
	60	45	-100	44	33	-155	31	14	22
	35	32	-130	27	21	-170	24	16	14
	50	21	-158	30	19	-160	30	29	19
	22	7	- 64	21	6	- 80	21	13	6
	18	5	- 64	17	5	- 30	20	72	6
	28	16	- 40	25	13	- 10	28	51	16
	29	19	-150	26	19	-110	42	82	25
	33	27	-172	30	21	-150	31	41	24
	24	9	- 40	22	7	- 50	22	23	7
	23	11	+68	22	10	+ 90	22	37	11
	34	28	+20	27	18	+ 10	26	25	16
	40	28	- 21	30	20	- 10	31	41	23
	48	39	- 78	38	25	- 80	36	26	22
	15	5	- 60	15	5	- 70	15	13	5
	12	6	+ 44	12	6	+ 40	12	28	6
	21	12	- 54	19	11	- 50	19	30	11
	27	21				- 50	38	62	24
	36	30	-154	29	29	-130	30	38	29

TABLE 6

Effects of Microstructure and Yield Strength on the Transverse Charpy V-Notch Energy and Temperature Corresponding to 100 Percent Fibrous Fracture Appearance of HY-80 Steel (DTMB Plate E103) Austenitized at 2000 F

Isothermal Treatment		Microstructure[1]	Yield[2] Strength ksi	100 Percent Fibrous Fracture Appearance	
				Transverse Charpy V-Notch Properties	
Temperature degrees F	Time Seconds			Energy ft-lb	Temperature degrees F
		100 M	80	70	+ 20
			100	57	+ 30
875	152	3 B-97 M	80	70	~ - 10
			100	57	+ 20
875	1600	17 B-83 M	80	~70	~ +100
			100	60	+115
1200	3350	9 F-91 M	80	60	- 5
			100	45	+100

1. Microstructure:
   - M = Martensite
   - B = Bainite
   - F = Ferrite
2. Room temperature yield strength

TABLE 7

Effects of Microstructure on Yield Strength and Transverse Charpy Energy Corresponding to 100 Percent Fibrous Fracture Appearance at 32 F of HY-80 Steel (DTMB Plate E103) Austenitized at 2000 F

Microstructure[1]	Properties at 100 Percent Fibrous Appearance at 32 F	
	Yield[2] Strength ksi	Transverse C_V (32 F) ft-lb
100 M	92	60
3 B-97 M	113	48
17 B-83 M	<80	~70
9 F-91 M	85	62

1. Microstructure
   M = Martensite
   B = Bainite
   F = Ferrite
2. Room temperature yield strength

TABLE 8

Effects of Cooling Rate on the Mechanical and Notch Toughness Properties of HY-80 Steel (DTMB Plate E103) Austenitized at 1640 F

Property[1]	Cooling Treatment[4]		
	Water Quenched	Air-Cooled	Slow-Cooled
U.T.S., ksi	116	104	104
0.2 Percent Y.S., ksi	103	84	83
Percent El. in one in.	24	25	24
Percent Red. in area	76	73	72
NDT, degrees F	-210	-130	-90
C_v at NDT,[2] ft-lb	29	25	30
C_v max,[3] ft-lb	56	55	51

1. Room temperature tensile properties.
2. Transverse Charpy V-Notch at NDT temperature.
3. Transverse Charpy V-Notch at 212 F.
4. Austenitized 1640 F for 1/2 hour, cooled as indicated to room temperature, held at -110 F for 1 hour, and tempered at 1150 F for 1 hour then water quenched.

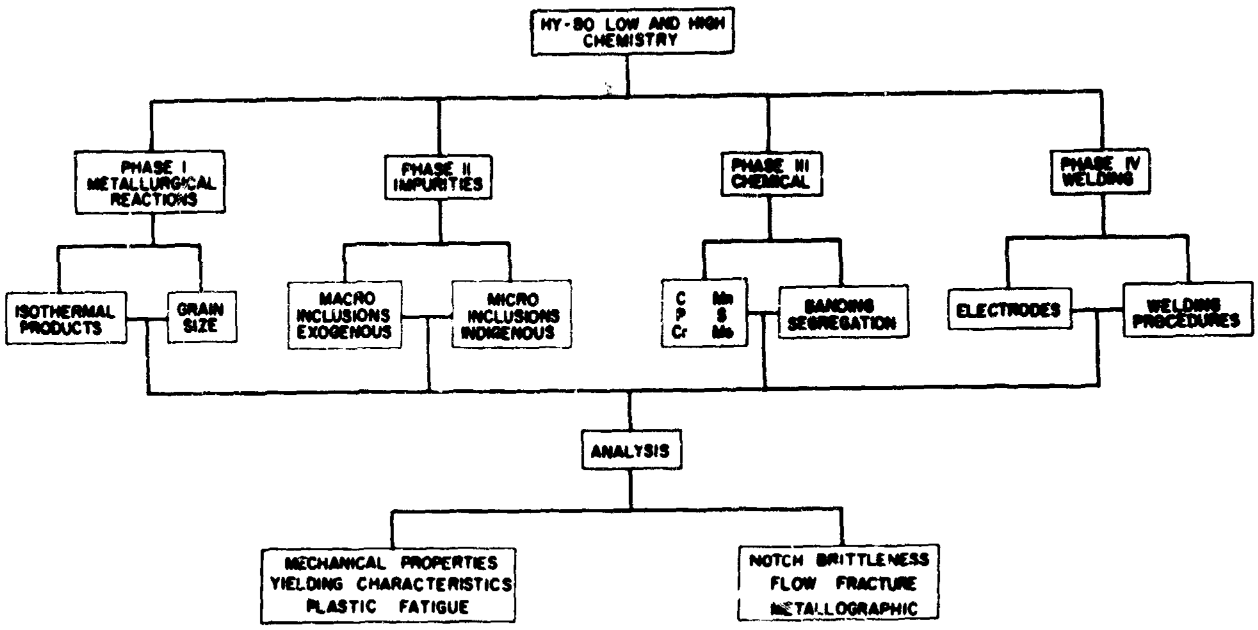


Figure 1 - Investigative Steps in the Study of HY-80 Steel

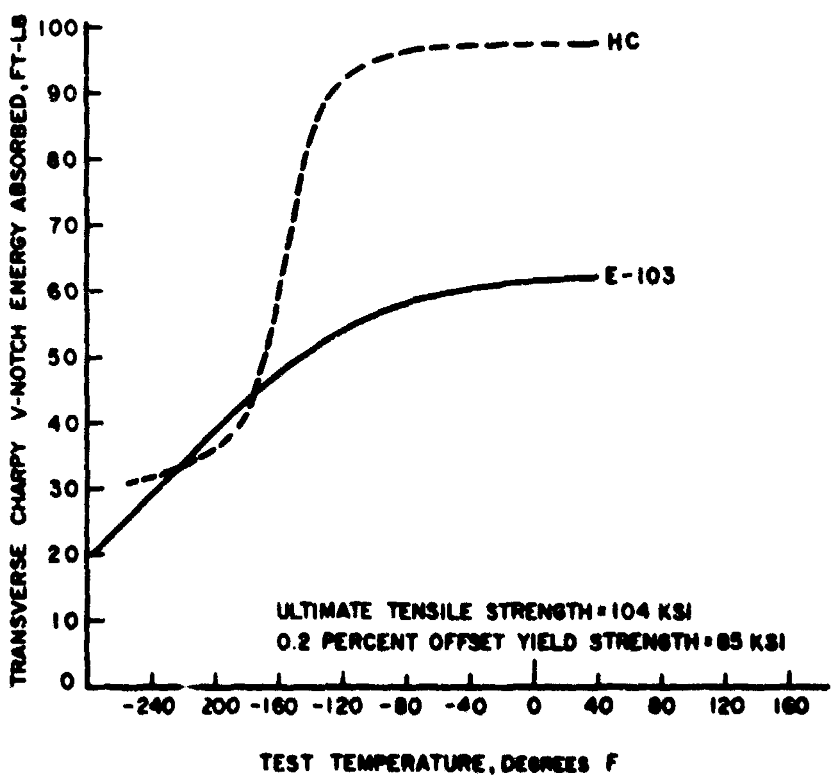


Figure 2 - Comparison of the Transverse Charpy Energy Absorbed for Two Selected HY-80 Steel Plates

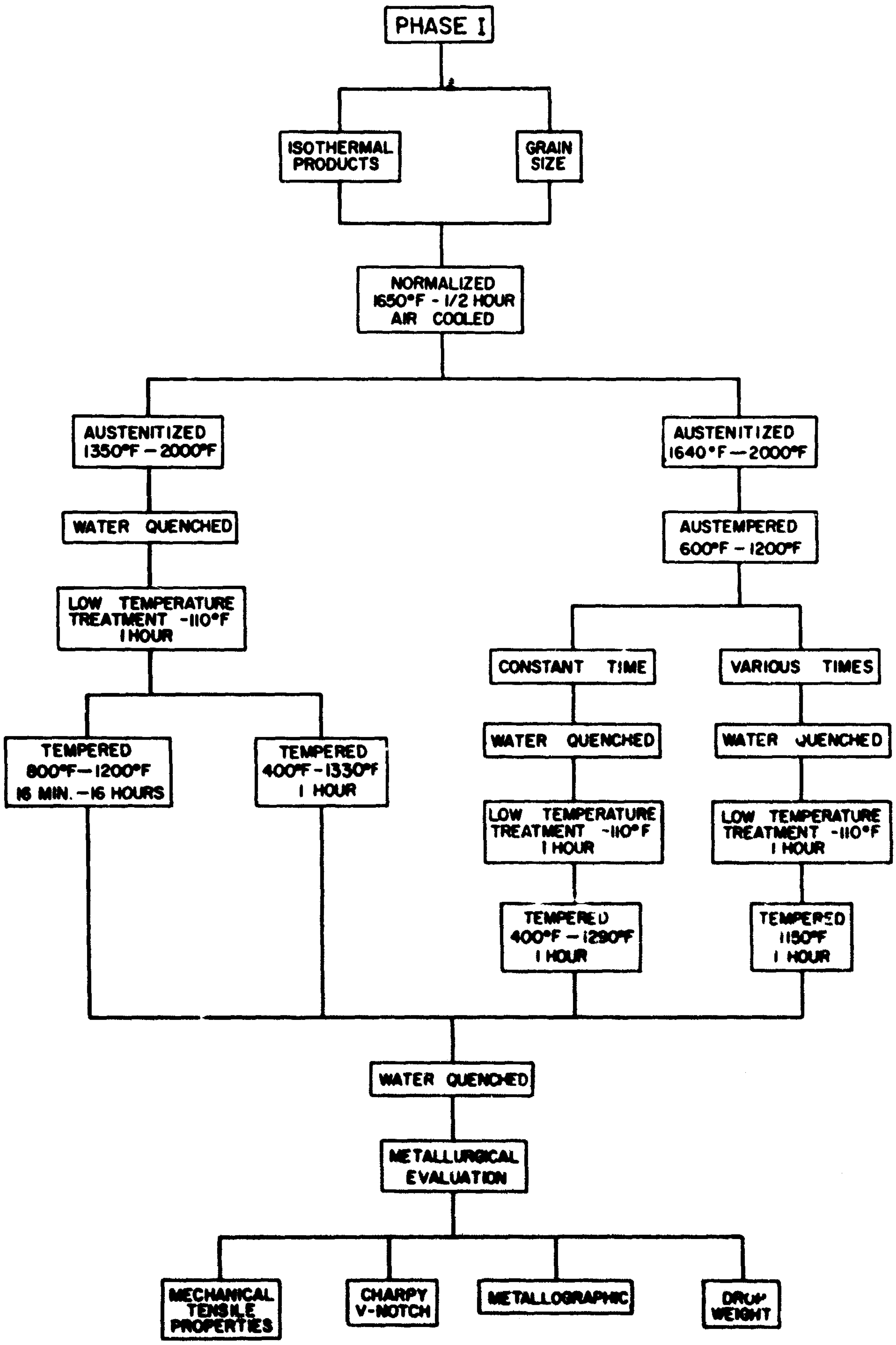


Figure 3 - General Outline of Heat Treatments

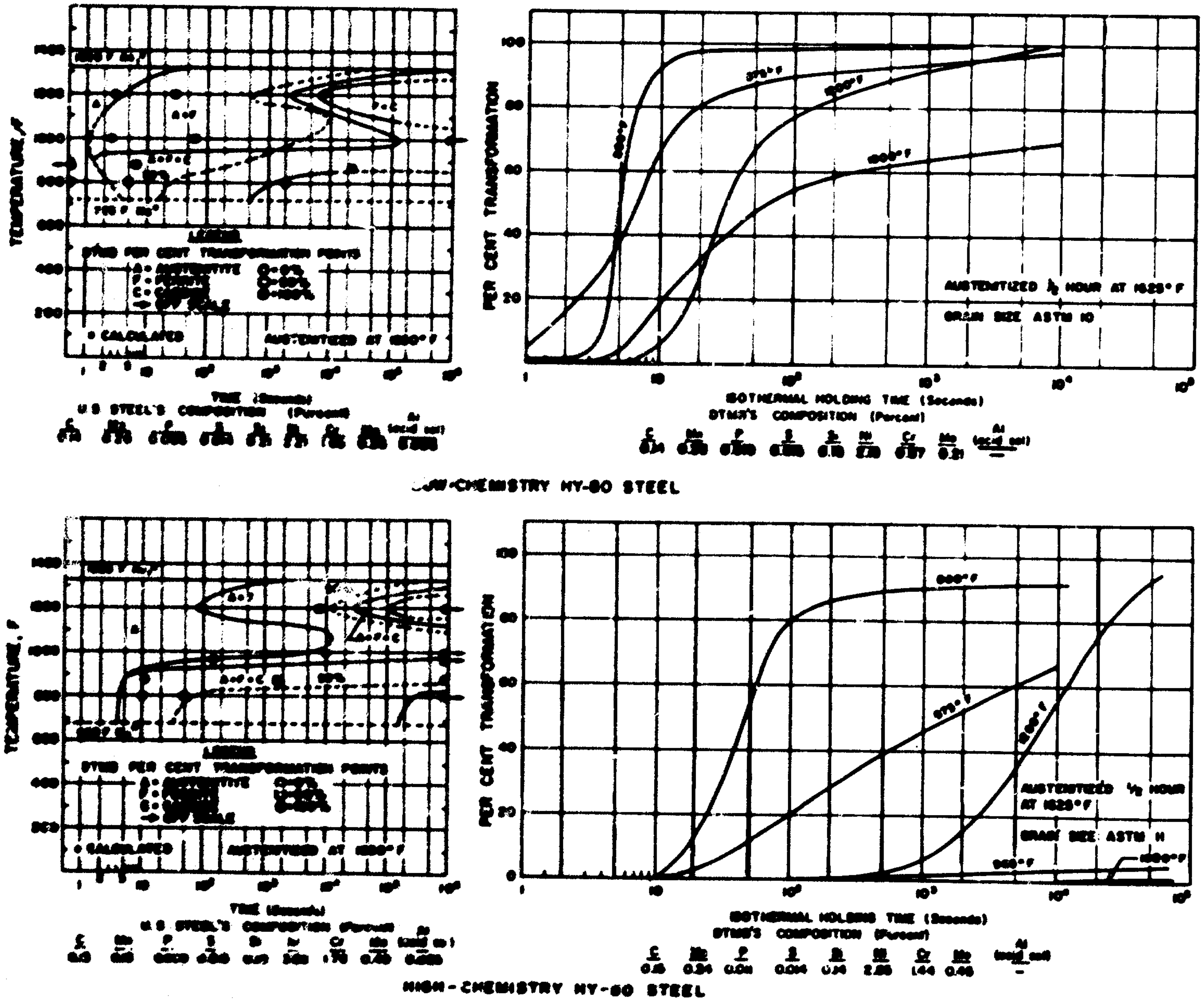


Figure 4 - Isothermal Transformation Data Developed at the David Taylor Model Basin Compared to Published Time-Temperature-Transformation Data

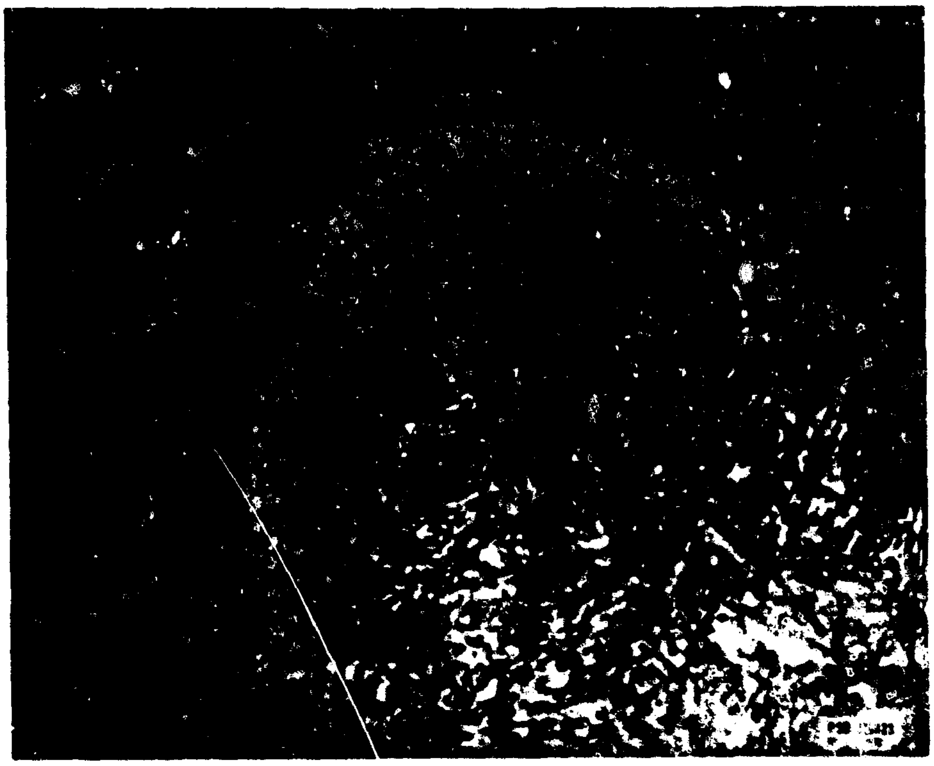


Figure 5a - 100 Percent Martensite - ASTM 9

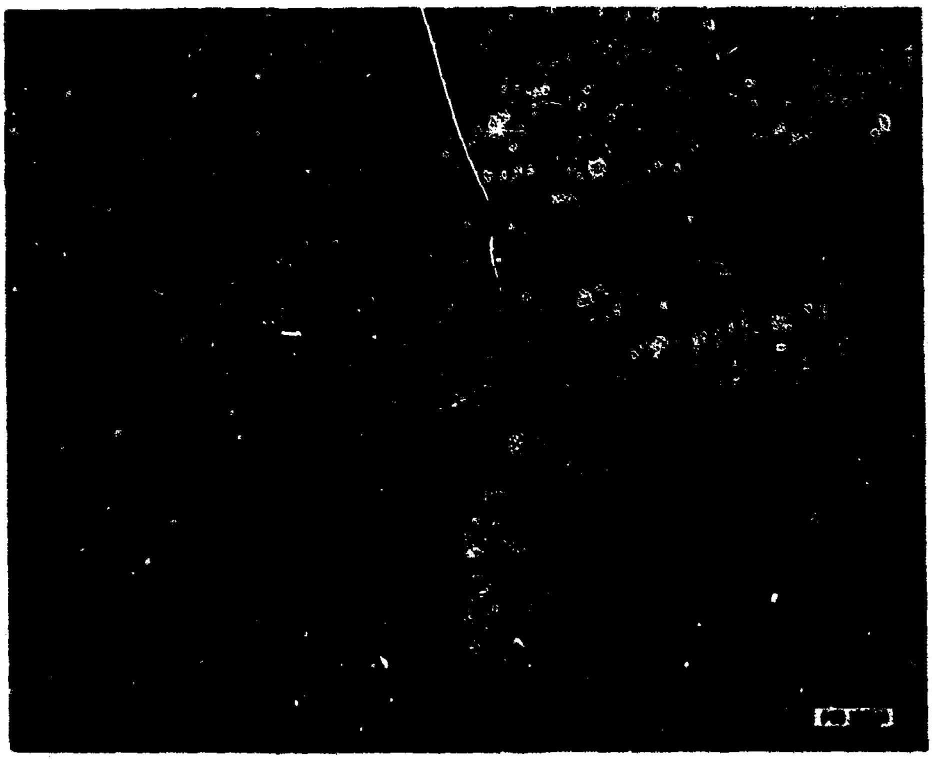
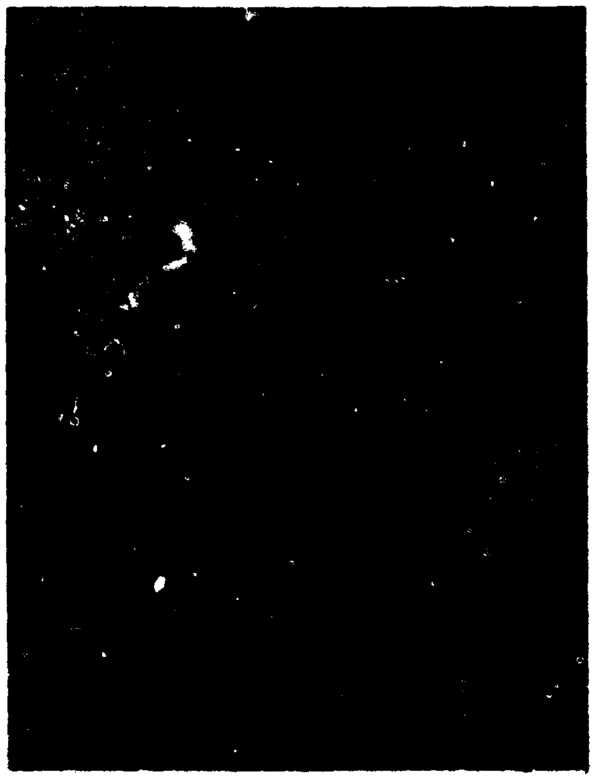


Figure 5b - 100 Percent Martensite - ASTM 3.5

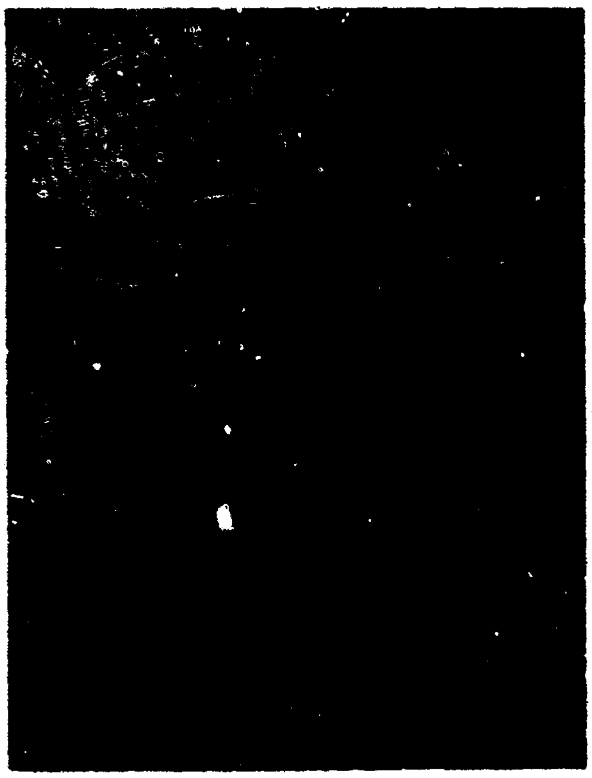
Figure 5 - Mictrostructure (1000X) and ASTM Micrograin Size of Fully Quenched Specimens Austenitized at 1640 and 2000 F

25% Bainite - 75% Martensite
875 F - 152 Sec



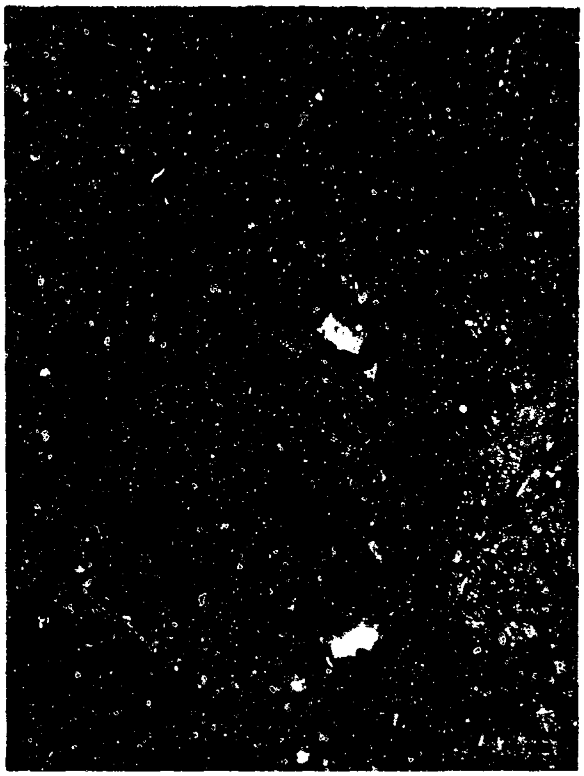
25% Ferrite - 75% Martensite
1200 F - 3350 Sec

50% Bainite - 50% Martensite
875 F - 1600 Sec



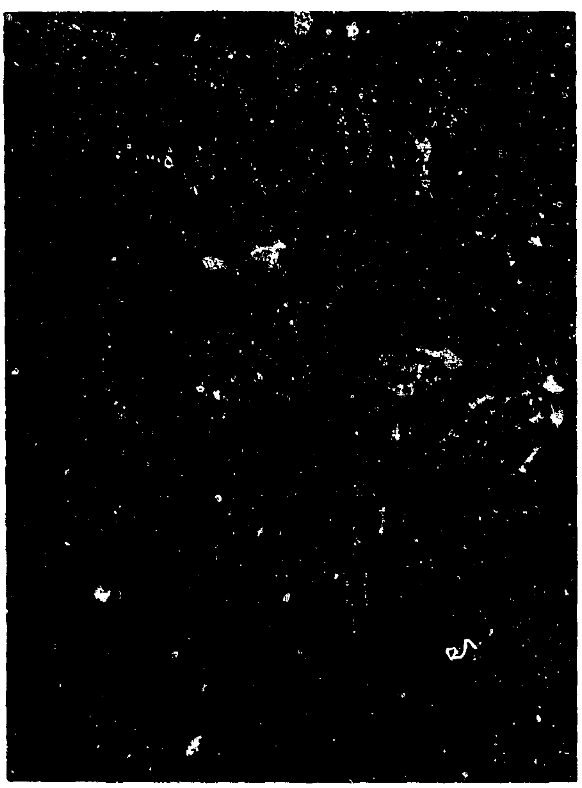
36% Ferrite - 64% Martensite
1200 F - 8500 Sec

Figure 6 - Microstructure (1000X) of Specimens Austenitized at 1640 F and then Isothermally Treated at 875 F and 1200 F



3% Bainite - 97% Martensite
875 F - 152 Sec

9% Ferrite - 91% Martensite
1200 F - 3350 Sec



17% Bainite - 83% Martensite
875 F - 1600 Sec

38% Ferrite - 62% Martensite
1200 F - 8500 Sec

Figure 7 - Microstructure (1000X) of Specimens Austenitized at 2000 F and then Isothermally Treated at 875 and 1200 F

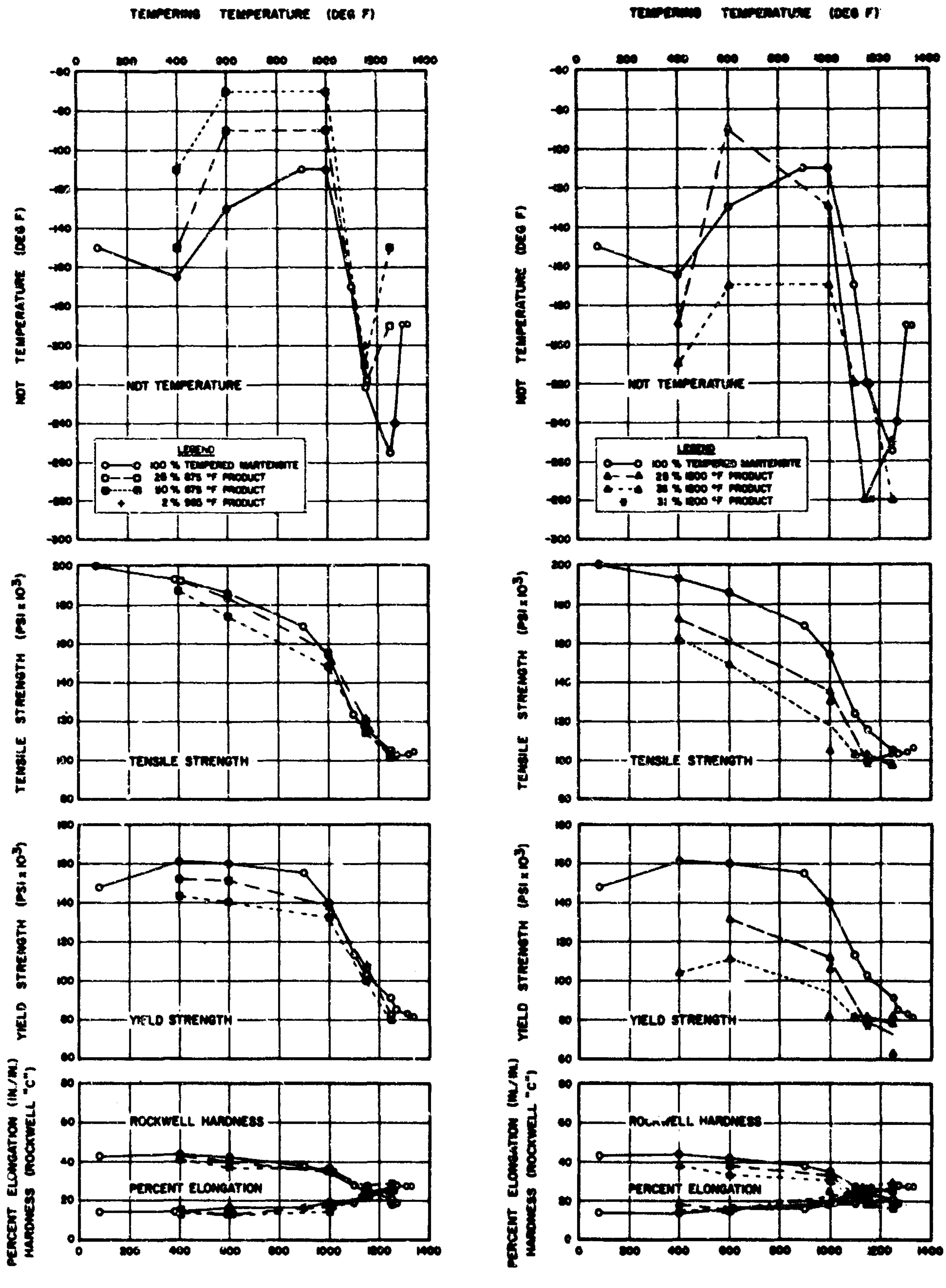


Figure 8 - Effects of Tempering Temperature on the Mechanical Properties of HY-80 Steel (DTMB Plate E103) Austenitized at 1640 F and Treated to Contain Various Amounts and Types of Isothermal Product

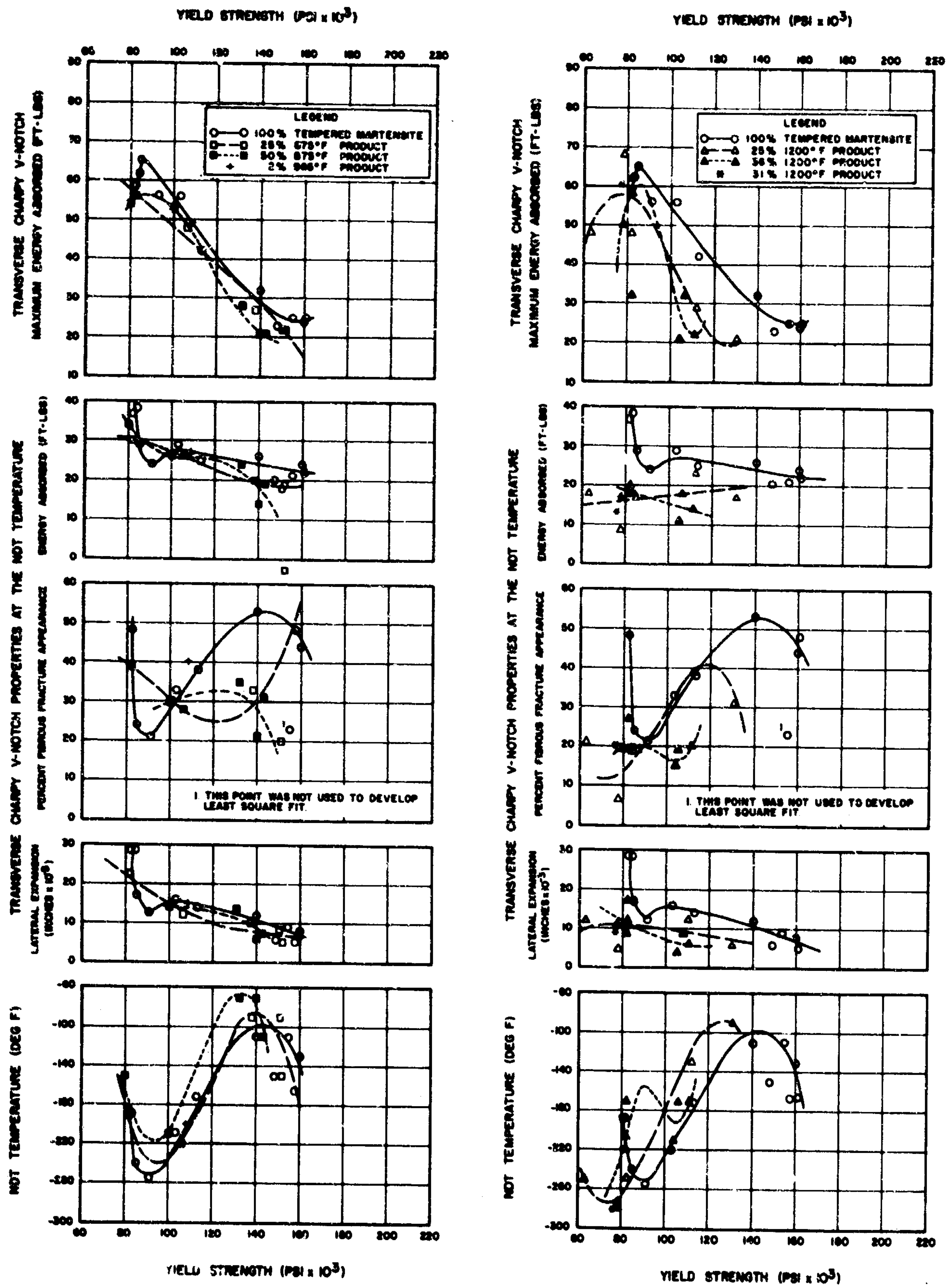


Figure 9 - Effects of Room Temperature Yield Strength Level and Nonmartensitic Products on the Notch Brittleness of HY-80 Steel (DTMB Plate E103) Austenitized at 1640 F

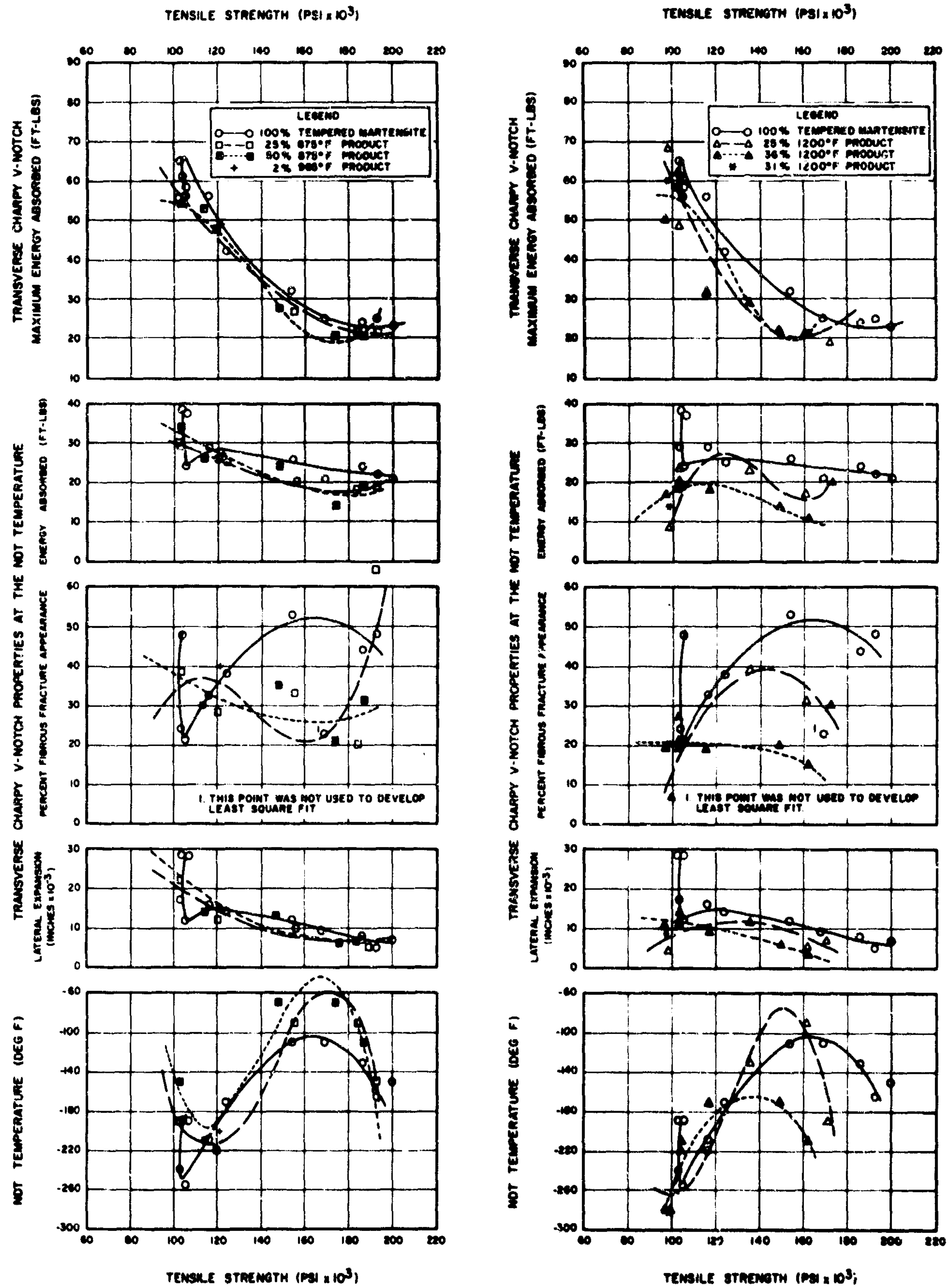


Figure 10 - Effect of Room Temperature Ultimate Tensile Strength Level and Nonmartensitic Products on the Notch Brittleness of HY-80 Steel (DTMB Plate E103) Austenitized at 1640 F

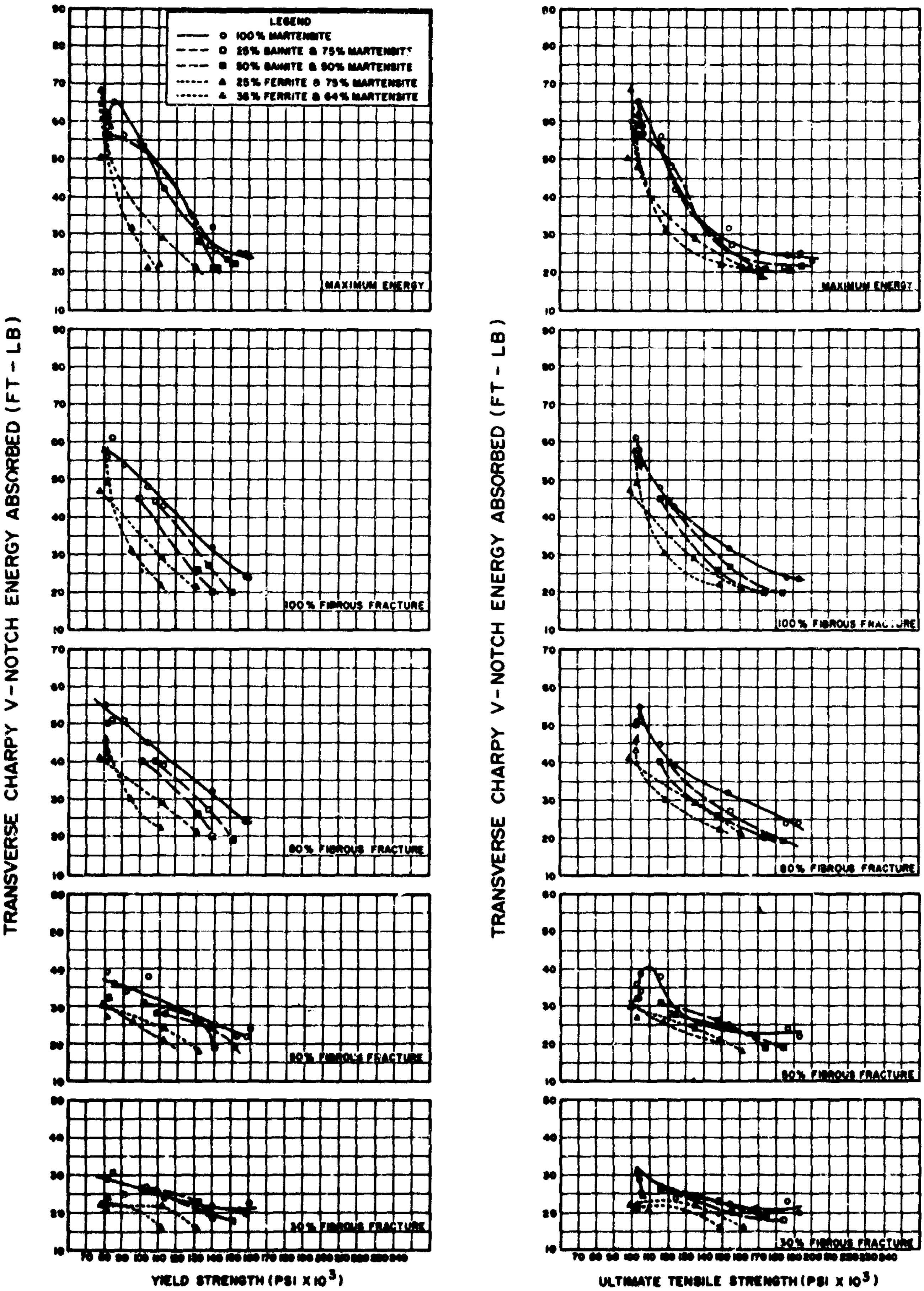


Figure 11 - Correlation between Room Temperature Strength Microstructure, and Transverse Charpy V-Notch Energy Absorbed at Maximum Energy and at a Given Fibrous Fracture Appearance for HY-80 Steel Austenitized at 1640 F

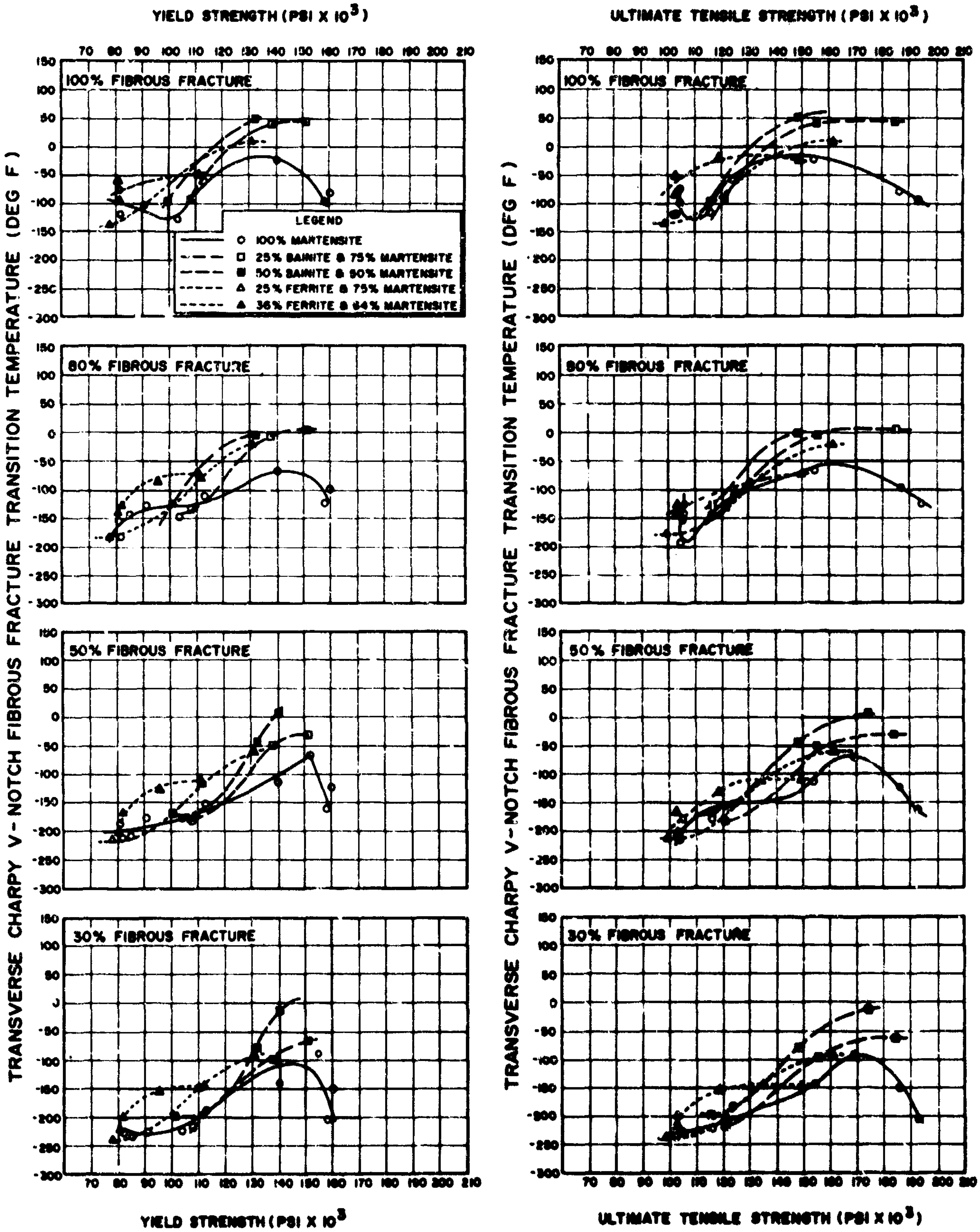


Figure 12 - Correlation between Room Temperature Strength and Transverse Charpy V-Notch Fibrous Fracture Transition Temperature for HY-80 Steel Austenitized at 1640 F

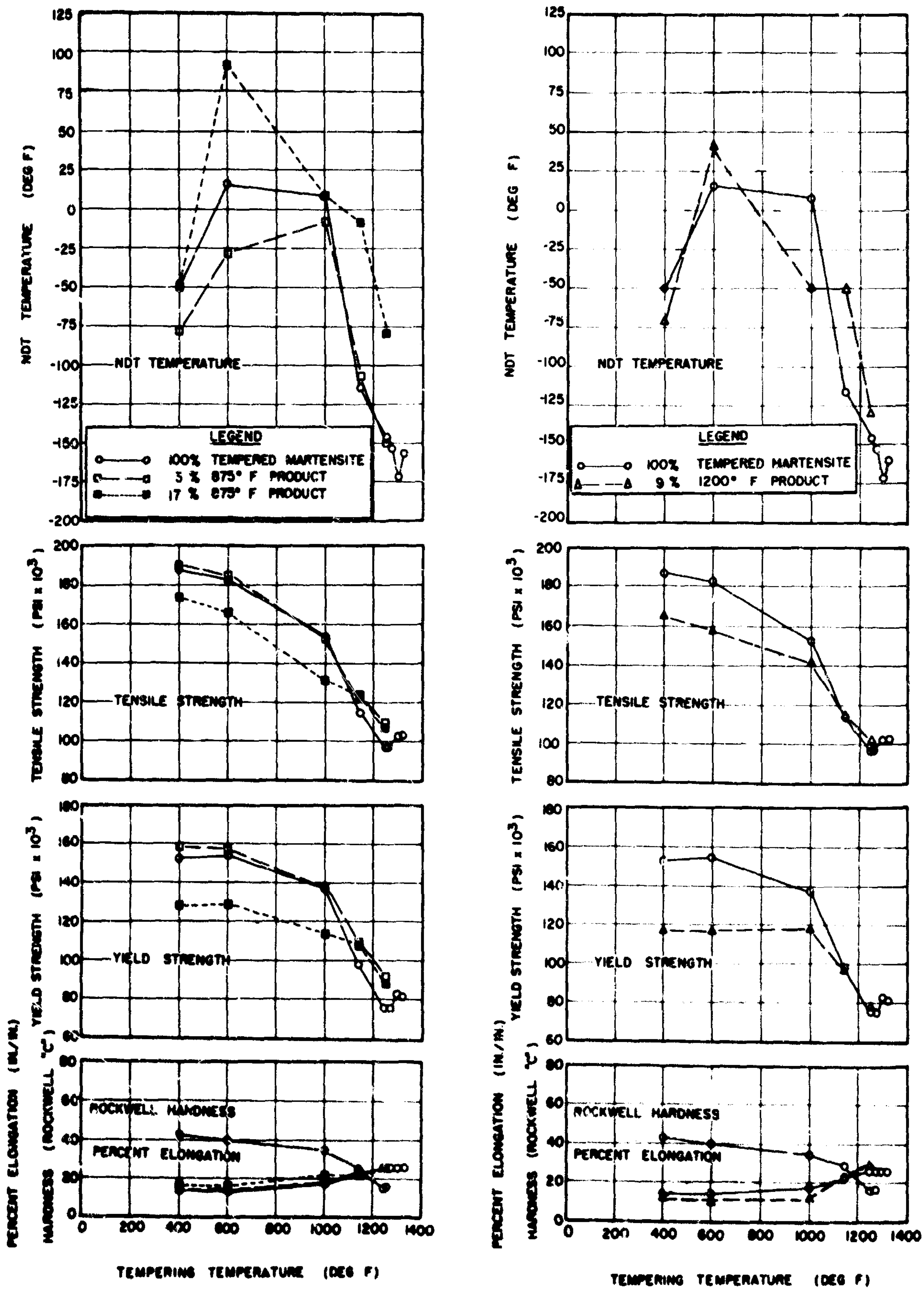


Figure 13 - Effects of Tempering Temperature on the Mechanical Properties of HY-80 Steel (DTMB Plate E103) Austenitized at 2000 F and Treated to Contain Various Amounts and Types of Isothermal Transformation Products

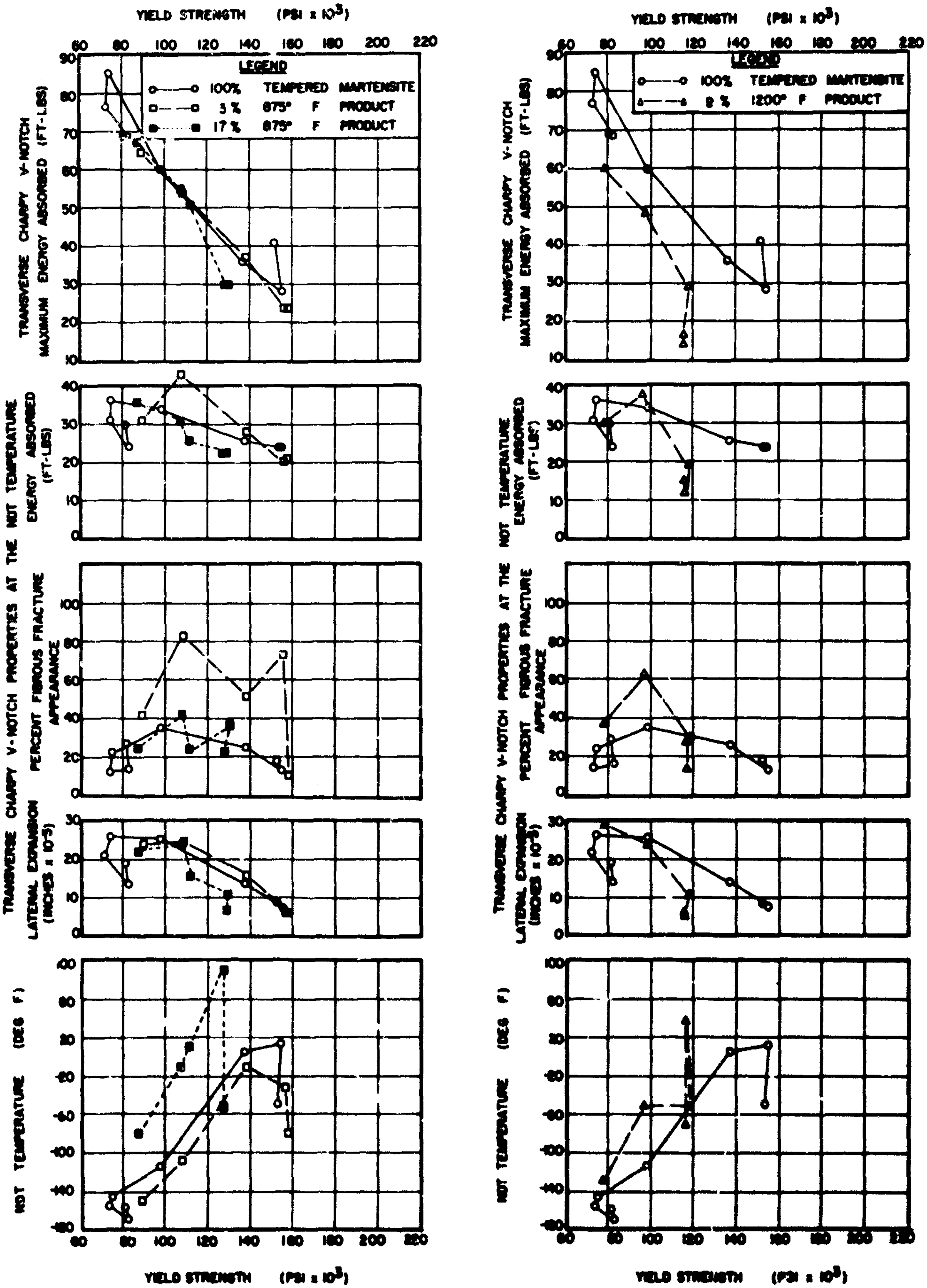


Figure 14 - Effects of Room Temperature Yield Strength Level and Non-martensitic Products on the Notch Brittleness of HY-80 Steel (DTMB Plate E103) Austenitized at 2000 F

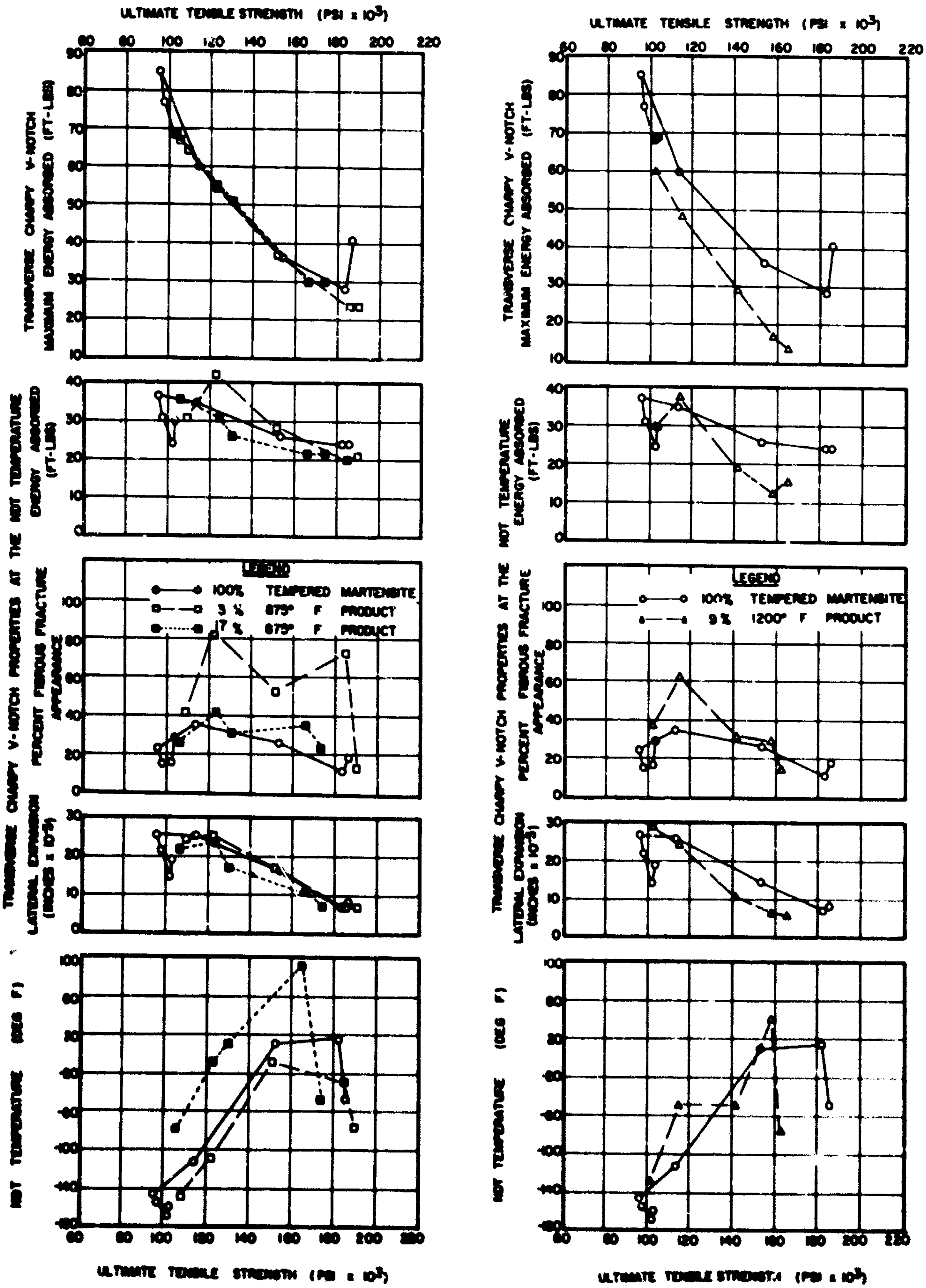


Figure 15 - Effects of Room Temperature Ultimate Tensile Strength Level and Nonmartensitic Products on the Notch Brittleness of HY-80 Steel (DTMB Plate E103) Austenitized at 2000 F

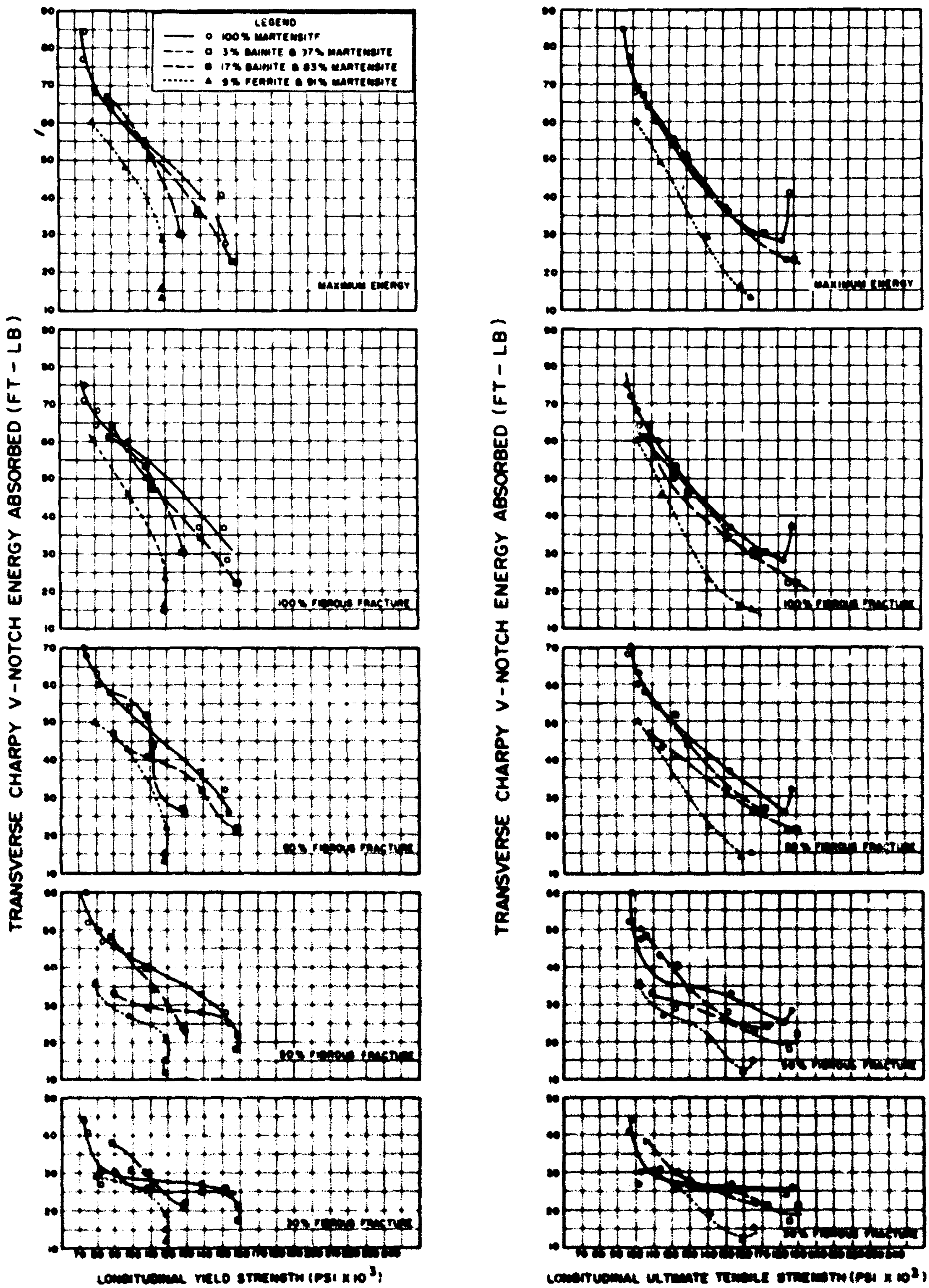


Figure 16 - Correlation between Room Temperature Strength, Microstructure, and Transverse Charpy V-Notch Energy Absorbed at Maximum Energy and at a Given Fibrous Fracture Appearance for HY-80 Steel Austenitized at 2000 F

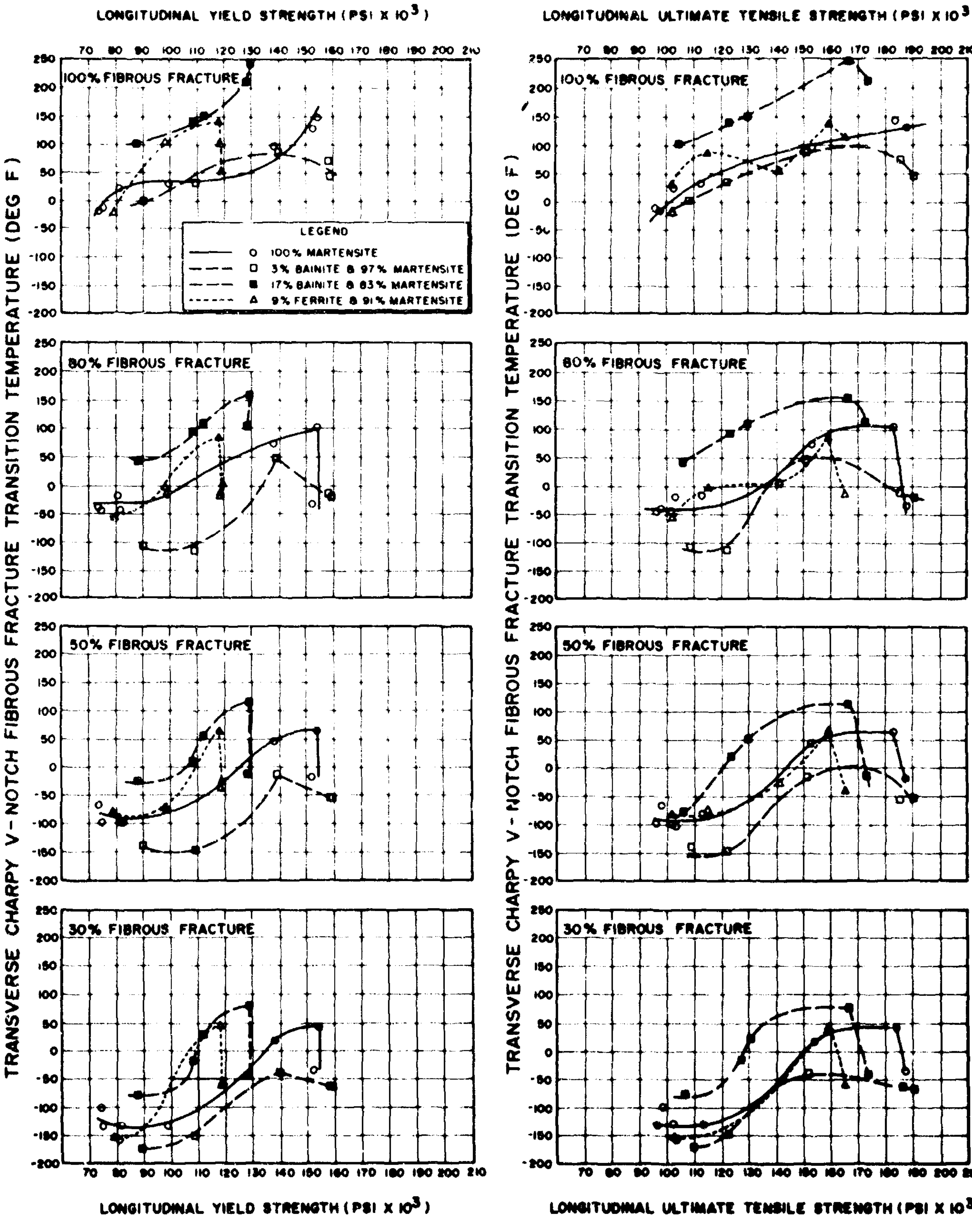


Figure 17 - Correlation between Room Temperature Strength, Microstructure, and Transverse Charpy V-Notch Fibrous Fracture Transition Temperature for HY-80 Steel Austenitized at 2000 F

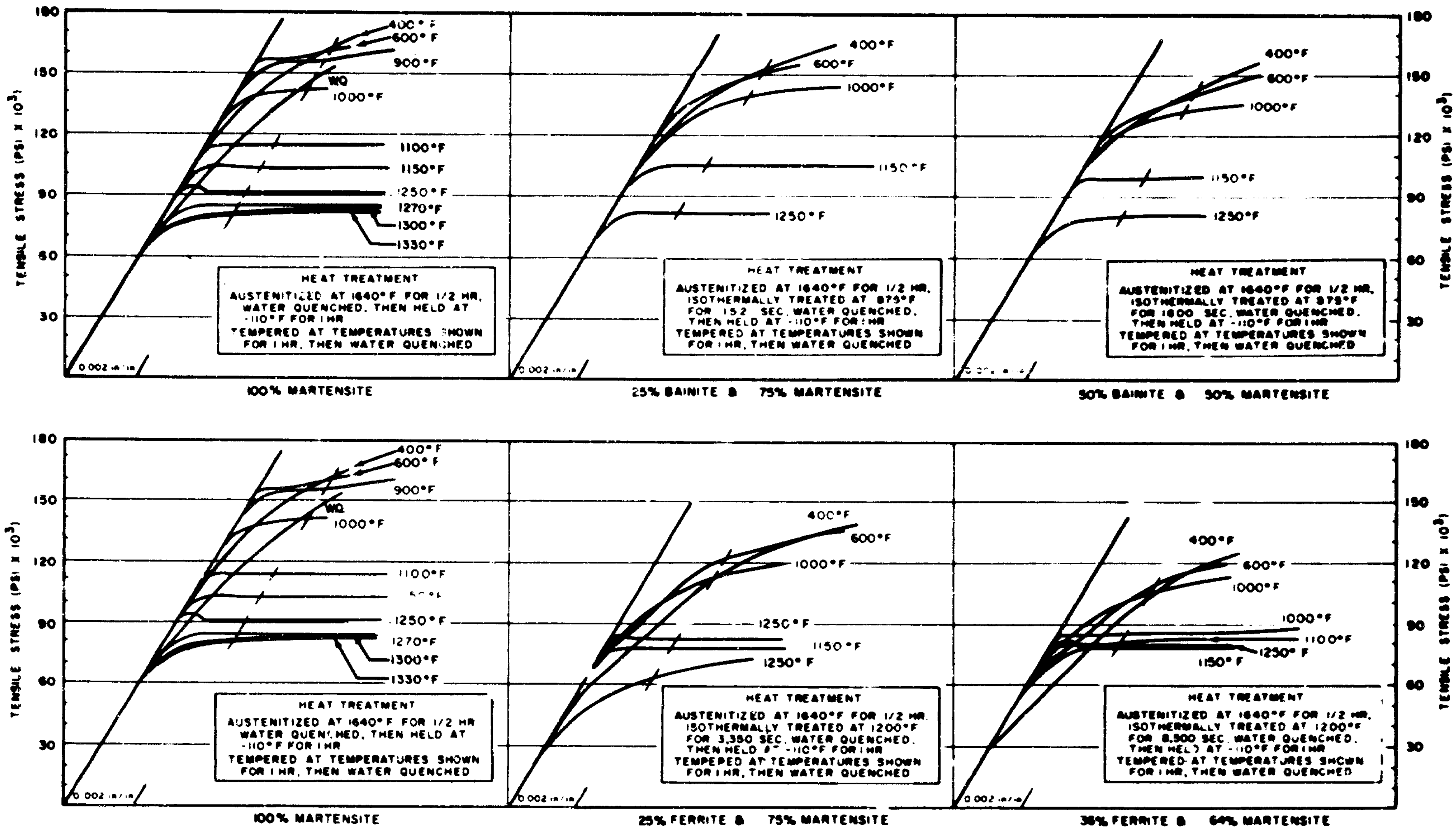


Figure 18 - Effects of Various Nonmartensitic Products on the Tensile Yielding Characteristics of HY-80 Steel (DTMB Plate E103) Austenitized at 1640 F and Tempered at Various Temperatures

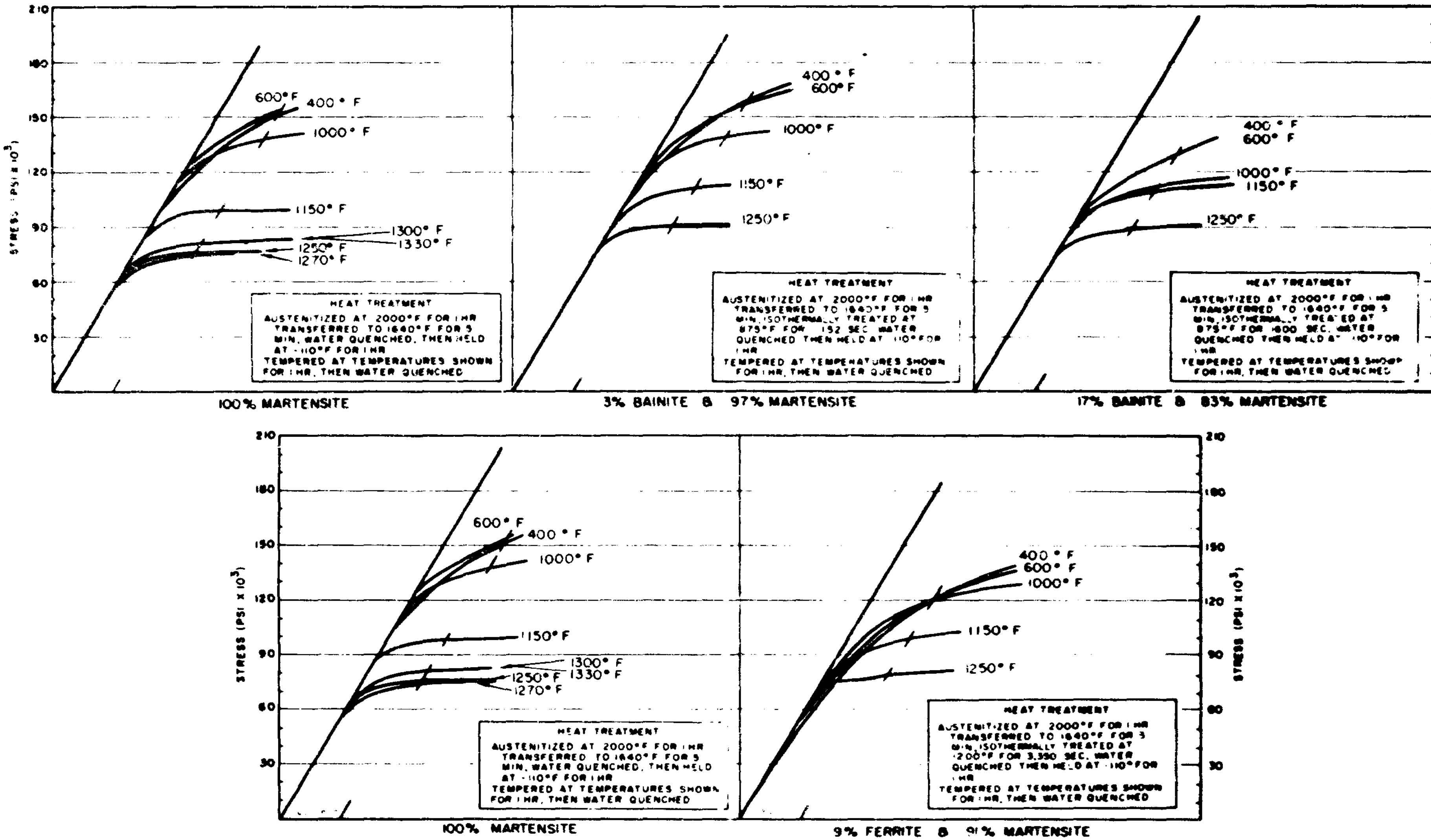


Figure 19 - Effects of Various Nonmartensitic Products on the Tensile Yielding Characteristics of HY-80 Steel (DTMB Plate E103) Austenitized at 2000 F and Tempered at Various Temperatures

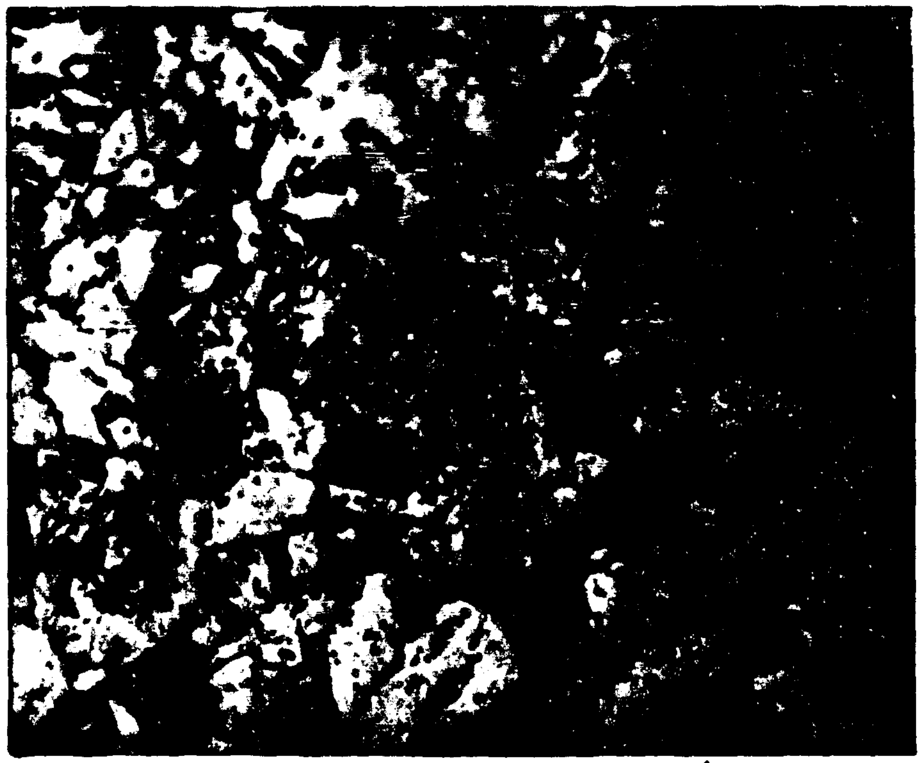


Figure 20a - Slow Cooled 9.5 F/min

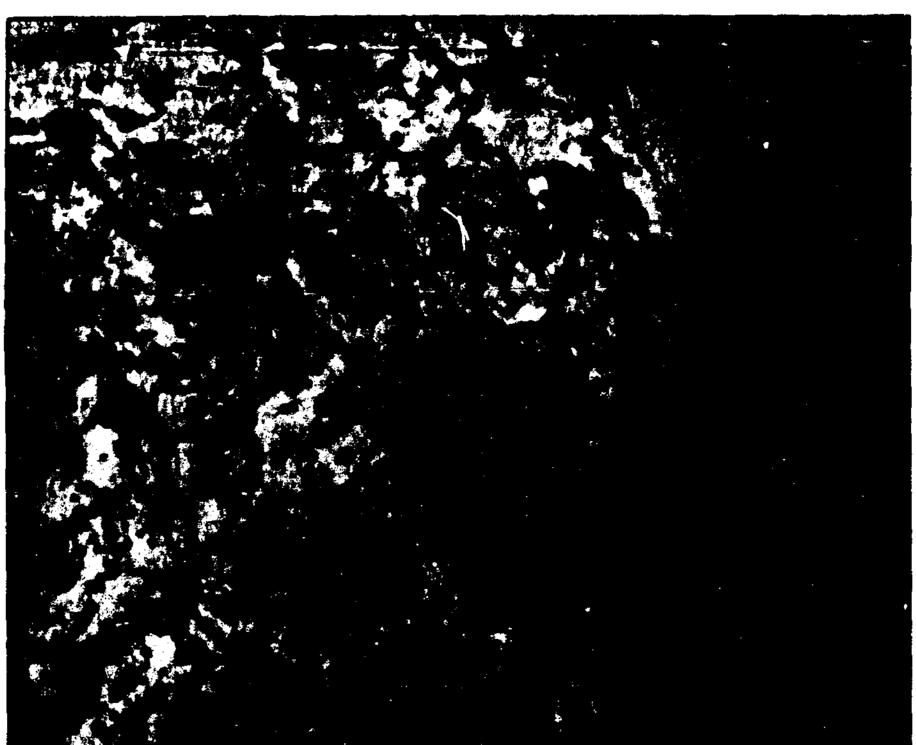


Figure 20b - Air Cooled 35.1 F/min

Figure 20 - Photomicrographs (1000X) of Slow-Cooled and Air-Cooled Specimens

APPENDIX

CHARPY V-NOTCH PROPERTY CURVES

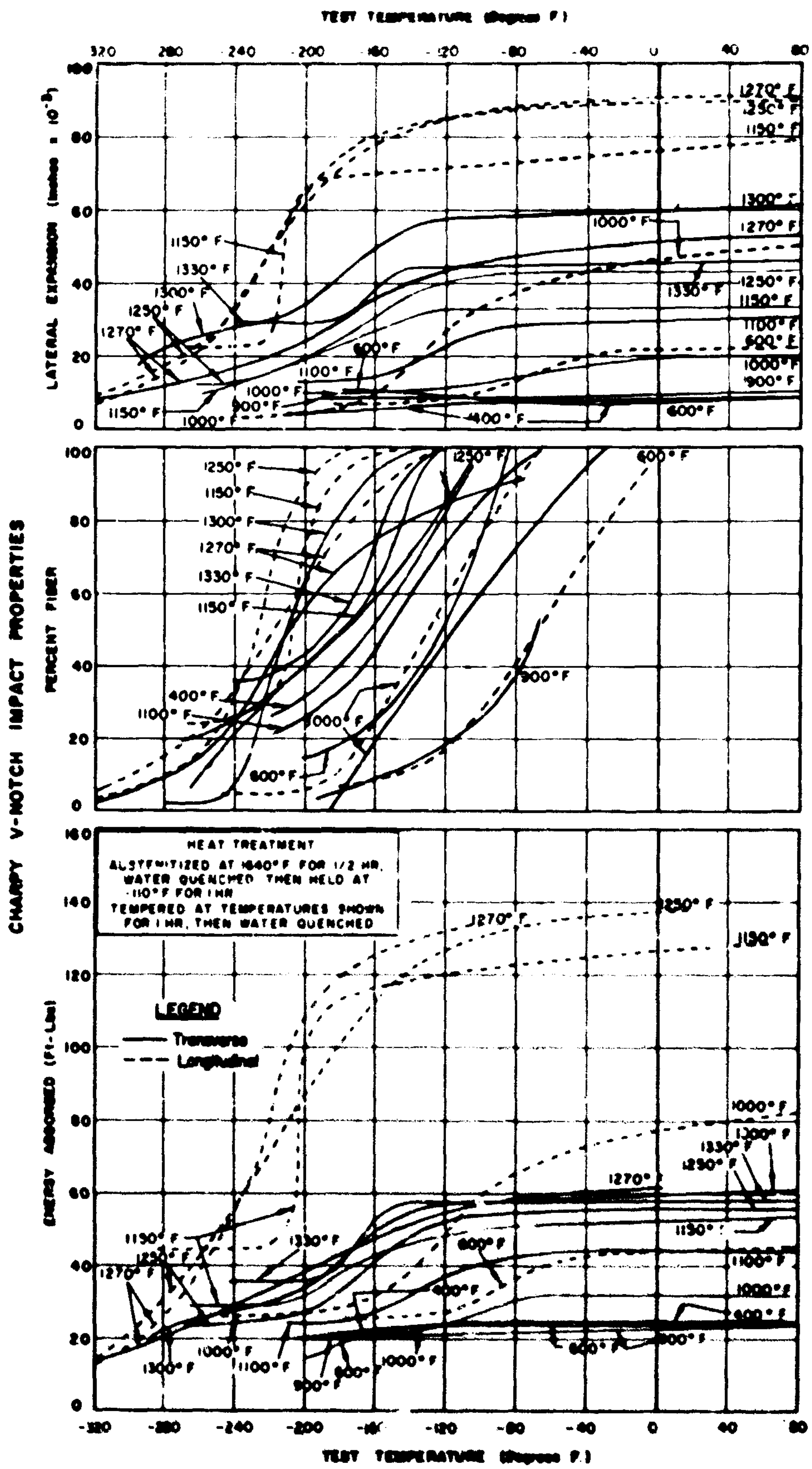


Figure A1 - Effects of Tempering Temperature on Charpy V-Notch Impact Properties of HY-80 Steel (DTMB Plate E103) Austenitized at 1640 F and Quenched to Contain 100 Percent Martensite

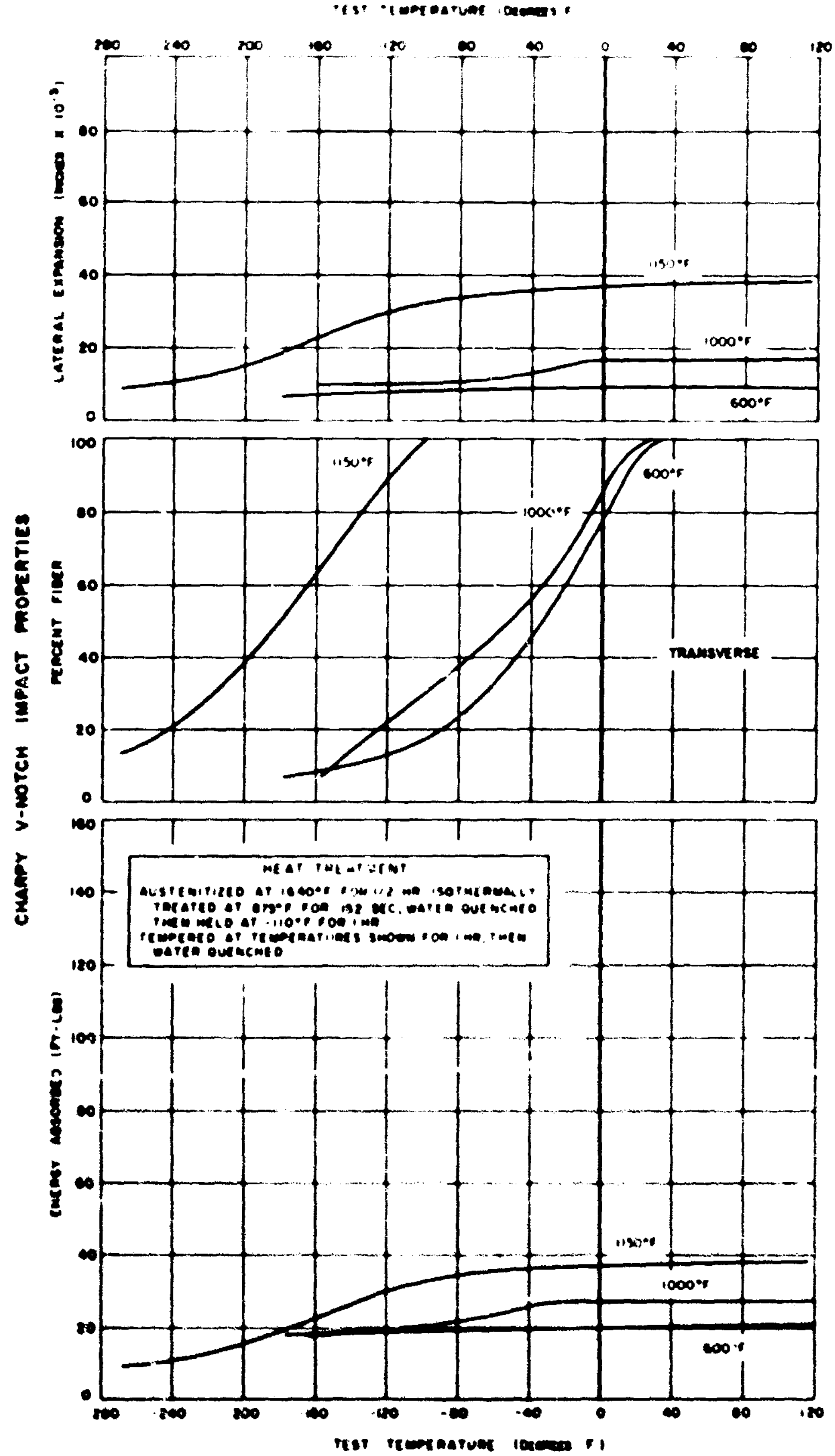


Figure A2 - Effects of Tempering Temperature on Charpy V-Notch Impact Properties of HY-80 Steel (DTMB Plate E103) Austenitized at 1640 F and Isothermally Treated at 875 F to Contain 25 Percent Bainite

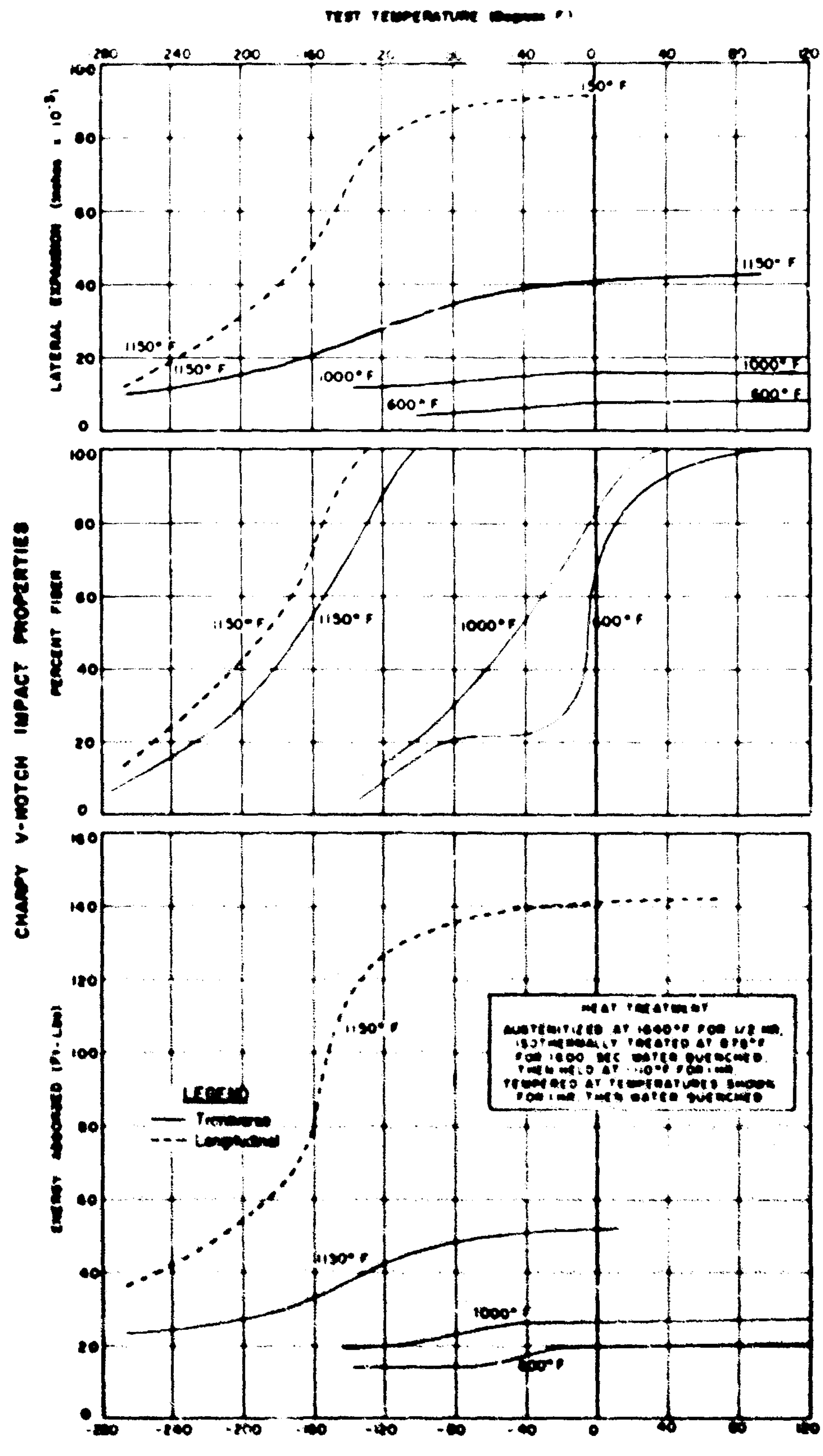


Figure A3 - Effects of Tempering Temperature on Charpy V-Notch Impact Properties of HY-80 Steel (DTMB Plate E103) Austenitized at 1640 F and Isothermally Treated at 875 F to Contain 50 Percent Bainite

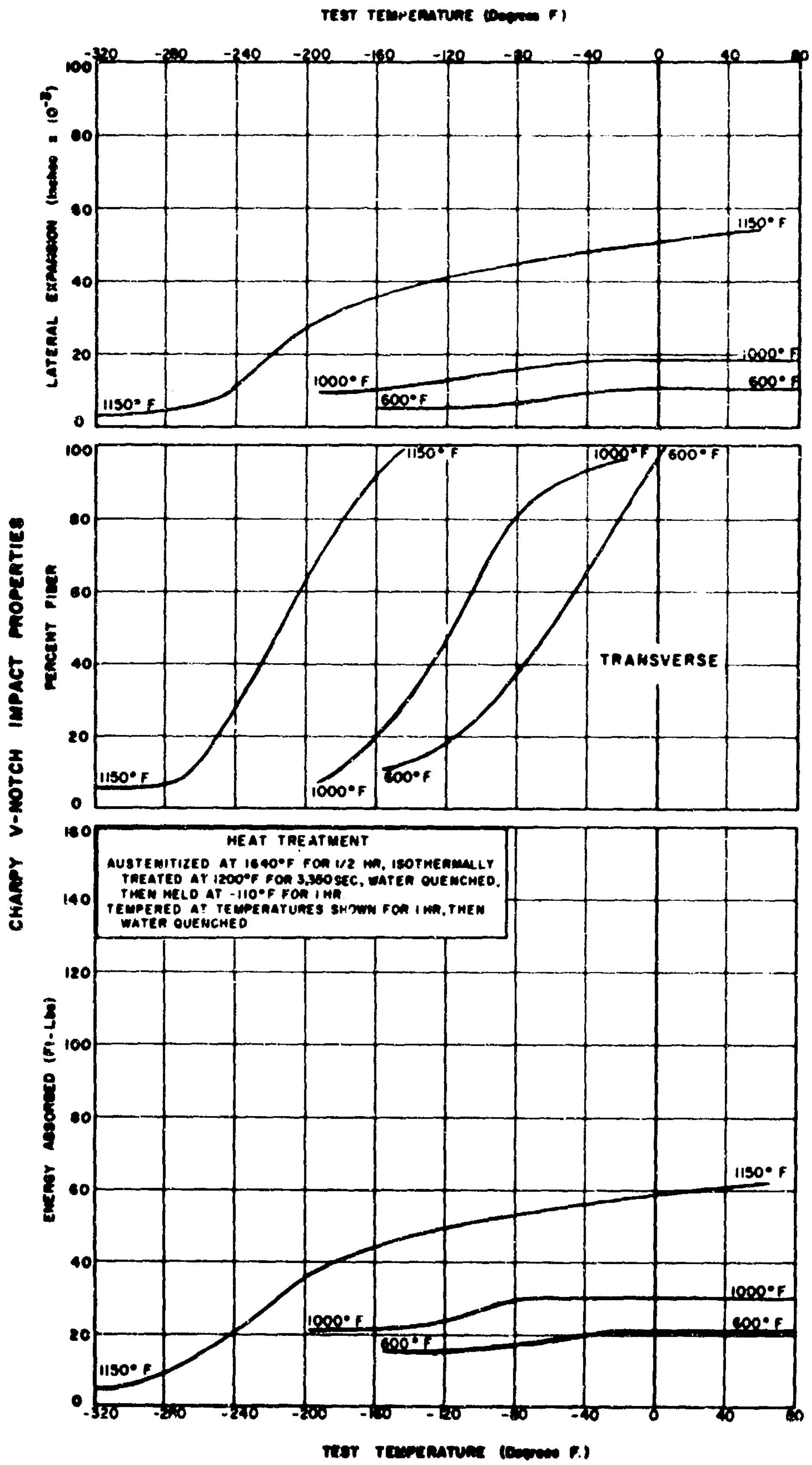


Figure A4 - Effects of Tempering Temperature on Chapry V-Notch Impact Properties of HY-80 Steel (DTMB Plate E103) Austenitized at 1640 F and Isothermally Treated at 1200 F to Contain 25 Percent Ferrite

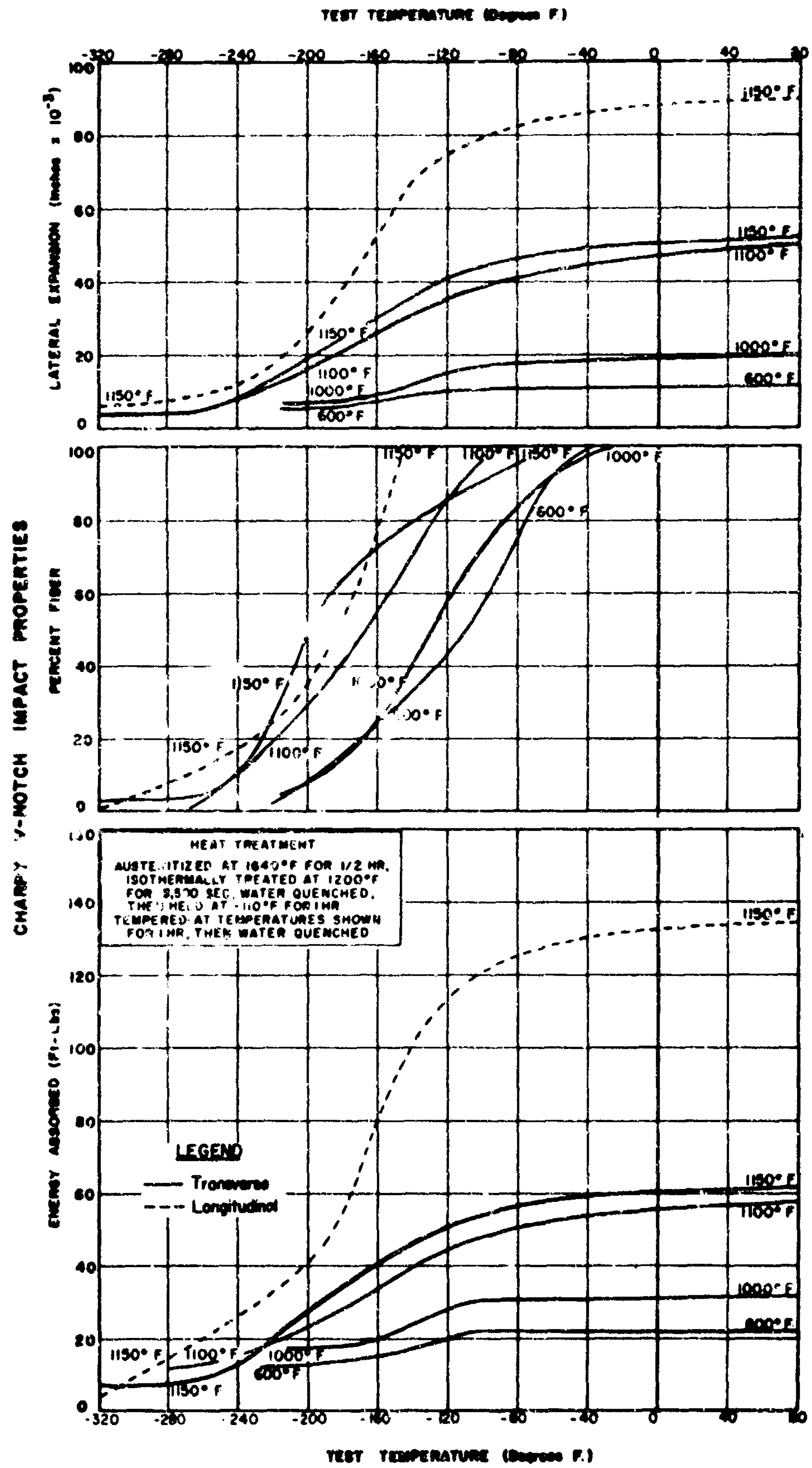


Figure A5 - Effects of Tempering Temperature on Charpy V-Notch Impact Properties of HY-80 Steel (DTMB Plate E103) Austenitized at 1640 F and Isothermally Treated at 1200 F to Contain 36 Percent Ferrite

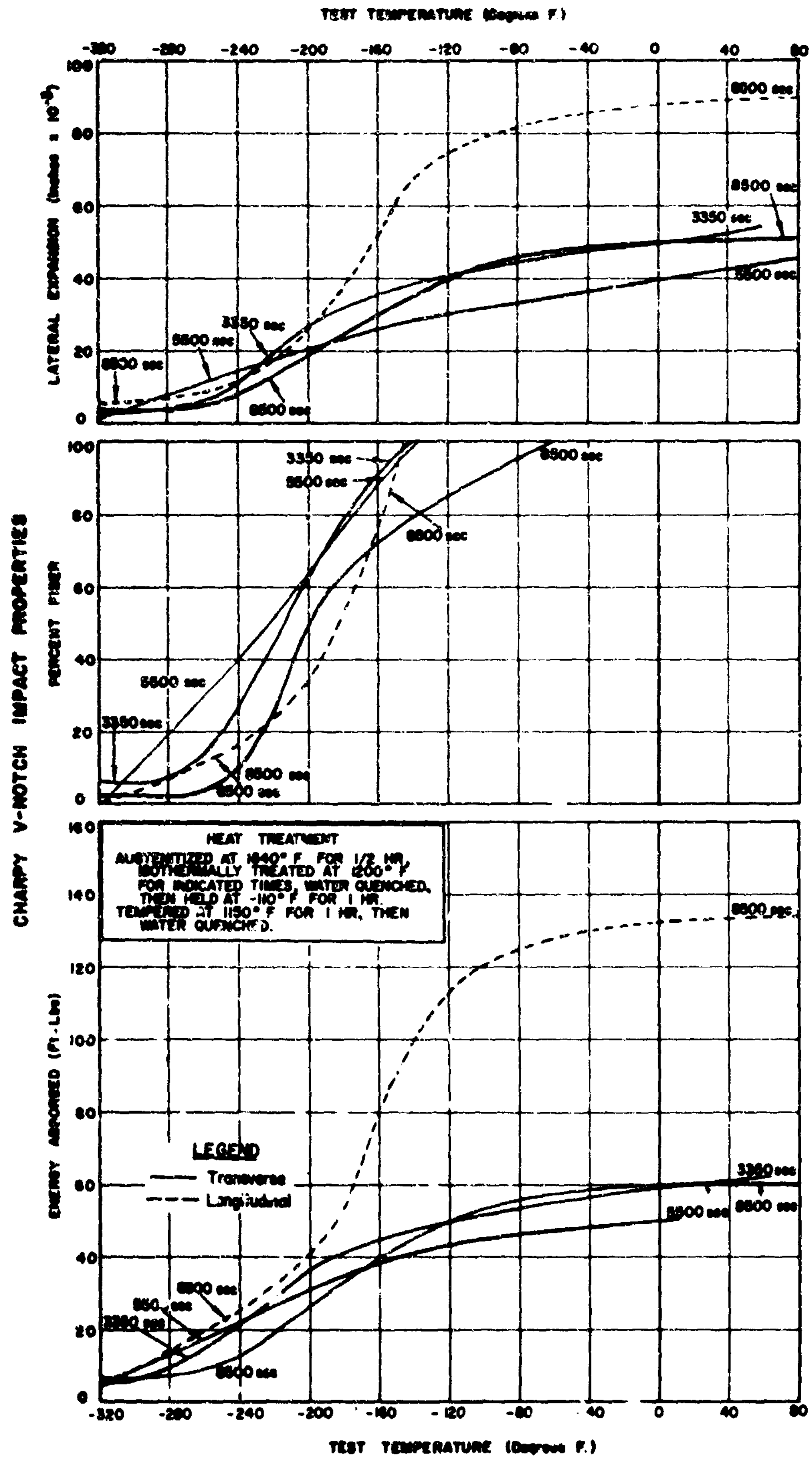


Figure A6 - Effects of Isothermal Holding Time on Charpy V-Notch Impact Properties of HY-80 Steel (DTMB Plate E10?) Austenitized at 1640 F and Isothermally Treated at 1200 F for Various Times

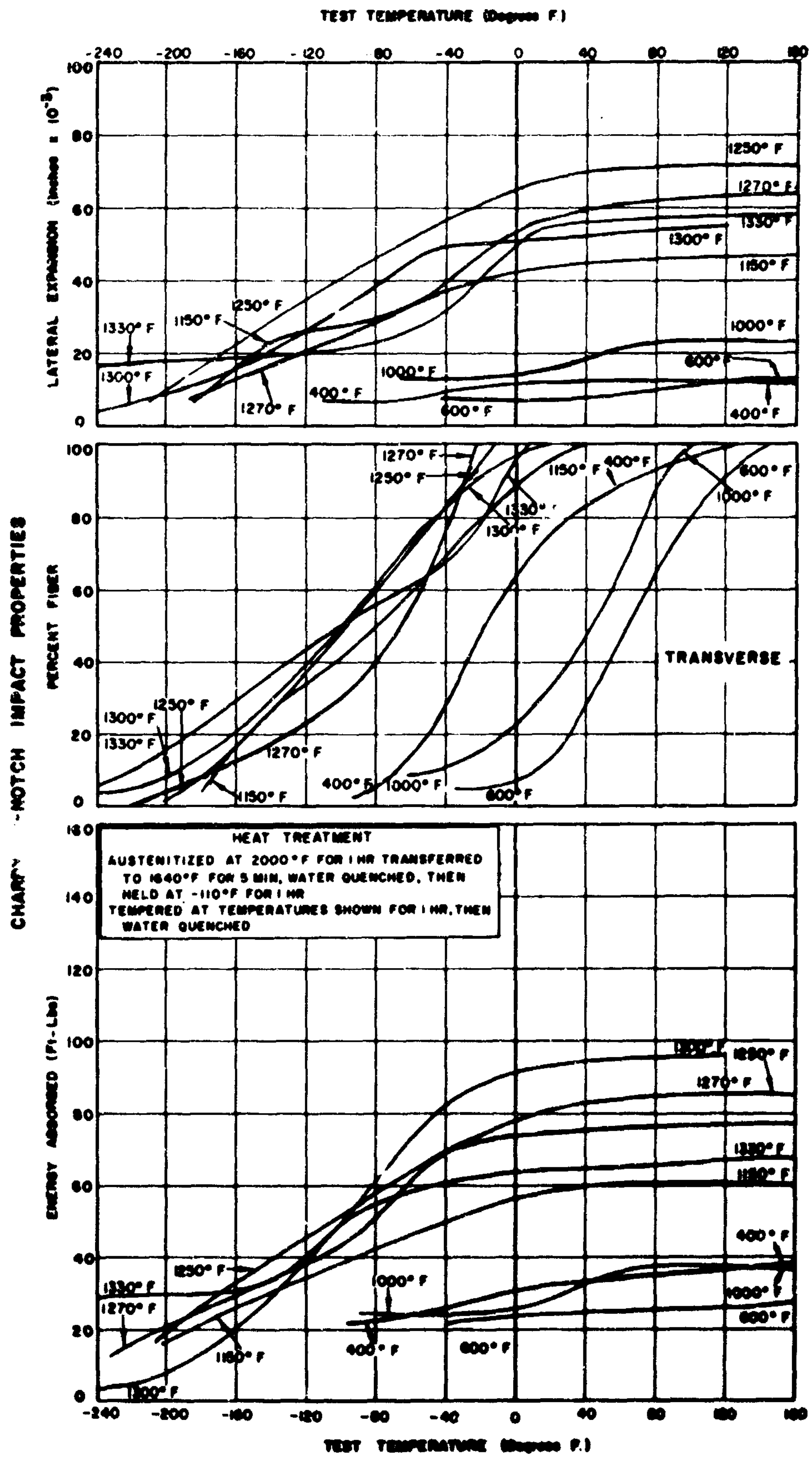


Figure A7 - Effects of Tempering Temperature on Charpy V-Notch Impact Properties of HY-80 Steel (DTMB Plate E103) Austenitized at 2000 F and Quenched to Contain 100 Percent Martensite

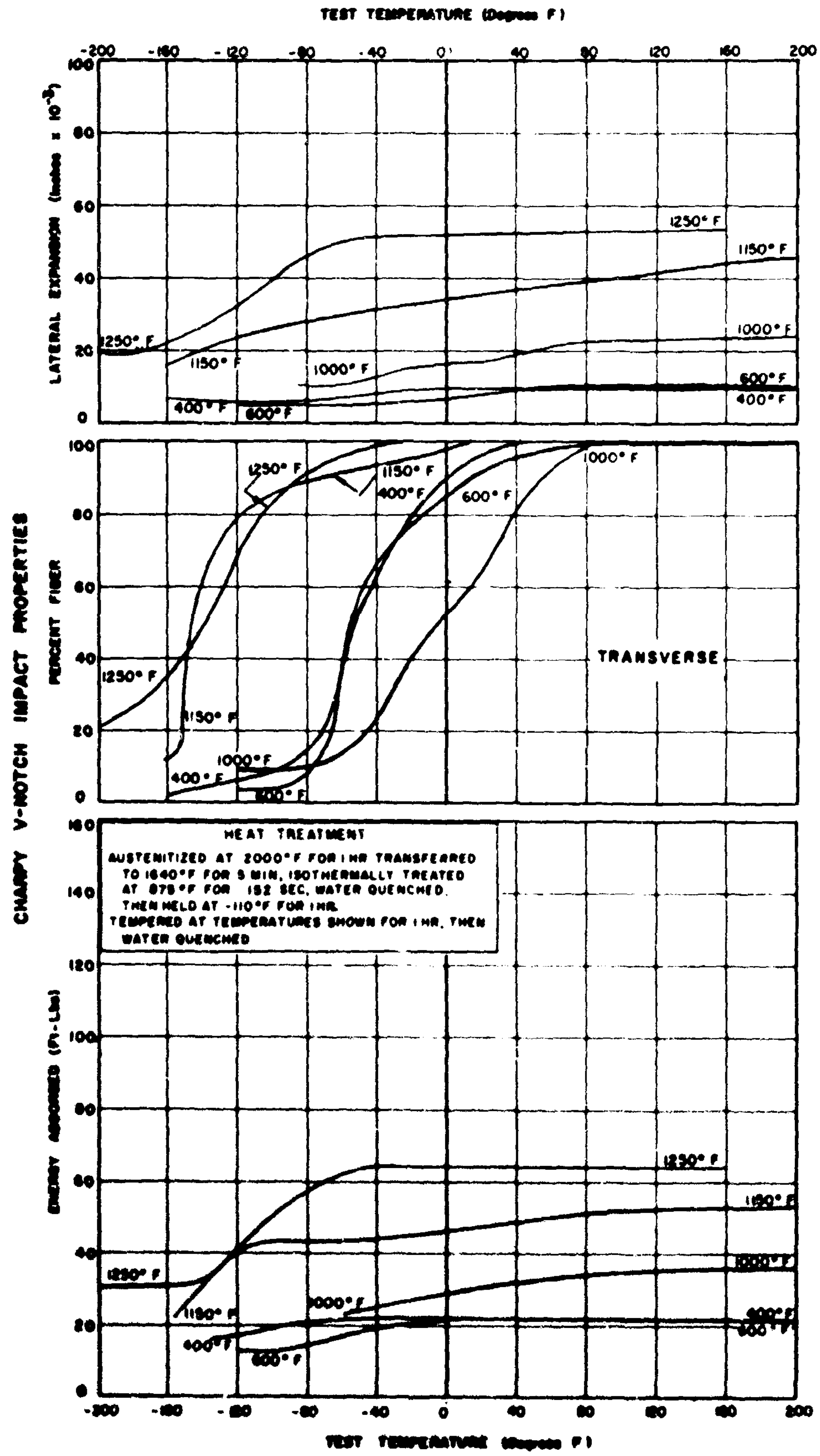


Figure A8 - Effects of Tempering Temperature on the Chapry V-Notch Impact Properties of HY-80 Steel (DTMB Plate K103) Austenitized at 2000 F and Isothermally Treated at 875 F to Contain 3 Percent Bainite

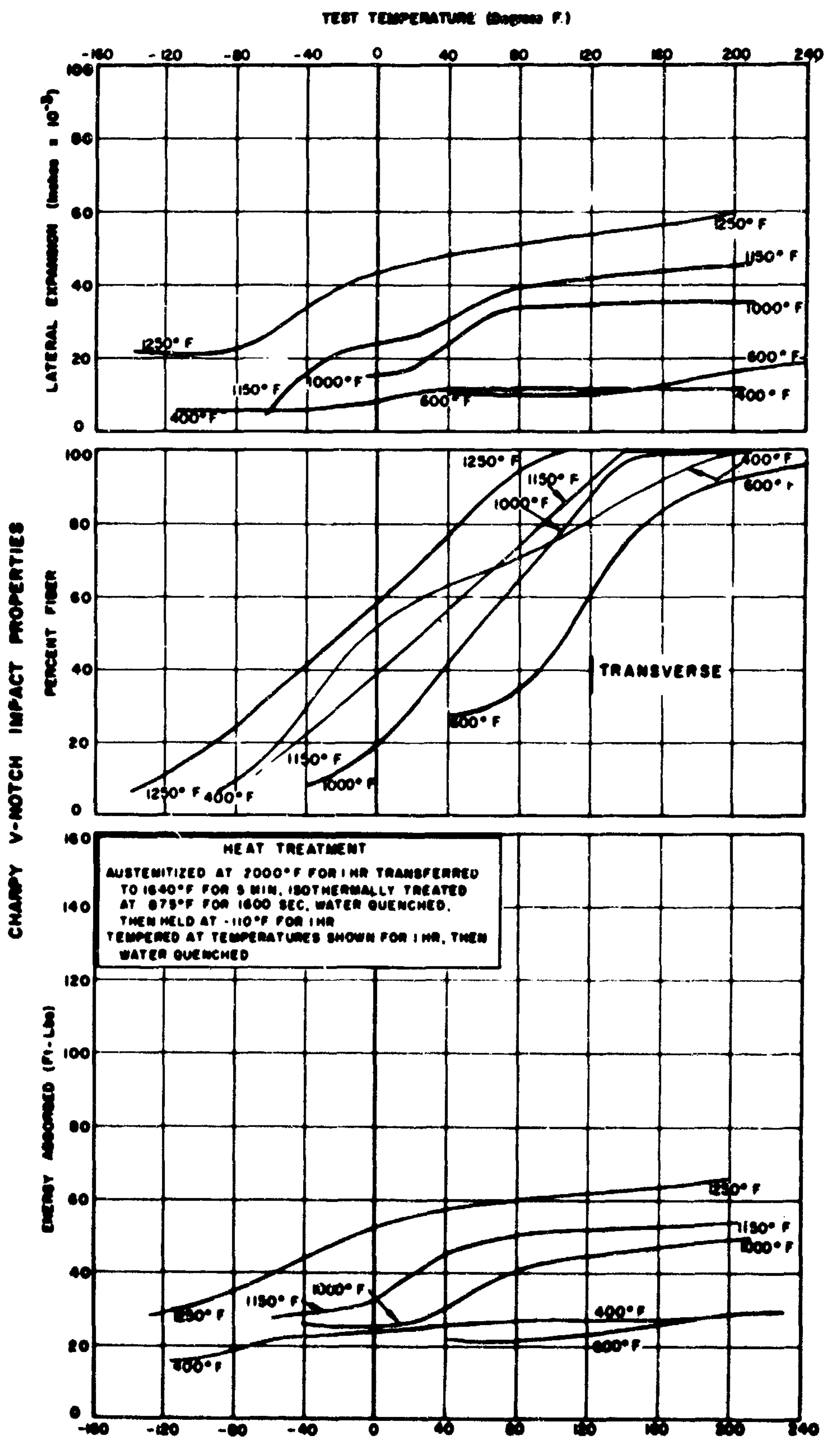


Figure A9 - Effects of Tempering Temperature on Charpy V-Notch Impact Properties of HY-80 Steel (DTMB Plate E103) Austenitized at 2000 F and Isothermally Treated at 875 F to Contain 17 Percent Bainite

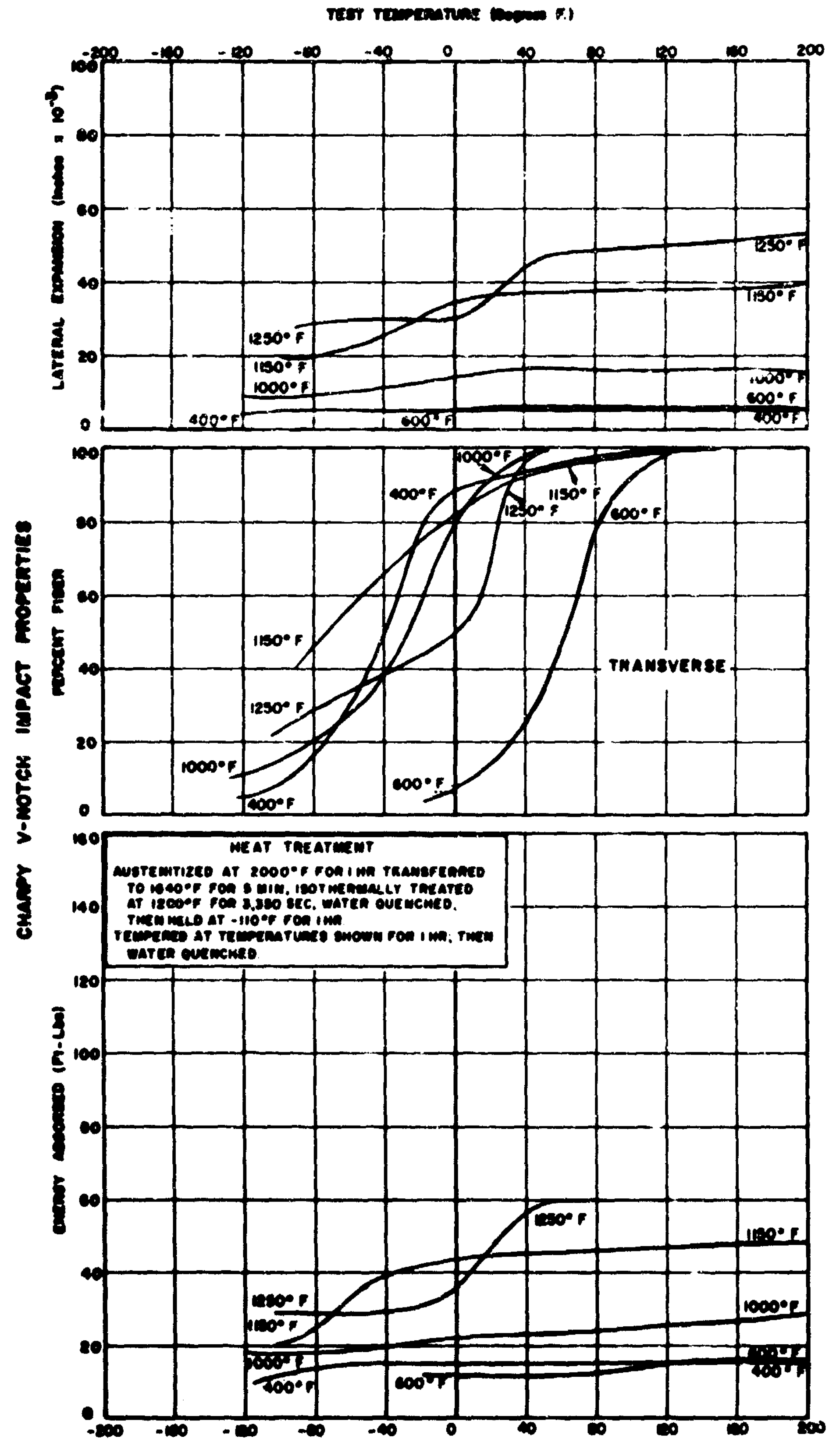


Figure A10 - Effects of Tempering Temperature on Charpy V-Notch Impact Properties of HY-80 Steel (DTMB Plate E103) Austenitized at 2000 F and Isothermally Treated at 1200 F to Contain 9 Percent Ferrite

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15. Puzak, P. P. and Babecki, A. J., "Explosion Tear Test Study of High Strength QT Steels," Naval Research Laboratory Report 5836 (6 Sep 1962).

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