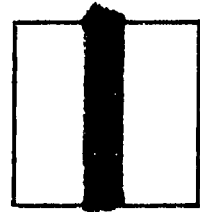


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WATERTOWN ARSENAL LABORATORY

EXPERIMENTAL REPORT

NO. WAL. 630/14

Temper Brittleness and Its Relation to the Heat Treatment
Of Ordnance Materiel

BY

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Watertown Arsenal Laboratory
Report No. WAL 630/14
Job No. 175

20 June 1945

Temper Brittleness and Its Relation to the Heat Treatment
of Ordnance Materiel

ABSTRACT

Temper brittleness is sometimes responsible for the low impact resistance of various items of Ordnance materiel. It is particularly important to avoid this type of embrittlement in armor plate and certain gun tubes for which high impact properties are necessary for satisfactory service life. Temper embrittlement occurs during:

- a. the period of slow cooling from tempering temperatures above 1100°F,
- b. tempering in the range of approximately 700°F to 1100°F,
- c. reheating to temperatures between approximately 700°F and 1100°F after once quenching from the temper.

Temper brittleness is caused by the precipitation of some unidentified constituent which manifests itself primarily by lowering the notched bar impact resistance or, more correctly, by raising the temperature at which brittle fracture occurs. The melting and refining practice, the direction of the test specimens with respect to the rolling or forging direction, the type and distribution of the microconstituents, and any other variables which influence the normal impact characteristics also influence the apparent degree of embrittlement caused by tempering treatments.

Manganese, chromium and nickel increase the tendency for temper brittleness to occur as well as its severity when it does occur. Steels of equal hardenabilities containing varying proportions of these three elements appear to possess approximately equal susceptibility to temper brittleness. Oxygen, nitrogen, phosphorus, and tin also appear to increase the susceptibility to temper brittleness, but the effect may be due to the fact that these elements also lower the impact properties of the unembrittled steel. In low and medium alloy steels molybdenum is so effective in retarding the precipitation of the embrittling constituent that it can be employed to eliminate or decrease the susceptibility to temper brittleness.

Various means of eliminating or minimizing temper brittleness are as follows:

- a. Employ steels containing 0.25% or more of molybdenum.
- b. Employ the minimum alloy content necessary for adequate hardenability.

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- c. Water quench after tempering especially if the tempering temperature is above approximately 1100°F.
- d. When the tempering temperature must be below approximately 1100°F, employ a tempering treatment involving the highest temperature and the shortest holding time practicable and water quench after tempering.
- e. Whenever necessary, select an alloy composition, such as one containing approximately 0.15% vanadium, which has a high resistance to softening so that a tempering temperature in excess of 1100°F will be required to produce the desired hardness. It will then be possible to water quench after tempering and avoid embrittlement.
- f. When choosing a composition for relatively thick sections where high impact resistance is required and where the section size is so great that water quenching after tempering provides cooling rates too slow to prevent embrittlement, select a steel which will have only sufficient hardenability to avoid the formation of pearlite during quenching. By virtue of the lower alloy content, as compared to a steel with sufficient alloy to permit full hardening, the steel will be less susceptible to temper brittleness. High impact resistance can be obtained in such bainitic steels only when they are tempered to relatively low hardnesses (approximately 200 BHN or 85,000 psi yield strength).
- g. Stress relieve at temperatures either below or above the embrittlement range of 700°F to 1100°F and follow the high temperature stress relieving treatment by water quenching.

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I. INTRODUCTION

For certain items of ordnance materiel a high degree of resistance to shock loading is necessary for satisfactory performance. During its service life, armor must be capable of withstanding extremely rapid applications of stresses which may exceed its yield and tensile strengths without more than local yielding and without the loss of its structural integrity. Artillery, particularly high velocity guns which have thin walls and high strengths, must have a high impact resistance in order to withstand prolonged firing. In all cases the impact resistance must be maintained at a reasonable level at all service temperatures which may be as low as minus 40°F on the ground and minus 65°F at flying altitudes.

It is apparent then that careful control must be exercised over all factors which influence the toughness of steel. One of these factors is temper brittleness and it is this phenomenon with which this report is concerned.

It has been known since approximately the turn of the century that certain alloy steels are subject to brittleness if they have been slowly cooled from the tempering temperature or if they have been tempered within a certain temperature range. This is the phenomenon of temper brittleness to which considerable attention was devoted shortly before and during World War I. It has often been called Kruppkrankheit (Krupp sickness) because it was observed in Krupp nickel-chromium steels which were widely used for guns and armor.

From the beginning of the present war up to the last half of 1943 the problem of temper brittleness in ordnance materiel produced in the United States received little attention partly because of the widespread use of low alloy steels which are relatively unsusceptible to temper brittleness and partly because the necessity of high resistance to impact was not at first recognized in certain ordnance applications. However, as strategy dictated the trend towards heavier armor it became necessary to increase the alloy content of such steels to maintain hardenability adequate to produce essentially martensitic structures upon quenching. It was immediately found that impact properties were obtained which were lower than expected for tempered martensite. It was at this time that the Watertown Arsenal Laboratory became aware of the role of temper brittleness in causing low shock resistance. Almost simultaneously, there was a trend toward the use of higher alloy contents in guns in order to develop fully hardened structures to obtain the high impact resistance which was considered necessary for successful functioning of new type, highly stressed gun tubes. Thus, the existence of the problem of temper brittleness in guns became evident through the interest in impact properties.

In order to clarify the problem of temper brittleness and to integrate the present knowledge of the phenomenon, Captain J. H. Hollomon of the Physical Metallurgy Section of the Watertown Arsenal Laboratory conducted an extensive literature survey and analyzed the available information in Report No. WAL 630/11, entitled "Temper Brittleness - A Critical Survey and Interpretation". It is the purpose of this paper to summarize some of the concepts contained in the above mentioned report and to suggest practical

methods whereby the temper embrittlement of ordnance materiel may be either completely eliminated or at least minimized. Whenever possible, data obtained from various sources are included to demonstrate the success or the limitations of the proposed methods of combating temper brittleness.

A bibliography of pertinent published and unpublished works is included at the end of the report.

II. THE TEMPER BRITTLENESS PROBLEM

A. Relation to Tempering Treatment

1. Precipitation Reactions during Tempering

The tempering of quenched steel involves primarily the formation and growth of carbide particles whose composition is a function of the chemical analysis of the steel and the tempering treatment employed. The internal stresses produced upon quenching are simultaneously reduced. Accompanying these changes there may be other reactions which depend upon the phase equilibria existing at the various tempering temperatures. The phenomenon of temper brittleness is believed to be the result of one such reaction.

Iron, when heated into the temperature range in which it becomes austenitic, can dissolve considerably greater quantities of carbon, oxygen, nitrogen, phosphorus, and many other substances than can be dissolved at lower temperatures at which the ferritic phase of iron is stable. The rapid allotropic change which occurs when steel in the austenitic condition is quenched will cause the dissolved substances to remain in solution in the ferritic phase in greater or lesser degrees of supersaturation. Reheating quenched steel to temperatures at which diffusion can occur will result in the precipitation of the elements or of compounds of the elements which were in supersaturated solution after quenching.

In addition to possessing different solubilities in ferrite and austenite, most of the nonmetallic elements always found in steel in more or less minute quantities are increasingly soluble in ferrite with increasing temperature up to the lower critical temperature. Consequently the temperature at which steel is tempered controls the amount of precipitation which can occur. Figure 1A represents a solubility diagram in which the solubility of element X in iron increases with increasing temperature. An amount of X equal to X_0 is completely soluble at the temperature T_0 , but when the temperature is reduced to T_1 , an amount of X equal to X_1 remains in solution while an amount equal to $(X_0 - X_1)$ is precipitated.

Whenever precipitation from a solid solution occurs, the precipitate first forms at grain boundaries and then randomly within the grains. When the total amount of precipitate that is formed is very small, the precipitate is largely confined to the grain boundaries. A theory to explain the embrittling effect of the temper brittleness precipitation is based upon the existence of the precipitate at grain boundaries^{1*}.

* Raised numbers refer to numbered bibliography at end of report.

time-temperature-transformation diagram shown in Figure 1B. When steel is tempered at a temperature above T_0 (approximately 1100°F) the temper brittleness constituent is completely soluble at the tempering temperature. If the steel is now cooled rapidly enough to avoid the nose of the "C" curve, the constituent will be retained in solution and no embrittlement will result. If, on the other hand, the steel is cooled sufficiently slowly from above the temperature T_0 , the cooling curve will intersect the "C" curve, and precipitation and consequent embrittlement occurs, the degree of which depends upon the length of time spent in the embrittling range of temperatures.

Steel which has been tempered at some temperature in excess of 1100°F and water quenched after tempering to prevent the temper brittleness transformation may become embrittled if it is subsequently heated to temperatures in excess of approximately 700°F.

B. Effect of the Temper Brittleness Transformation on the Physical Properties of Steel

1. Impact Properties

For steels which do not become embrittled by any tempering practice, it is found that the impact resistance at any testing temperature decreases as the hardness is increased. Figure 2A demonstrates the more or less linear relationship between impact resistance and hardness of a fully quenched steel.

The temper brittleness precipitation, which occurs by the mechanism illustrated by the "C" curves of Figure 1B, causes the relation of impact resistance to hardness to become less simple. The behavior of a typical steel which can become embrittled by tempering is shown by the curves of Figure 2B. The impact resistance increases with decreasing hardness until, in this case, a tempering temperature of approximately 350°F is reached. In the range of tempering temperatures of 350°F to 1000°F the impact resistance decreases because of the increasing amount of precipitation which occurs during the tempering operation. The decrease in impact resistance resulting from tempering in the range of 350°F to 1000°F occurs in spite of the fact that continual softening of the steel occurs. When the tempering temperature is at 1100°F and higher, water quenching after tempering avoids the embrittlement, whereas furnace cooling does not. The relatively small increase in the impact resistance of the furnace cooled specimens tempered above 1000°F is largely traceable to the greatly reduced hardnesses developed at the higher tempering temperatures.

The irregular shape of the curves in Figure 2B can be explained by reference to Figure 3, which was plotted by Hollomon² from data of Greaves and Jones. The curves of Figure 3 were obtained by drawing lines through points representing constant decreases in the impact resistance of a series of specimens which had been embrittled by holding for various times at temperature within the embrittling range. All specimens had received an identical prior treatment which included water quenching after tempering. The similarity of the curves representing constant decrease in impact resistance to the "C" curve of Figure 1B is significant. It was on the basis of these curves that Hollomon made the reasonable assumption that the amount of decrease in impact resistance is proportional to the amount of embrittling constituent which precipitates.

Hollomon² replotted data of Greaves and Jones³ in the manner shown in Figure 4 where the variation of impact resistance for constant tempering times in the embrittling range is plotted against hardness. To obtain a given hardness using different tempering times the tempering temperature was necessarily varied. The data of Figure 4 can be fully explained by a consideration of the "C" curve shown in Figure 3. It is apparent that the loss in impact resistance demonstrated by the specimens tempered for 10 minutes, 1 hour, and 4 hours resulted from the precipitation of the embrittling constituent at the tempering temperature since the specimens were, in all cases, water quenched after tempering. No embrittlement occurred during the first 4 minutes at temperature over the entire range of tempering temperatures, indicating that the nose of the "C" curve was located at least 4 minutes from the abscissa on the time scale. As the length of hold at the tempering temperature is increased, the impact resistance for a constant hardness decreases because more precipitation occurs at the longer holding times.

It is thus apparent that the effect on impact resistance is a significant manifestation of temper brittleness. Although this effect is ordinarily considered to be merely a lowering of the impact resistance, this is not true per se. For an explanation of how the impact resistance of steel is affected by the temper brittleness transformation it is necessary to consider the way in which impact resistance varies with the testing temperature.

In the case of normal unembrittled specimens tested at various temperatures, say between +200 and -100°F, the impact resistance at the lower temperature almost invariably will be less than at the higher temperature. The change may occur gradually or abruptly and the curve may have any one of an infinite number of shapes depending on the microstructure, strength and quality of the steel and the form of the impact specimen. Lowering of the impact resistance is accompanied by a change in the fracture from a ductile fibrous one to a crystalline fracture. When the change in impact energy is abrupt the temperature or temperature range at which this occurs is referred to as the impact transition temperature or transition range.

Actually the effect of temper brittleness is to displace the impact temperature curve in such a way that any change from one level of impact resistance to another or from one type of fracture to another occurs at a higher temperature than for specimens which are otherwise identical except that they are unembrittled. The shift in the impact-temperature curves is illustrated in Figure 5 for two typical steels with two degrees of embrittlement.

For the steel of Case A in Figure 5, the impact resistances at T_3 and higher temperatures are the same for the embrittled and normal specimens, at T_2 the normal specimen and the one with the least amount of embrittlement are the same, but at T_1 all the specimens are different. For the steel of Case B there is some difference at all three temperatures. If T_1 , T_2 and T_3 represent -40°F, +70°F, and +100°F, respectively, then Case A may be considered to be a typical steel which has been fully hardened and tempered and Case B may be considered to represent the same steel incompletely hardened and tempered. Thus it appears that temper brittleness may or may not be detected by impact tests depending upon the normal impact characteristics of the steel and the testing temperature used.

The degree of temper brittleness induced in a steel has been expressed by the susceptibility ratio which is defined as the impact resistance of a non-embrittled specimen divided by that of the embrittled specimen. This means of quantitative expression is of value only if it is determined for a temperature within or above the impact transition range when the impact test at that temperature also represents service conditions. For the steel of Case B in Figure 5, determination of the susceptibility ratio at a temperature below T_1 would not adequately indicate the degree of embrittlement and may lead to erroneous conclusions regarding its adequacy for service.

2. Tensile Properties

The effects of the embrittling precipitation are not readily recognized by any alteration in the reduction of area values of static tensile tests. There has, however, been some evidence of anomalous types of tensile fractures with very slight reduction of static ductility but these occur only when steel is very severely embrittled. It has often been observed that the elastic limits of water quenched, hence unembrittled, specimens were lower than those of embrittled specimens but this has usually been attributed to the difference in the residual stress condition. The high residual stresses in water quenched specimens would be expected to lower the elastic limits.

C. Factors Affecting the Susceptibility to Temper Brittleness

1. Alloy Content

Plain carbon steels containing less than approximately 0.6% manganese are not susceptible to temper brittleness. In general, the susceptibility to temper brittleness increases with increasing amounts of the alloying elements most commonly added to steel, namely, manganese, nickel and chromium. Recent work at the Watertown Arsenal on a series of induction melted 0.30% carbon and 0.40% molybdenum steels containing varying amounts of manganese, nickel, and chromium showed that all three elements increase the susceptibility to temper brittleness. Figure 6A shows the ratio of impact energies of specimens which had been furnace cooled after tempering to specimens which had been water quenched after tempering plotted against the sum of the manganese, nickel, and chromium contents. These steels had all been quenched to martensite, tempered at temperatures above 1150°F and tested at a temperature of -40°F.

Replotting of the same data described above shows that any combination of manganese, nickel, and chromium having a constant hardenability (using Grossmann's multiplying factors) will have about the same susceptibility to temper brittleness, see Figure 6B. It may be inferred from this that the relative effect of these three elements upon the susceptibility to temper brittleness is of the same order of magnitude as their effects upon hardenability. Manganese appears to have a much greater effect upon increasing the susceptibility to temper brittleness than does either nickel or chromium, but, on the other hand, manganese is also much more potent than the other two elements in increasing hardenability.

Molybdenum has been found capable of completely eliminating the loss of impact resistance resulting from slowly cooling after tempering in low and in some medium alloy steels, but when the susceptibility to embrittlement is very high, molybdenum may lower but will not entirely eliminate

the tendency to embrittlement. Molybdenum seems to lower the susceptibility to temper brittleness primarily by lowering the rate of transformation during tempering or during the slow cooling through the embrittling range. The lowering of the rate of transformation appears to be accomplished by the shifting of the "C" curve to the right in exactly the same fashion that molybdenum increases the hardenability of steel by shifting the pearlite "C" curve to the right. Data exist which show that, when steels containing molybdenum are tempered in the embrittling range for very long times to allow maximum precipitation to occur, molybdenum actually increases the degree of the resultant embrittlement.

Vanadium appears to increase the susceptibility to temper brittleness only slightly. Tin, oxygen, and phosphorus appear to increase the susceptibility more or less markedly, possibly because they cause considerable alteration of the impact vs. temperature curve even when the steel is not embrittled.

The exact mechanism whereby alloy content influences temper embrittlement is not understood. There are, however, at least two possible explanations for this behavior. Increased alloy contents may shift the solubility line to the left, as shown in Figure 7A, or may cause more of the element responsible for temper brittleness to be present in steel, shifting the amount from X_0 in steels of low susceptibility to X_0' in steels of high susceptibility, as shown in Figure 7B.

2. Microstructure

Because of the fact that the type and distribution of microconstituents in steel profoundly affect both the impact energy level and the shape of the impact vs. temperature curve, the manifestation of temper brittleness through a lowering of the impact energy of embrittled steel is greatly influenced by microstructure. For example, steel heat treated to a tempered martensitic structure and free from temper brittleness will suffer a transition from ductile to brittle fracture, as determined by impact testing, at low temperatures. If the same steel is moderately temper embrittled, the temperature of brittle fracture will be raised, but may still be below room temperature. It would then be necessary to conduct impact tests at subzero temperatures to determine that the steel had been embrittled, because room temperature tests will yield identical results for the unembrittled and the embrittled steel. If, however, the same steel is incompletely quench hardened, so that the microstructure consists of mixtures of tempered pearlite or bainite and martensite, the temperature of brittle fracture is raised and may be in the vicinity of room temperature. If the same steel is now temper embrittled to the same extent as previously, the temperature of brittle fracture may now be considerably higher than room temperature. Room temperature impact tests will, in this case, distinguish between the ductile and the brittle steel, whereas room temperature impact tests would fail to distinguish between the ductile and the temper brittle martensitic steels.

A considerable amount of effort has been unsuccessfully expended in an effort to demonstrate, by metallographic means, the occurrence of the temper brittleness precipitate. Recently, however, an etchant has been developed at the Watertown Arsenal which shows a grain boundary attack on embrittled steels while unembrittled steels show no corresponding attack.

3. Melting and Refining Practice

There is considerable evidence that many steels made in a basic furnace have lower susceptibility to temper brittleness than acid steels of similar composition. This is believed to be due to the higher sulfur and phosphorus contents of acid steels. It is not at all unusual for acid steels produced for some ordnance requirements to have a combined total of sulfur and phosphorus contents in excess of 0.070%, whereas that of basic steel is generally no more than half that amount. It is believed that the higher sulfur and phosphorus contents of acid steels lower the quality level and thereby raise the temperature of brittle fracture. When temper brittleness is superimposed upon the effects of high sulfur and phosphorus contents, the loss in impact resistance becomes more marked than when the steel is of an initially high quality.

Aluminum killed steels generally show less tendency to become temper embrittled than those of similar analysis not treated with aluminum. This is probably due, at least in part, to the effect of aluminum in decreasing the grain size of steel and in raising both the impact and quality levels.

In general, the apparent susceptibility of a steel to temper brittleness is affected by the factors which influence the shape of the curve of impact vs. temperature for the unembrittled steel. These factors include the cleanliness and freedom from segregation, the amount of rolling or forging, and the orientation of the specimen with respect to the rolling or forging direction.

III. AVOIDANCE OF TEMPER BRITTLENESS

A. Selection of Chemical Composition

1. Hardenability Considerations

For components which require through hardening and tempering as their heat treatment, the selection of a chemical composition is based primarily on the hardenability requirement which is dependent on the size and form of the item when it is treated and upon the severity of the quench. Where optimum impact properties are desired it is necessary to consider that the susceptibility of steel to temper brittleness increases as the amount of alloy is increased. For this reason, as well as the economic considerations, it is desirable to employ the minimum amount of alloy that will permit complete hardening with the quenching practice used. It is obvious that the quenching practice should be as drastic as possible, realizing that quench cracking and excessive distortion must be avoided.

Special consideration must be given to ordnance structures in which the section thickness is so great that very high alloy contents must be employed if hardenability sufficient to produce full hardening upon water quenching is desired. As shown in Figure 6, the susceptibility to temper brittleness becomes so pronounced that embrittlement cannot be avoided, particularly in view of the relatively slow cooling rates which occur in heavy sections during quenching.

Table I contains data obtained at Watertown Arsenal⁷ from a series of experimental steels designed, with the exception of the last composition, to produce martensite upon quenching in 6" thick sections. The susceptibility to temper brittleness was determined by heat treating small sections. The water quenching after tempering of sections approximately 6" to 8" thick was simulated by air cooling a one-inch diameter round from the tempering temperature. The data indicate that thick sections of steels of high susceptibility to temper brittleness will be brittle in heavy sections even when water quenched after tempering. The data of Table I have been plotted, Figure 3, to show that for 3-inch plates the maximum impact resistance obtainable is lower than the optimum value by a fractional amount which is nearly proportional to the susceptibility ratio. The last composition of Table I (2.5% Cr, 0.50% Mo) has been used successfully for sections up to 10" in thickness and has been found to possess excellent impact properties at hardnesses below approximately 260 Brinell as shown in Table II.

Steel No. 1 of Table II was designed to possess sufficient hardenability to completely transform to martensite upon quenching in a 4" section. The susceptibility of this steel to temper embrittlement is so great, however, that inferior shock properties were obtained in the middle of the section even though the steel was quenched from the tempering temperature. The retempering of small sections cut from the center of the section demonstrated the magnitude of the susceptibility to temper brittleness.

Steels No. 2 and 3 are of the 2.5% Cr, 0.5% Mo type which transform to an essentially bainitic microstructure when quenched in the section sizes involved. Nevertheless, when tempered to approximately 200 BHN, both steels develop excellent impact properties. Steel No. 2 developed no temper embrittlement whatsoever in a 4" section while steel No. 3 was only moderately temper embrittled in a 10" thick section.

Thus, the necessity for coping with severe temper embrittlement in compositions designed to produce adequate hardenability for heavy sections may often require the specification of an under-alloyed steel selected because of its low susceptibility to temper brittleness and its ability to produce essentially bainitic structures free from injurious amounts of precipitated ferrite or pearlite.

2. Effect of Composition on Temper Brittleness

The effects of the various elements in promoting temper brittleness have already been outlined. These effects of the various alloys together with the economic aspects and their possible effect in causing quench cracks should be considered in the selection of an alloy composition.

It is well to emphasize again that in most cases, where other alloys and other variables are such that the susceptibility to temper brittleness is not too great, .3 to .5% of molybdenum will decrease the tendency toward embrittlement during tempering or during cooling after tempering. The adverse effect of molybdenum after prolonged heating (a matter of many days) in the embrittling range is seldom of importance in major ordnance items.

3. Effect of Composition on Tempering Temperature

In some instances it may be necessary to consider the effect of the chemical composition on the tempering temperature required to obtain the desired strength or hardness. The effect may be of considerable importance for steels susceptible to temper brittleness when the desired strength or hardness is so high that the tempering temperature would be below 1100°F for an alloy steel which softens rapidly upon tempering. If the required hardenability is obtained by use of chromium, molybdenum, vanadium, or other such elements which retard softening it may be possible to temper above 1100°F and avoid embrittlement by water cooling from the tempering temperature.

In this respect vanadium is particularly effective. By the addition of .20% vanadium to some alloy steels containing 0.30 to 0.40% carbon, hardnesses as great as 350 to 400 Brinell can be obtained by tempering at temperatures above 1100°F. To obtain such hardnesses in moderately alloyed steels not containing vanadium, tempering temperatures below 1100°F are required and the temper brittleness precipitation occurs during the tempering cycle, resulting in the impairment of the impact properties.

B. Avoidance of Temper Brittleness in Steels Tempered below 1100°F

It has been shown that for steels which are tempered below 1100°F the temper brittleness precipitation proceeds at the tempering temperature and water quenching from the temper is only slightly effective in preventing embrittlement. Thus, when the tempering temperature is in the embrittling range, the manufacturer may often have to content himself with keeping the embrittlement to a minimum rather than entirely eliminating it. The safeguards that should be employed when temper brittleness is expected to be a problem in steels tempered below 1100°F are the use of the minimum alloy content required for full hardening, the addition of at least 0.25% molybdenum to the steel, and the use of the highest temperature-shortest tempering time cycle practicable.

The reason that the highest temperature-shortest tempering time cycle should be employed when tempering in the embrittling range of temperatures is that the rate of softening increases more rapidly with increasing temperature than does the rate of precipitation of the temper brittleness constituent.

It may be possible to avoid temper brittleness, particularly where the items to be treated are small, by departing from conventional tempering treatments which usually involve holding times seldom less than one hour and often as much as 18 hours. The possibilities of this procedure are illustrated by Figure 9 which presents data for transverse V-notch Charpy specimens from a gun tube of relatively high strength. The curve AR is representative of the properties of the original tube which was tempered in the embrittling range at 960°F. Curve B represents the properties of small quenched specimens tempered in the embrittling range at a slightly higher temperature and then furnace cooled. Curve A represents specimens treated like those in Curve B but water quenched from the tempering temperature. Curve C represents small quenched specimens tempered to the same hardness* as the other specimens but at a temperature above 1100°F for a very short time and followed by water cooling. The difference between curves AR and B can be considered to represent the brittleness caused by incomplete hardening during quenching and by

*Methods of obtaining equal hardnesses with different time-temperature tempering treatments were first described in a Watertown Arsenal Report¹⁰ which has been abstracted in the form of Technical Bulletin¹⁰.

the different tempering treatment. The difference between Curves B and A represents the temper brittleness that is a consequence of the method of cooling even when the tempering temperature is below 1100°F. Finally, the difference between Curves A and C represents the temper brittleness that develops at the tempering temperature and is a consequence of the different time-temperature combination without any effect from cooling rate.

These data indicate that tempering treatments involving temperatures above 1100°F, short holds, and water cooling would be better practice for developing high impact resistance at a high hardness than present conventional tempering treatments. The practicability of this procedure is limited by the size of the item to be treated, the degree of control which can be exercised over time and temperature of tempering, and the necessity for preventing hardness gradients traceable to temperature gradients. Short time, high temperature tempering cycles require a degree of control not possible in all plants, and suffer from the disadvantage that relatively slight variations in tempering time and temperature may produce large variations in physical properties.

C. Avoidance of Temper Brittleness in Steels Tempered above 1100°F

The problem of temper brittleness in steels which are tempered at temperatures above 1100°F to produce the desired physical properties is simplified to the extent that the temper brittleness transformation does not proceed simultaneously with the tempering reaction. Such steels become temper embrittled only during cooling from the tempering temperature through the range of 1100°F to 500°F sufficiently slowly to allow the transformation to occur. Obviously, temper embrittlement can be most effectively prevented in steels tempered above 1100°F by quenching the steel in water immediately after withdrawal from the tempering furnace.

Water quenching after tempering, unfortunately, is not always a panacea that is readily applicable in all cases. Water quenching from the tempering temperature may induce so undesirable a stress condition that the part may distort excessively during subsequent machining or may perform unsatisfactorily in service. Generally, however, sufficient tolerance exists in armor structures so that the slight distortion engendered by water quenching is not serious. Experience will quickly uncover those cases in which rapid cooling from the tempering temperature must be employed with discretion. It is possible to reduce the residual stresses slightly by removing the material from the water quenching bath when it has cooled down to about 500°F and allowing it to cool to room temperature slowly. Likewise, after the water quench from the elevated tempering temperature, a retempering treatment at about 600-700°F may prove beneficial in lowering the stresses about 20 to 40% without danger of embrittlement. Because of the smooth cylindrical contours of gun tubes, producers have experienced little difficulty with distortion following water cooling from the tempering temperature.

D. Welding and Stress Relieving Problems with Steels Susceptible to Temper Brittleness

The welding of steels susceptible to temper brittleness does not generally introduce the danger of embrittlement because in weldments the rates of cooling from elevated temperatures are usually rapid and the time spent in the embrittling range is short. Welding processes, such as Unionmelt welding, which

involve the heating of rather large masses of metal may result in temper brittleness adjacent to the weld because of the lower cooling rates and consequent increase in the length of time spent in the embrittling range. These same processes may be undesirable from viewpoints other than temper brittleness because of the poor properties resulting from the presence of high temperature transformation products in the base metal adjacent to the weld.

The stress relieving of any steel susceptible to temper brittleness will impair its impact properties when the stress relieving is conducted at temperatures within the embrittling range (700-1100°F), see Figure 3. Some relief of stress without loss of impact properties can be accomplished at temperatures up to 700°F, but the stresses will rarely be decreased by more than approximately 40%¹¹. The effect of stress relieving a susceptible steel within the embrittling range is shown by the data of Greaves and Jones¹¹ and is plotted in Figure 10. The data in Table III, supplied by a producer of cast armor¹², indicate that temper embrittlement during stress relieving in the embrittling range can be somewhat reduced but not eliminated by minimizing the time at the stress relieving temperature and water quenching after stress relieving (thereby inducing additional stresses).

Stress relieving without danger of causing temper embrittlement can be performed at temperatures in excess of 1100°F providing the material is water quenched after tempering. The water quenching necessarily induces a stressed condition, but there are many instances where the latter stresses will be more favorably disposed than the initial stresses the relief of which was desired.

TARLE I

Impact Properties of Compositions Designed for Heavy Sections. Heat Treated in Small Sections and Water Quenched and Furnace Cooled after Tempering. Also Air Cooled in 1" Diameter Rods after Tempering to Simulate Water Quenching of 8-Inch Sections.

V-notch Charpy Impact Data

*SMALL SECTION RESULTS (5/8" Rods)

C	Mn	Ni	Cr	Mo	Oil Quenched - Cooled to below 4° Temperature before Tempering		FURNACE COOLED FROM TEMPER		Temper Brittleness Susceptibility Ratio at -40°F.		*1" DIAMETER RODS	
					Hardness, Rc	Ft. Lbs. at -40°F.	Hardness, Rc	Ft. Lbs. at -40°F.	Oil Quenched - Cooled to below 4° Temp. before Tempering	Air Cooled FROM TEMPER	Hardness, Rc	Ft. Lbs. at -40°F.
.29	1.33	2.27	1.63	.44	40.4	25.5	6.6	25.5	4.70	24.5	24.0	
.28	1.32	3.07	1.56	.52	45.9	25.0	10.8	25.0	4.33	21.2	30.8	
.33	1.12	3.41	1.71	.46	43.8	27.5	14.2	29.0	3.08	37.5	25.0	
.27	1.44	3.09	2.22	.61	30.0	25.0	2.2	25.0	13.65	9.5	24.5	
.29	1.39	3.15	2.06	.84	29.2	27.5	3.4	28.0	8.60	16.4	27.0	
.29	1.41	3.21	1.79	1.02	31.6	28.5	3.1	27.5	10.20	17.1	25.5	
.31	.76	--	2.57	.45	54.7	28.5	45.0	27.0	1.21	61.4	24.0	

All specimens were fully quenched out to martensite. Impact values are average of duplicate tests.

TABLE II

Impact Properties of Heavy Cast Steel Sections Heat Treated in Full Size

Steel No.	Chemical Composition				Thick-ness Inches	V-Notch Charpy Impact Properties Heat Treated in Full Size Sections				Specimens from Middle of Section Retempered at 1200°F. and				Susceptibility Ratio
	C	Mn	Si	Cr		Mo	Y	Water Quenched from Draw	1" below Surface	Middle of Section	Water Quenched	Furnace Cooled		
							Ft.Lbs. +70°F.	Ft.Lbs. -40°F.	Ft.Lbs. +70°F.	Ft.Lbs. -40°F.	Ft.Lbs. +70°F.	Ft.Lbs. -40°F.	Ft.Lbs. -40°F.	
1	.27	1.44	1.58	1.31	.46	.13	34.2	17.4	29.5	12.1	21.3	3.5	6.1	
2	.29	.95	—	2.61	.58	$\frac{B}{.001}$	67.5	63.7	78.1	69.4				
3	.26	.75	—	2.67	.45	—	103.4	101.6	106.5	55.3	72.0	45.2	1.6	

TABLE III

Effect upon Impact Properties of Stress Relieving

a Steel Susceptible to Temper Brittleness

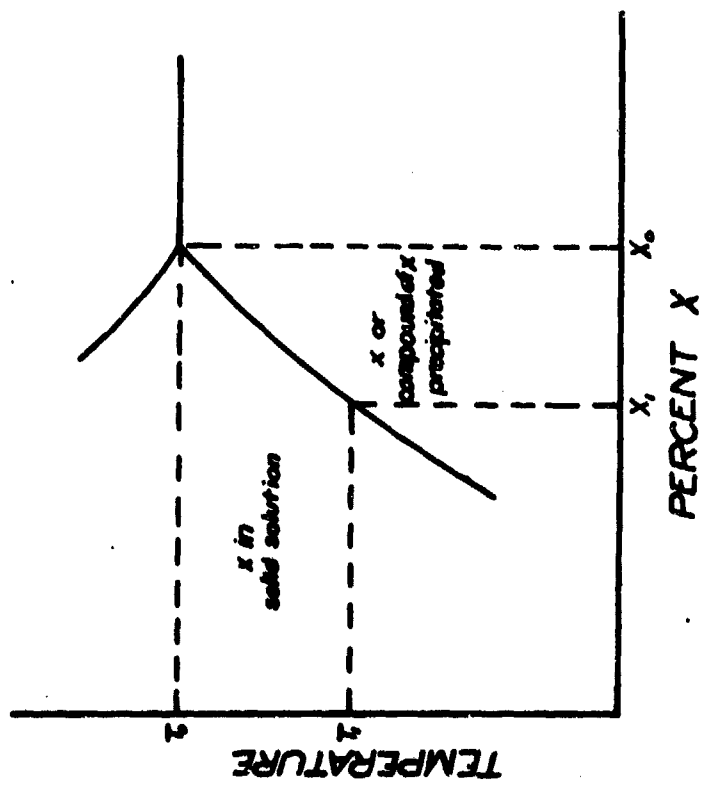
(Data supplied by American Steel Foundries, Chicago, Ill.)

6"x6"x10" sections heat treated as follows:
 1750°F. - 6 hrs. - air cooled.
 1250°F. - 3 hrs. - air cooled.
 1650°F. - 3 hrs. - water quenched (blocks cut in half).
 1160°F. - 6 hrs. - water quenched.

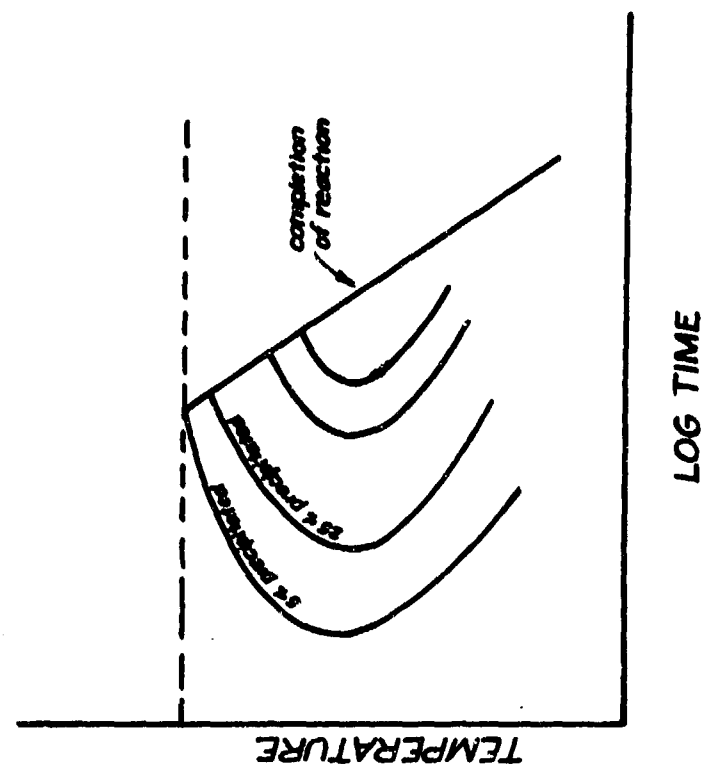
Composition (Nominal)

Composition (Nominal)				Deox.
C	Mn	Cr	Si	Mo
.20/.25	.60	1.50	1.50	.60
				2#/ton

Treatment	Average Izod Impact - Ft. Lbs.		
	Room Temp.	-40°F.	-80°F.
1. Standard, no stress relief.	38.7	38.1	33.1
2. Stress relieve - 1025°F. - 1½ hrs. Water quench.	34.0	29.6	27.3
3. Stress relieve - 1025°F. - 6 hrs.	33.6	27.2	22.7
4. Stress relieve - 1025°F. - 1½ hrs. Air cool.	34.3	28.3	24.1
5. Stress relieve - 1025°F. - 6 hrs. Air cool.	36.4	22.6	18.3
			Average BBE
			258
			269
			255
			269
			261



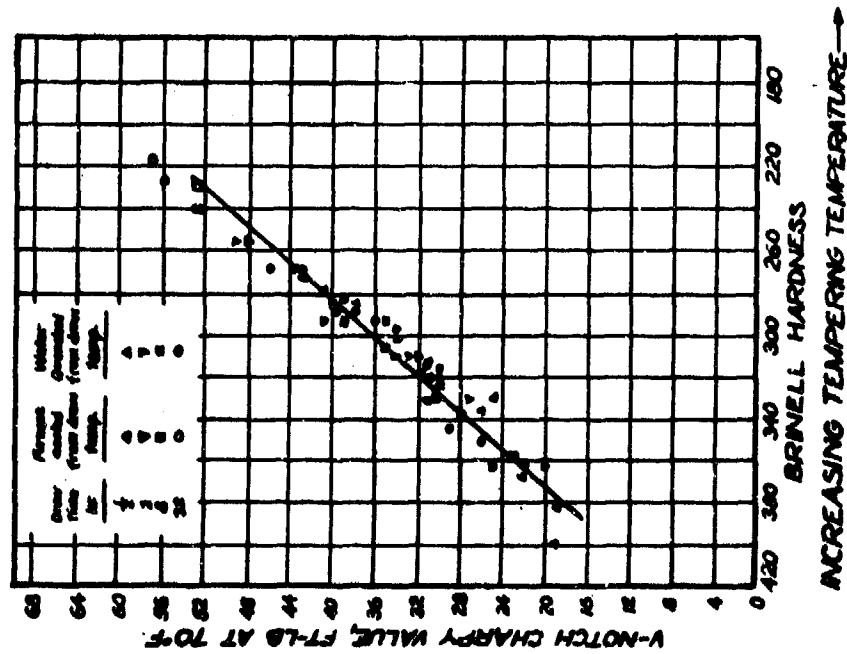
A EQUILIBRIUM DIAGRAM OF SYSTEM IN WHICH ELEMENT X HAS VARYING SOLUBILITY BELOW TEMPERATURE T_1 .



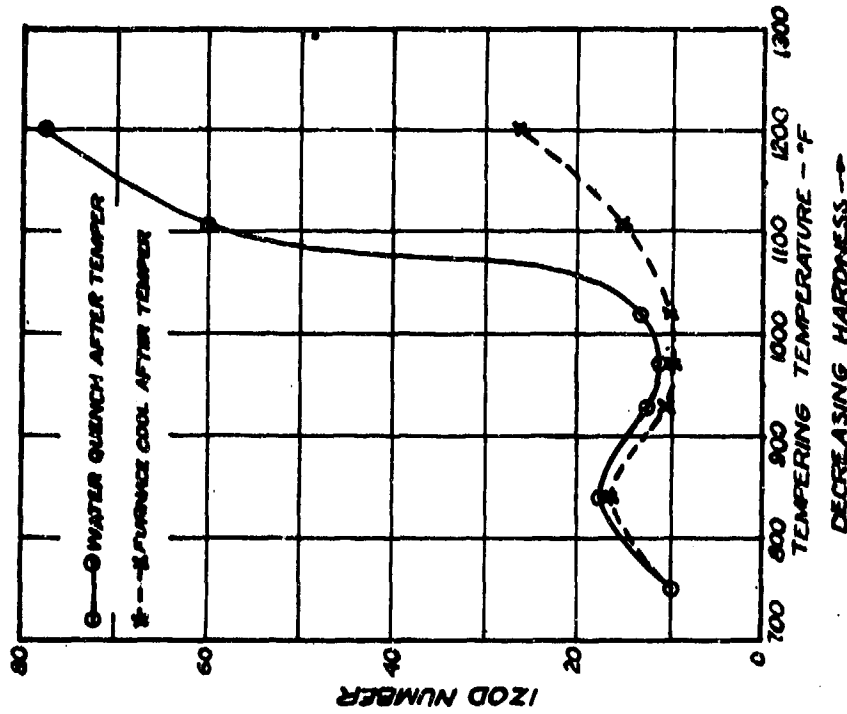
B TYPICAL ISOTHERMAL TRANSFORMATION CURVES ILLUSTRATING AMOUNT OF SUBSTANCE X PRECIPITATED AS A FUNCTION OF TIME AND TEMPERATURE (AFTER HOLLOMON¹)

SCHEMATIC REPRESENTATIONS OF THE BASIC CONCEPTS OF THE TEMPER BRITTLENESS PRECIPITATION

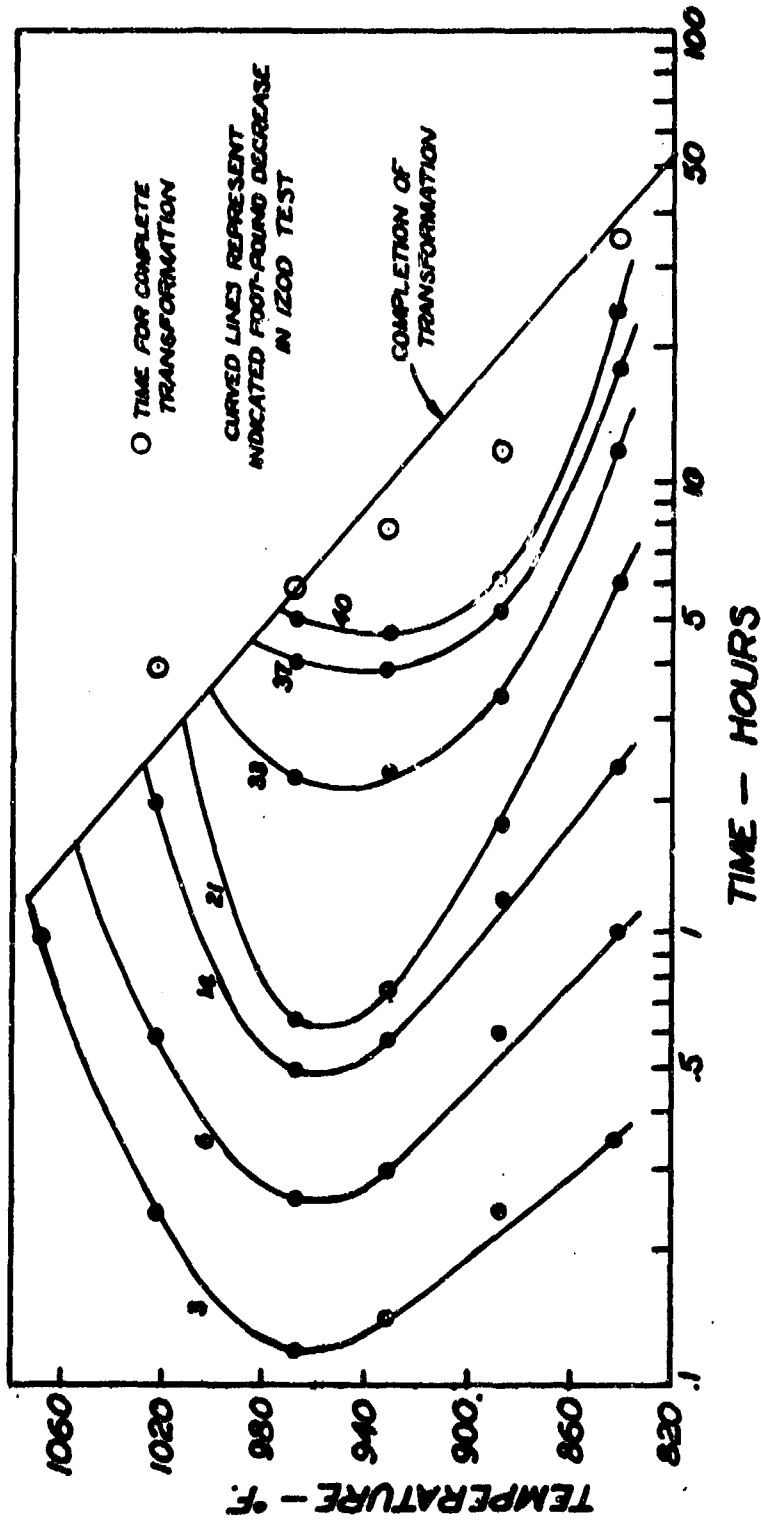
FIGURE 1



**A. RELATION OF IMPACT TO HARDNESS
IN A NON-SUSCEPTIBLE STEEL
(AFTER LOHSE ET AL.)**

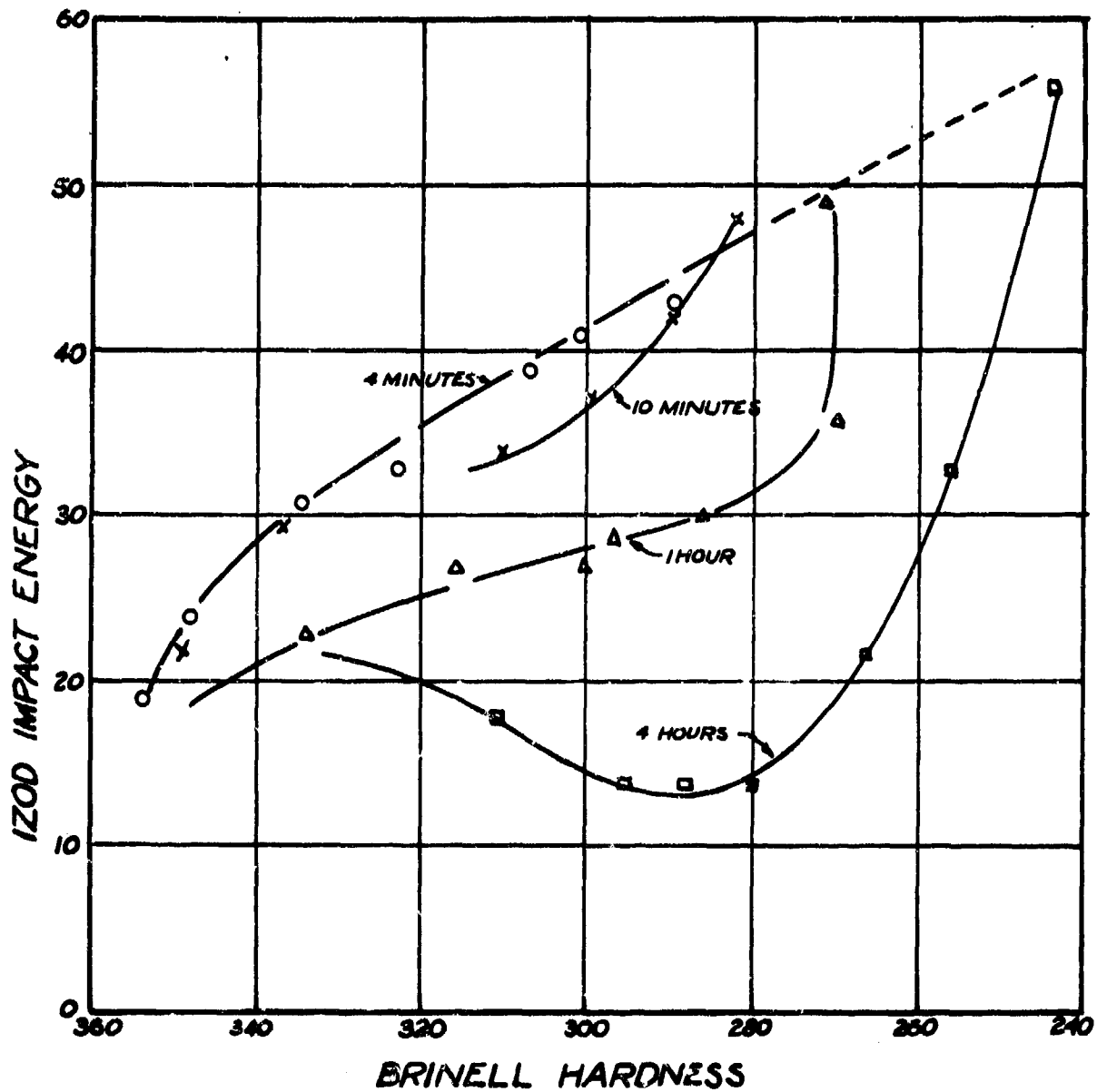


**B. RELATION OF IMPACT TO TEMPERING TEMPERATURE
IN A SUSCEPTIBLE STEEL
(AFTER NAGASAWA)**



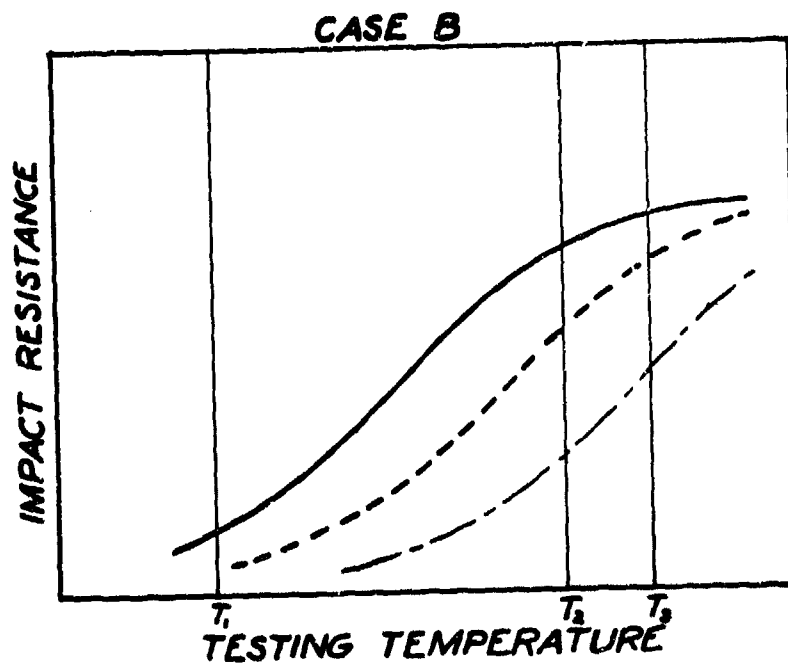
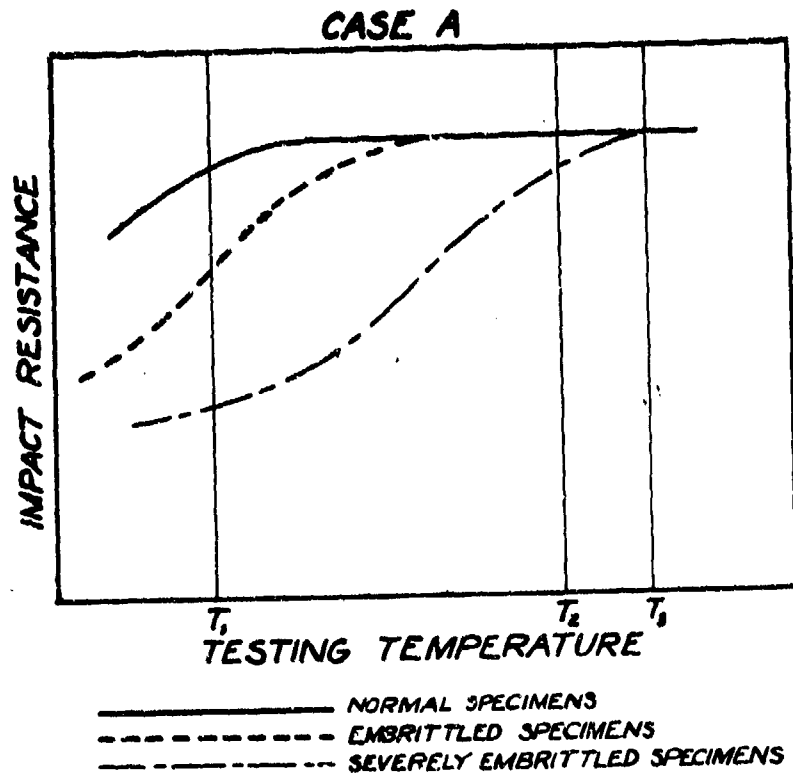
TEMPER BRITTLENESS TRANSFORMATION
 AT CONSTANT TEMPERATURE
 (DATA OF GREAVES AND JONES³ - PLOT AFTER HOLLOWAY²)

FIGURE 3



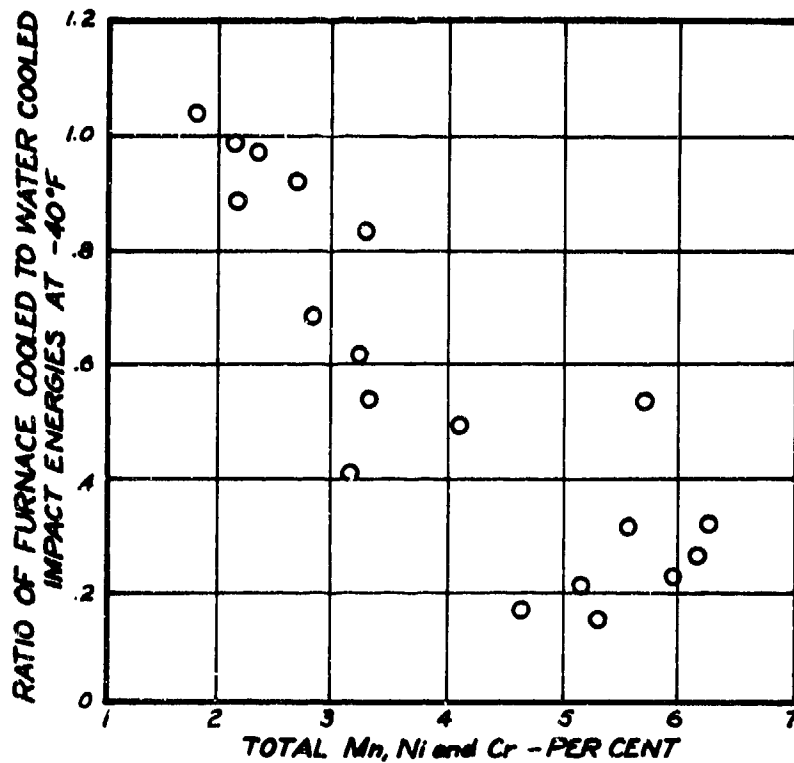
**EFFECT OF TEMPERING NICKEL-CHROMIUM STEEL
AT VARIOUS TEMPERATURES AND TIMES
FOLLOWED BY WATER QUENCHING
DATA OF GREAVES AND JONES³ - PLOT AFTER HOLLOMON²**

FIGURE 4

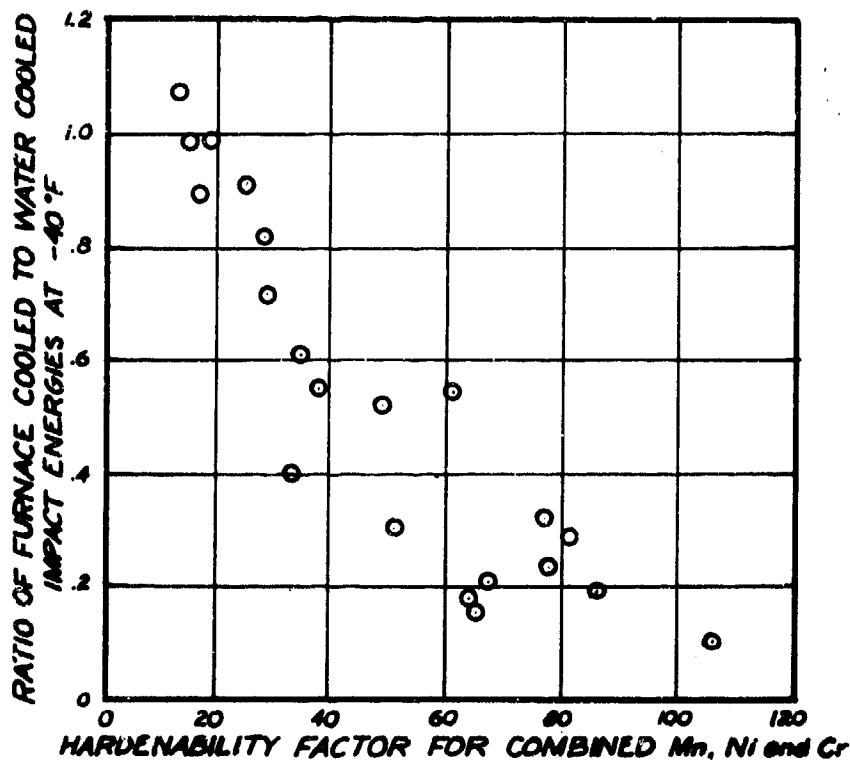


**TYPICAL CURVES SHOWING EFFECT OF
TEMPER BRITTLINESS ON IMPACT PROPERTIES**

FIGURE 5



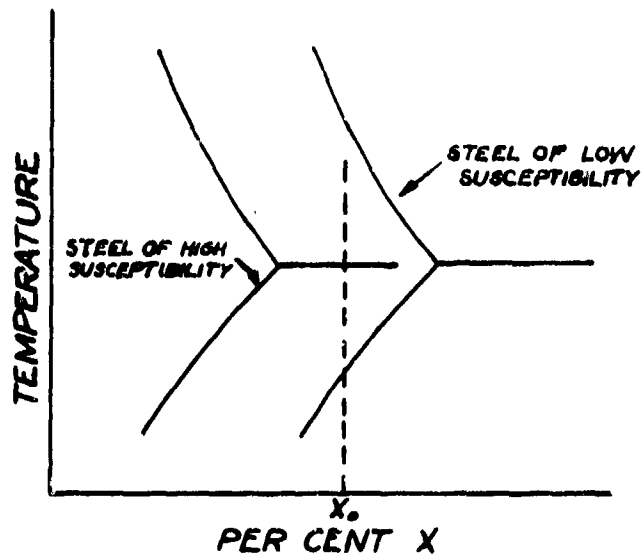
A. EFFECT OF ALLOYING ELEMENTS ON SUSCEPTIBILITY TO TEMPER BRITTLINESS (AFTER ZORNIG ET AL¹)



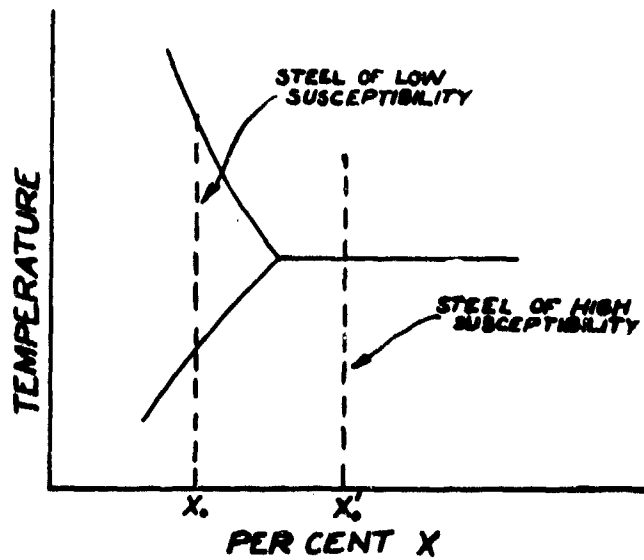
B. RELATION BETWEEN HARDENABILITY AND SUSCEPTIBILITY TO TEMPER BRITTLINESS

FIGURE 6

A. SOLUBILITY CHANGE

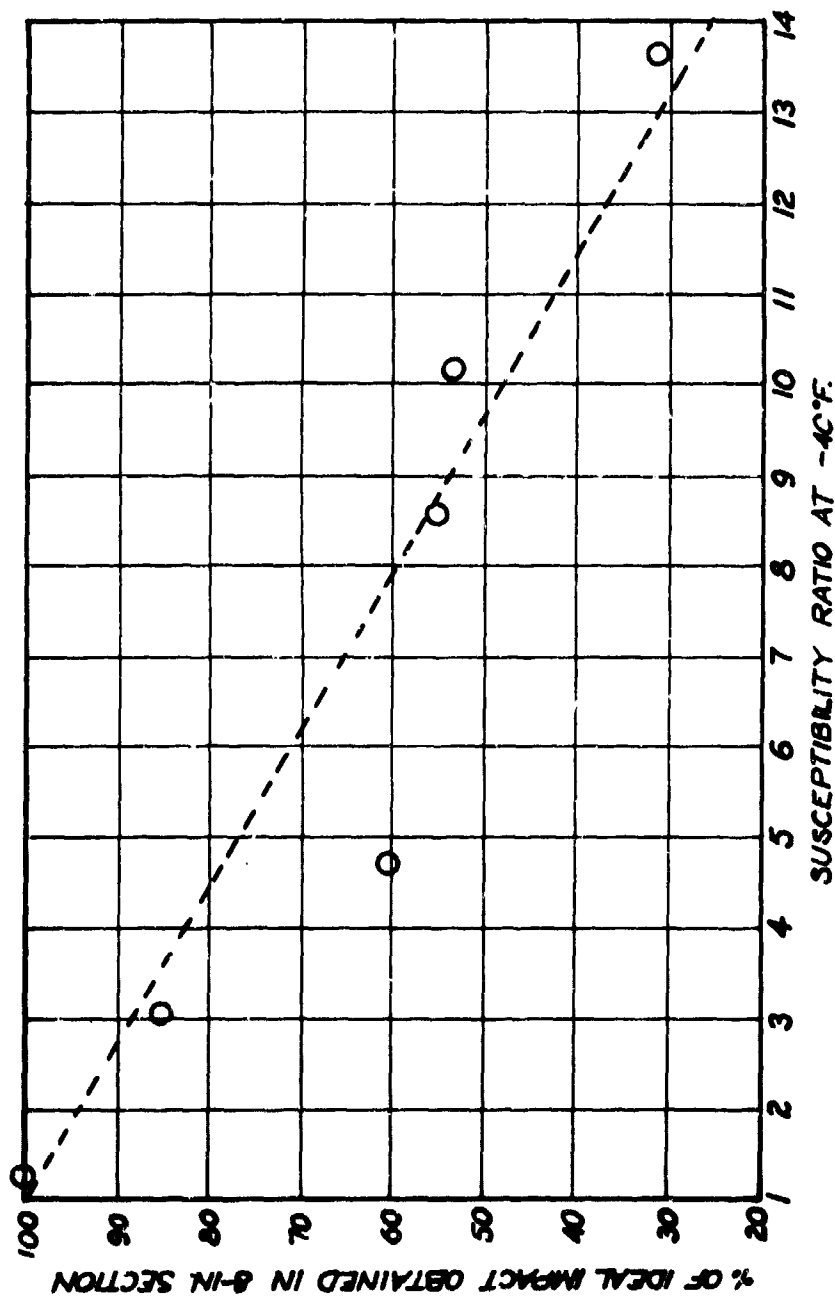


B. CONCENTRATION CHANGE



EQUILIBRIUM DIAGRAMS
ILLUSTRATING POSSIBLE MECHANISMS OF
INCREASING SUSCEPTIBILITY

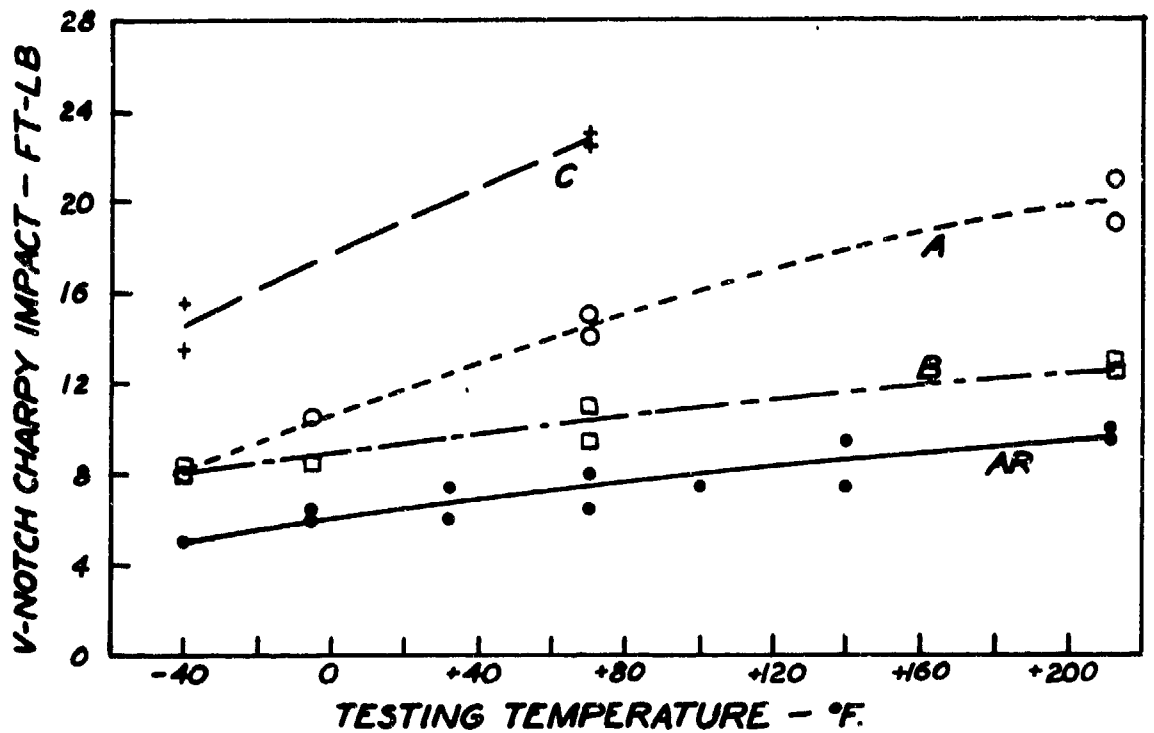
FIGURE 7



**RELATION BETWEEN SUSCEPTIBILITY TO TEMPER BRITTLENESS
AND IMPACT PROPERTIES OF HEAVY SECTION**

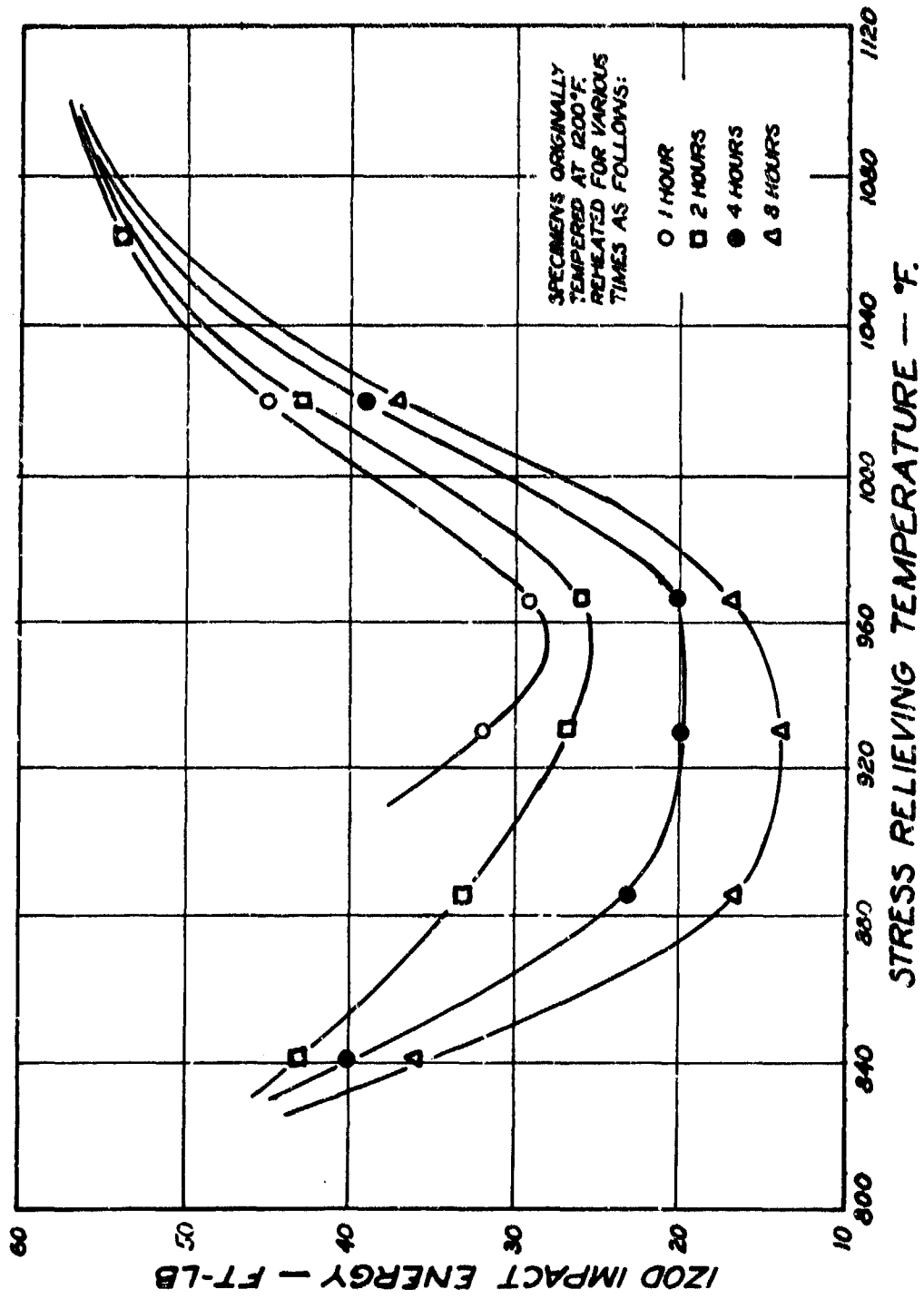
FIGURE 8

●—● AS RECEIVED, WATER AND OIL QUENCHED FROM 1600°F,
 TEMPERED 12 HOURS AT 960°F, AIR COOLED.
 ○—○ SMALL SPECIMENS; OIL QUENCHED FROM 1600°F, THEN—
 TEMPERED 5½ HOURS AT 1020°F, FURNACE COOLED.
 ○—○ " " " " " " WATER " "
 +—+ " 8 MINUTES " 1150°F, " "



EFFECT OF TEMPERING TREATMENT ON
 IMPACT PROPERTIES

FIGURE 9



EFFECT OF STRESS RELIEVING A SUSCEPTIBLE STEEL
 IN THE EMBRITTLING RANGE
 (DATA OF GREAVES AND JONES³ - PLOT AFTER HOLLOWOM)

FIGURE 10

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