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Brittle fracture of carbon steel

Ronald Robert Stang
New Jersey Institute of Technology

BRITTLE FRACTURE OF CARBON STEEL

BY

RONALD ROBERT STANG

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ABSTRACT

This thesis is a report on the research and engineering efforts made, since 1957, to further define the causes and means for the prevention of catastrophic brittle fracture of carbon steels at ambient temperatures. All of the data based on the literature published from 1958 to 1965 has been critically examined and correlated.

Included are discussions of the factors affecting brittle fracture and the tests used to predict resistance of steels to brittle fracture. Correlations of tests with actual service performance and relationships between tests are discussed. A review and critical evaluation of present day steel specifications as they affect brittle fracture is presented.

A number of recommendations for the prevention of brittle fracture are made, including chemical composition, material testing, manufacturing, and quality control procedures.

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PREFACE

The purpose of this report is to review and discuss the recent work done on the catastrophic brittle fracture of carbon steel structures at ambient temperature. Based on this information, recommendations were made for the prevention of brittle fracture. Since a number of books were published in the period 1957-1958, summarizing prior work, this report concerns itself mainly with the literature published since 1957.

Much of the information published on the subject has not been in agreement; however, the author has tried to tie together the diverging points of view in a critical manner.

The author wishes to express sincere appreciation to Dr. Charles L. Mantell for his guidance, interest, and encouragement during the course of this work.

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INTRODUCTION

Carbon steel plate, when stressed in tension, will usually fail in a ductile fashion, with considerable energy absorption accompanied by plastic deformation. However, the same material can, under certain conditions, fail in a brittle manner.

The failure of engineering structures due to brittle fracture is often catastrophic. Some major examples are: the splitting up or serious structural failure of many ships during World War II, some even at dockside; failure of oil storage tanks during water testing; collapse of a number of bridges of the Vierendeel truss type in Belgium; and numerous pressure vessel, drum, and steel stack failures. Many of these failures resulted in death or injury and great financial loss.

Brittle fracture is characterized by (a) almost complete lack of ductility, negligible energy absorption and a brittle or faceted appearance of the fracture surface; (b) the fractured surface often has a characteristic "Chevron" appearance, the apices of the chevrons pointing to the origin of fracture; (c) the high speed at which fracture occurs (approaching thousands of feet per second); (d) relatively low stress levels required to sustain a running crack; and (e) almost all fractures originated at a flaw, void or structural discontinuity. The cleavage cracks originate at the steel's ferrite grain boundaries and propagate along the (1,0,0) planes of ferrite crystals. (7,11). The chevron pattern appears to be associated with the cracks proceeding in a discontinous fashion along the planes of the crystals.

The following conditions must be present for brittle fracture initiation to occur: (a) the metal temperature is low enough to inhibit plastic flow, (b) a flaw such as a crack or notch is present, and (c) the loading must be such as to develop a small amount of yielding or deformation in the area of the flaw (47, 44). Often high strain rate or impact loading also contribute to brittle fracture.

The initiation of brittle fracture is determined by the behavior of the small volume of metal near the crack which reacts to the applied stress. If plastic flow occurs, the structure is not endangered since the adjacent large body of metal assumes the burden of supporting the applied stress. However, if no plastic flow occurs in the area of the flaw, a sharp crack extends into the body of the surrounding metal by a high speed repetition of the crack tip cleavage process resulting in propagation of the brittle fracture and subsequent failure of the structure. The stress required to propagate the crack is considerably less than that needed to initiate it.

In the past, brittle fracture was usually assumed to be associated with low ambient temperatures in the range of -20°F to +20°F. However, through recent analysis of many failures and random testing of vessel steels, it has been shown that ordinary steels can be brittle at all ambient temperatures. A temperature of about 100°F is required before the danger is negligible (15).

Austenitic steels exhibit little or no tendency for brittle fracture. However, ferritic steels, which are commonly used in ship, tank, and pressure vessel construction, are susceptible to brittle failure mainly because they lose ductility as their temperature is lowered. At some temperature, variously described as the "transition temperature" or "nil-ductility temperature", the ferritic steels change from a predominantly ductile to a predominantly brittle behavior. This transition temperature will vary dependant upon the chemical composition, manufacturing process, plate thickness, etc. of the steel in question. The transition from ductile to brittle behavior is developed sharply within a relatively narrow temperature range.

The sharpness of the transition provides the basis for the transition temperature approach to the brittle fracture problem and also provides a means for the development of analytical methods for the design of fracture safe steel structures. The transition temperature basis has been accepted as the best approach by the majority of researchers in the field of brittle fracture and therefore will serve as a basis for the following study of this problem.

A considerable amount of research concerning brittle fracture of normal carbon steels was done in the past and is still continuing today. Three excellent books were published in the years 1957-1958 (24, 42, 49) which summarize work done prior to 1958. However, these writings leave many questions and problems unanswered or without much actual proof. Some of the more important are:

1. What is the role of residual stress, chemical composition, and welding on brittle fracture?

2. The problem of duplicating brittle fracture in service.

3. The mystery of how a rapidly moving crack, with no evidence of triaxiality at its point of origin, is initiated in service failures under static stresses of low average value.

4. What is the effect of thermal stresses?

5. The effect of cold-forming on transition temperature.

6. The role of metallurgical variables, resulting from welding, on brittle fracture initiation.

7. How can brittle fracture resistance of steels be better predicted?

8. Can better inspection techniques be employed?

9. Is there a better correlation between tests and actual service failures possible?

10. Can a new specification be written which will give more assurance that brittle fracture will not occur, without incurring prohibitive costs?

The following chapters of this report hope to answer some of these questions, give a summary of work done since 1957, and provide a practical steel specification for minimizing the possibility of brittle fracture.

CHAPTER II

FACTORS AFFECTING BRITTLE FRACTURE INITIATION AND PROPAGATION

There are many factors that affect the ability of a steel to resist brittle fracture. They can be broken down into two basic groups. The first being those that affect the brittle resistance of the steel itself as measured by transition temperature. It includes chemical composition, grain size, hot and cold working procedures and plate thickness. The other group is concerned principally with fabrication and design; such as notches and flaws in the structure, residual stresses, stress relieving, prestraining and welding effects. In order to provide some additional background for this study, it was thought best to review the effect of triaxiality on brittle fracture and the transition temperature features of common structural steels.

Theory of Triaxiality

The widely accepted theory of triaxial stress and its effect on notch brittleness was developed independently by Mesnage in 1906, and Ludwick in 1923, and is still valid today. A triaxial stress can be developed in a plate containing a sharp crack or notch as follows (29).

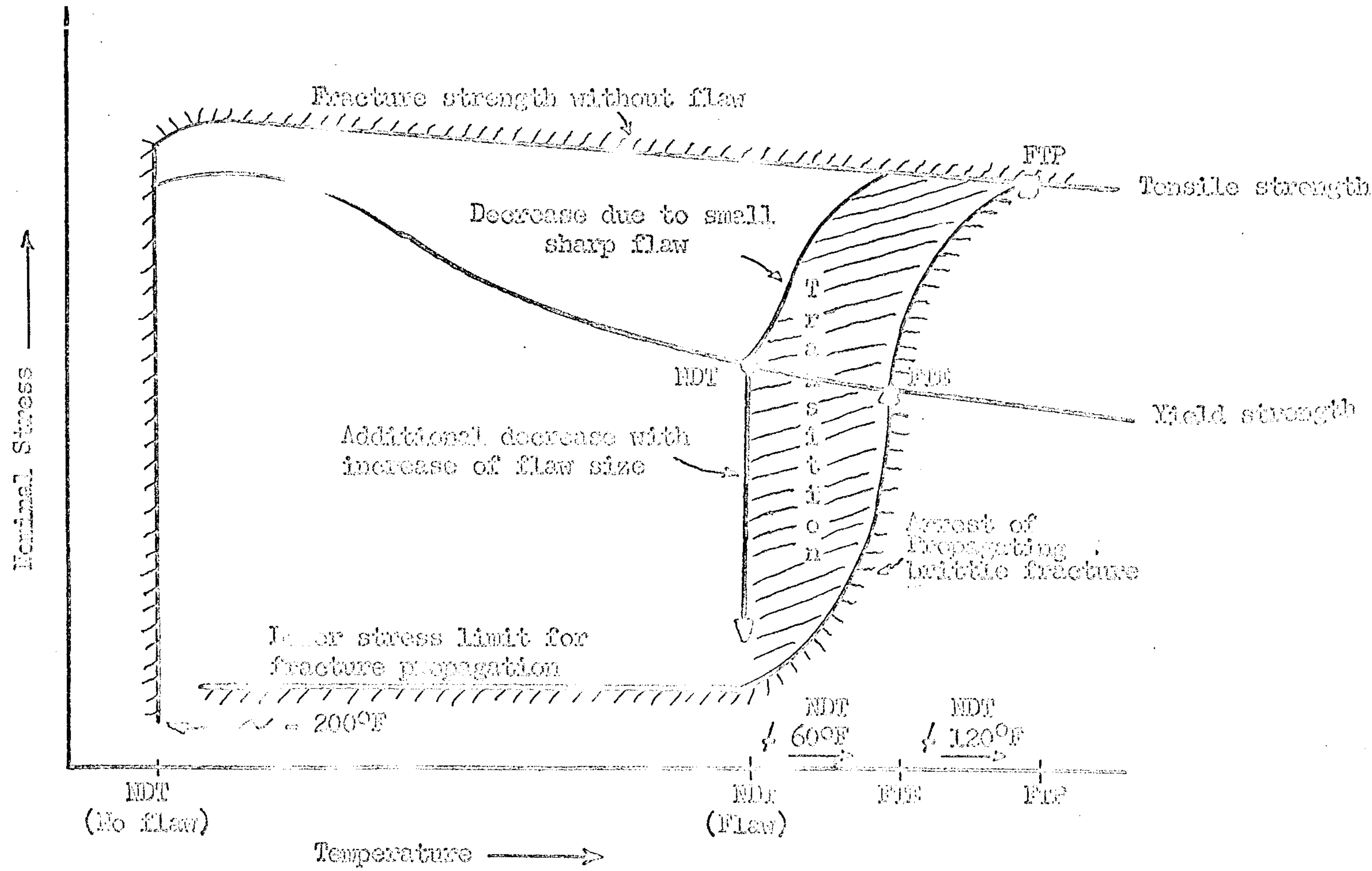
If an average elastic stress is put on a plate in a dirction perpendicular (axial dirction) to the crack or notch, a comparatively high axial stress will exist just behind the root of the crack. In the area near the crack root, the state of stress will be biaxial because of the presence of the notch. However, behind the crack root, and a short distance from it, the stress will be of average value. If plastic flow is to occur, there must be lateral contraction at the crack root in order to preserve constant volume of the material. Opposing this lateral contraction is the large amount of material behind the root of the crack which is stressed to a lower value. This gives rise to a state of triaxial stress, the third stress being perpendicular to the plane of the plate and tending to contract the material laterally at the root of the notch. This third stress is transverse tension.

A consequence of this transverse tension is that the axial stress at the crack root will build up beyond the yield stress before flow can occur. It is therefore evident, that if a sharp crack is present in a stressed plate, the stress at the root of the crack must rise to about three times the normal uniaxial yield stress of the material before plastic flow can occur. This may mean that the fracture strength of the material is reached before yielding occurs. A state of triaxial stress, and some other rate of stress application, neither of which by itself is sufficient to cause brittle fracture initiation, may together permit it to occur.

Transition Temperature Features of Steels

A basic understanding of the transition temperature features of steel is necessary before discussing the factors affecting brittle fracture and the test methods used to determine brittle fracture resistance. The generalized stress-temperature diagram for fracture iniation and crack arrest, or fracture analysis diagram, as it is sometimes called, is discussed below.

Figure I (44) outlines the transition temperature features of typical structural steel. Referring to Figure I, the tensile and yield strength curves for a flaw free specimen are shown to increase with decreasing temperature, down to a temperature of about -200°F. A similar specimen containing a small sharp flaw would have a decreasing fracture strength as indi ated by the dashed line. The temperature at which the decreasing fracture stress, for fracture initiation, becomes contiguous with the yield strength curve is defined as the nil-ductility temperature (NDT). As flaw size increases, the fracture strength decreases further. Below the NDT, a brittle crack can propagate under a stress much lower than is required to develop it. The propagation stress is normally below the design stress.



TRANSITION TEMPERATURE FEATURES OF STEELS

FIGURE I (44)

The second curve is the fracture arrest relationship between stress and temperature. It represents the temperature of arrest of a propagating brittle fracture for various levels of applied nominal stress. The crack arrest temperature is defined as the "fracture transition elastic" (FTE). It is the highest temperature above which stresses higher than yield stress are required to maintain propagation (47). The "fracture transition plastic" (FTP) is the temperature above which fractures are entirely by shear and the stress required for fracture approximates the tensile strength of the steel. Below the NDT, there is a critical stress (about 8000 PSI) below which brittle cracks cannot propagate.

The shaded area between the two curves is called the transition zone, where the behavior of the steel is somewhat erratic. It is bounded on the low temperature side by conditions necessary for brittle crack initiation and on the high temperature side by conditions which would arrest a running brittle crack.

The nil-ductility temperature, or its equivalent, may be determined for a certain steel by a number of tests directly, or by correlation with other tests. These tests include the Naval Research Laboratory drop weight test, crack arrest tests, and various Charpy notch tests. A discussion of these tests and their correlation with each other and with actual service failures will be included in a later chapter.

Chemical Composition

The ductile to brittle transition temperature can be changed by varying steel composition. Increasing carbon, phosphorus, arsenic, molybdenum, or boron content raises the temperature. The addition of manganese, nickel, silicon, sulphur and aluminum decrease transition temperature (22, 58).

Increasing the carbon content has a major effect on raising the transition temperature. It has a greater effect on fracture initiation than on propagation. This is probably due to the adverse effect of carbon on weldability.

Manganese often has been reported to have the beneficial effect of reducing transition temperature. The effect on transition temperature is greater than the actual effect on service failures. Its beneficial effect may result from its strengthening influence which allows a lower carbon content for the same tensile strength, and lower carbon reduces transition temperature.

Phosphorus will strongly increase susceptibility to failure and particularly fracture initiation. It is important because it imparts a greater notch sensitivity in areas affected by welding or oxygen cutting.

Transition temperature is reduced by the addition of silicon. It is effective up to about 0.25 per cent, but higher amounts tend to raise the transition temperature.

Arsenic up to about 0.20 per cent has no effect on the transition temperature of both welded and unwelded steel. Above 0.20 per cent there is some reduction in ductility with weld bead cracking occurring. Above 0.50 percent arsenic promotes notch root cracking. (14).

Molybdenum and boron are harmful; while small amounts of nickel (up to 1.8 per cent), aluminum, and sulphur are helpful. The effect of composition change on transition temperature as measured by a number of brittle fracture test methods is shown in Table I for carbon, manganese, silicon, and phosphorus (22).

Plate Thickness, Grain Size, and Heat Treatment

As thickness of steel plate is increased, the susceptibility to brittle fracture also increases. This is more associated with the greater chance of having inclusions, cracks, flaws, non-homogeneous heat and rolling effects, and construction defects than with the thickness affecting the transition temperature itself (58). However, some notch toughness tests conducted by Agnew and Stout (1) indicate a rise in transition temperature of about 30°F

Change In Transition Temperature °F

Element Varied	Tear Test	10 Ft. Lb. Charpy Keyhole	15 Ft. Lb. Charpy V-Notch	15 Ft. Lb. Charpy V-Notch	DWT NDT	Kinzel 1% Lat. Cont.	ESSO Brittle [illegible]
0.1% C	+ 33	+ 20	+ 25	+ 35	+ 45	+ 50	+ 50
0.1% Mn	- 4	- 7	- 10	- 7.5	---	None	---
0.1% Si (0.2% max)	-30	---	---	- 28	---	---	---
0.1% Si (0.5% min)	+ 15	---	+ 13	---	---	---	---
0.01% P	+ 5	---	+ 13	+ 3.2	None	+ 12	---

APPROXIMATE CHANGE IN TRANSITION TEMPERATURE PRODUCED BY VARIOUS ELEMENTS (22)

TABLE I

when going from one-half inch to one-inch plate.

Heat treatment and resultant grain size are important in transition temperature change. Decreasing the ferritic grain size serves to lower the transition temperature and increase notch toughness (21, 29, 50), but based on the service performance of ship plate, Williams (58), found that grain size by itself had very little direct effect on brittle fracture initiation.

A fully killed (deoxidized) steel will have a lower transition temperature than a semi-killed or rimmed (non-deoxidized) steel (29). Normalizing usually improves as-rolled plate and the use of a lower finishing temperature is also helpful. Conventional normalizing procedures, because of retarded cooling rates, produce inferior notch toughness material with excessive ferrite grain and pearlite aggragate size. This problem is minimized by the use of liquid quenching following normalizing (19). If spray quenching is used, a further improvement is noticed (10).

In Europe, controlled low temperature hot rolling is practiced to provide increased notch toughness in hot rolled plate product. It involves making the last passes at lower than normal temperatures and has shown an improvement of 20-45°F in transition temperature (54). It seems to be associated with refinement in grain size, but the improvement decreases as the quality of the steel increases.

Cold Forming

The greater the amount of cold forming done in fabrication, the more susceptible the material is to brittle fracture. Studies by the Ship Structure Committee(17) on initiation of brittle fracture have shown that prior cold working of steel plates in tension has caused the steel to fracture at about 70 per cent of yield load. If the cold working was in compression, the fracture load may be reduced to as low as 59 per cent. Heat treatment after cold forming, if done at high enough temperatures, can restore the original ductility of the material.

Flaws

Almost all fractures originate at a flaw, void, or structural discontinuity and where stress concentration existed (17, 58). The severity of the flaw or notch enhances the chances of brittle fracture. Actual length or type of flaw has little influence on initiation of brittle fracture, but does affect the stress required for initiation or propagation. The depth of the flaw shows only slight effect (51).

Fatigue cracks, as such, are not severe brittle fracture initiators. However, appreciable aging of these cracks can lead to initiation, particularly with severe drop in temperature (56). The influence of defects on initiation and propagation is strongly dependent upon their location with respect to the non-uniformly distributed residual stresses and plastic strains.

Welding

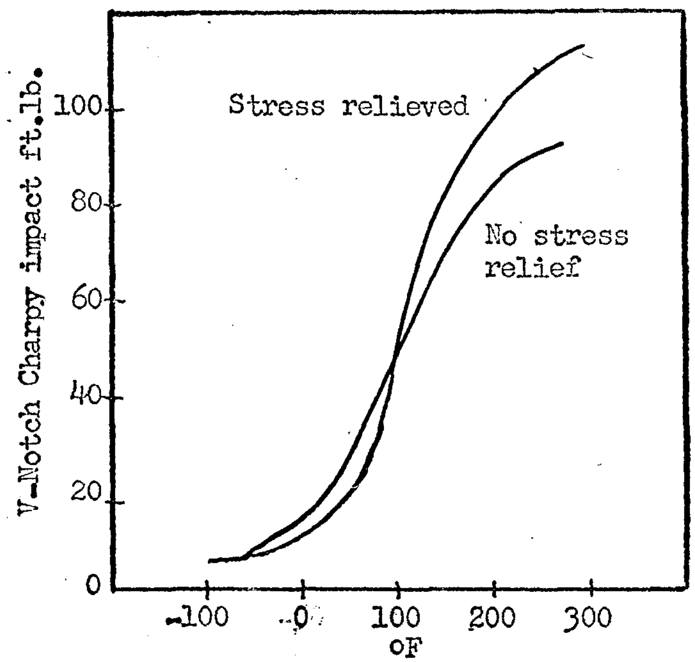
Welding raises the transition temperature by creating zones in the weld bead vicinity that more readily generate cleavage cracking. The exhaustion of cold ductility by hot extension occurs during the cooling of welded plates and provides some explanation of fracture initiation close to welds. Studies by Williams (58), Zar (60), and Wells (56) indicate that fracture in welds only occurs where obvious welding defects are present or where the weld metal is appreciably more brittle than the parent metal.

Some tests by Sopher et.al. (51) indicate that when weld cracks ended in sound weld metal, brittle fracture did not initiate. Apparently, the stretching at high temperatures embrittles the steel adjacent to the welds (36). Preheating of the weld area prior to and during welding helps to prevent the formation of hard brittle microconstituents and microfissure in the weld (30), but does little to reduce residual stresses (37). Preheat temperatures of 440-600°F are most effective. Post heating of the weld showed little change in the transition temperature of the weld. However, stress relieving does help and a combination of preheating and stress relief gives the best results. Figure II (3) shows the effects of preheat and stress relief on E-7015 carbon steel weld metal.

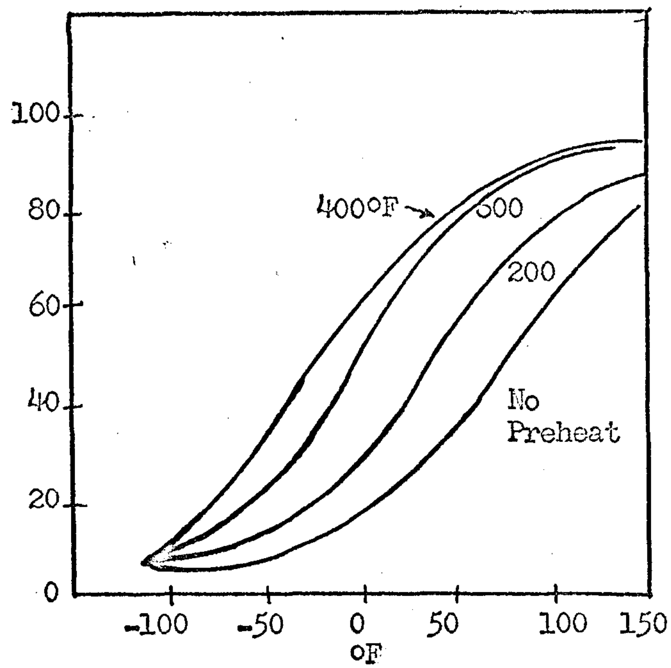
Residual Stress, Pre-Straining, and Stress Relief

The effect of residual stress on initiation of brittle fracture has perhaps created the greatest controversy among researchers in this field. Work done by investigators prior to 1958 seemed to indicate that residual stress had very little effect in structures where defects did not exist. Where there are defects, residual stresses become important because they add their weight to the other normal stresses in the weakened area.

Since 1957, considerable work has been done concerning the effect of residual stresses and straining on brittle fracture initiation and propagation. Based on extensive test work of Mylonas, et.al.(13, 33, 34,35) residual stresses did not contribute significantly to the initiation of brittle fracture of precompressed notched plates, axially compressed bars, or bars subjected to reversed bending as long as ductility is ample. Their brittle fracture by exhaustion of ductility was produced mainly by compressive prestraining and aging. The material was



Effect of stress relief



Effect of preheat

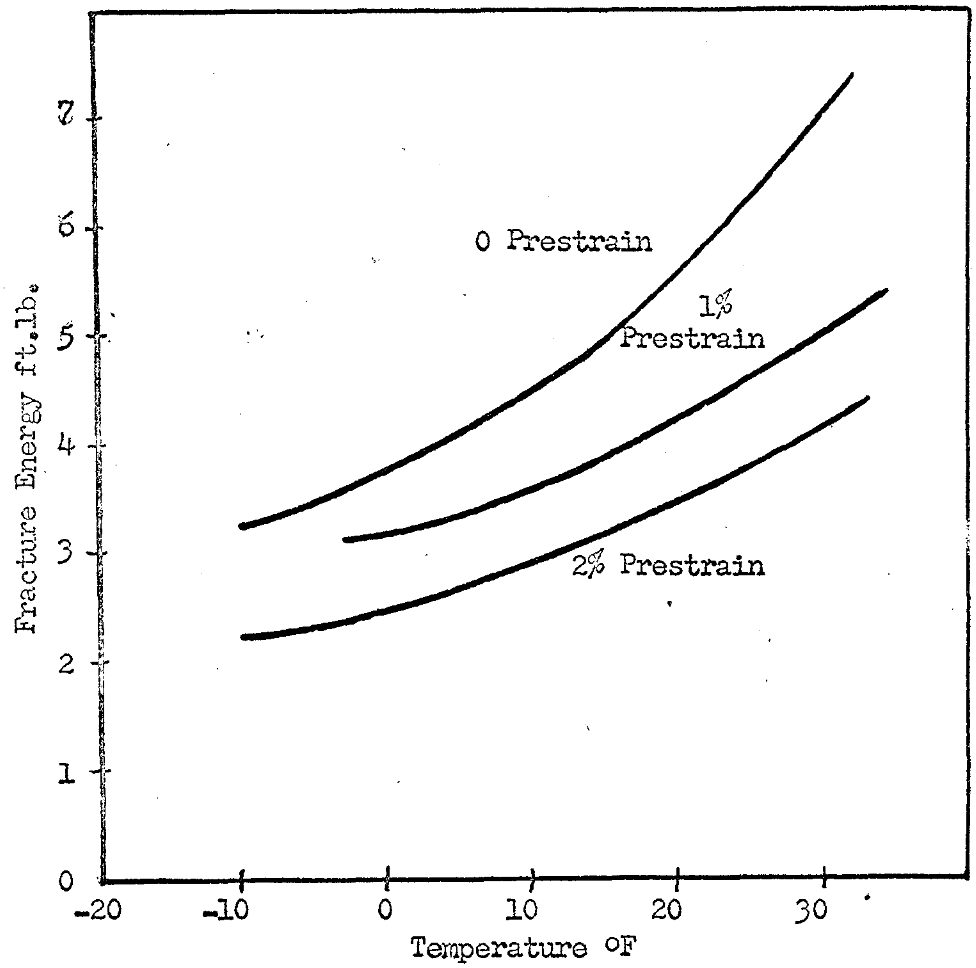
EFFECT OF STRESS RELIEF AND PREHEAT ON E-7015 CARBON STEEL WELD METAL

FIGURE II (3)

unable to deform sufficiently without breaking since the prestrain had exhausted too much of the original ductility in the region of the notches. Figure III (35), shows the effect of prestraining on the fracture energy required to cause failure. Large fields of residual stress may have some effect on brittle fracture but they have a greater influence on propagation. This work also shows the need for stress relieving but that its main function is the restoration of ductility, not the reduction of residual stresses.

Boyd (9) is in agreement with Mylonas's findings, but the latter are somewhat disputed by Freudenthal and Larsen, who believe that residual stresses are most important with prestrain and resultant exhaustion of ductility just acting as an enforcement. Barton and Hall (8) in their tests of prestressed steel plates found that brittle fracture occurred in every prestrained specimen, even those with no external load.

Kihara and Masubuchi (25) believe that high tensile residual stresses originating in the region near the weld may act as a trigger to initiate a brittle fracture if sharp notches are present. They found that preloading at high temperature helps to distribute residual stress and induces a favorable effect on reducing brittle fracture.



EFFECT OF COMPRESSIVE PRESTRAIN ON FRACTURE ENERGY

FIGURE III (35)

Vinckier (55), in his tests on welded steel discs with high residual stresses in the center and with compressive stresses on the outside, found that brittle fracture can easily be initiated in sound weldments without application of external loads. This occurs provided the material is cooled to below its transition temperature and the area around a notch is plastically exhausted by previous treatment. He also found that stress relieving at 1150°F provided a safeguard against brittle fracture. However, if new residual stresses are put in a stress relieved specimen and local cooling is applied, brittle fracture can initiate. With this series of tests he showed that stress relieving of plate benefits from removal of residual stress and not changes in metallurgical effects, which is in dispute with later findings of Mylonas (34).

Wells (56) believes that there is little doubt that extensive plastic precompression can lower the subsequently applied tension ductility and thereby increase the chance of brittle fracture. As far as propagation is concerned, he states that it is influenced by the elastic stress field through which the crack passes and is affected alike by externally applied and residual stresses. The character of the crack is controlled by the stress environment at the tip no matter how applied.

In their two-stage fracture tests, Nordell and Hall (37), found that low stress fractures in one inch plate initiated and propagated from notches that terminated in regions of high-tensile residual stress and thermally-effected material of higher transition temperature than the base metal. Thermal stress relief reduced residual stresses significantly and restored the properties of the material near the weld. Mechanical stress relief only reduced residual stress. Earlier work by Rolfe, Hall and Newmark (48) showed that a residual compressive strain field also affected brittle fracture in that it could act as an effective crack arrester where high tensile residual stresses are expected.

CHAPTER III

BRITTLE FRACTURE TESTS

The information in this chapter is intended to describe briefly various test methods used to evaluate brittle fracture resistance as normally measured by a transition or nil-ductility temperature. A comparison of tests as they correlate with service failure or other tests will be discussed in Chapter IV.

In general, brittle fracture resistance or notch toughness tests may be divided into two groups (53). The first measures a fracture-transition temperature and the other a ductility-transition temperature. The fracture transition temperature indicates the temperature above which a fracture is not likely to propagate. The ductility (or nil-ductility) transition indicates the temperature above which fracture is not likely to initiate unless forced by appreciable deformation. The ductility transition temperature is quite sensitive to mechanical factors and welding variables, while the fracture transition temperature is not (22).

Fracture Transition Temperature Tests

The Crack-Starter Explosion Test is carried out by supporting a plate on a circular die and deforming the plate by an explosion. Temperatures are defined for fracture without deformation (NDT), propagation through elastically loaded sections (FTE) and propagation through plastically loaded sections (FTP).

The Navy Tear Test is used to determine the fracture transition temperature at which the mode of failure, from tearing, changes from shear to predominantly cleavage.

In the S O D Test, a fine crack is initiated in the test specimen and it is loaded at a nominal tensile stress of 18000 PSI using a 15° wedge and backing up the specimen with a 5000 pound weight. The fracture is initiated by an impact load on the wedge, and the lowest temperature at which the crack will not propagate across the specimen is called the SOD transition temperature.

The Robertson Test is similar to the SOD test in that the specimen is placed under load and fracture is initiated by an impact load on the edge of the specimen. It is usually run with a temperature gradient across the specimen, the crack being initiated at the cold temperature. The temperature of the plate where the crack stops is referred to as the Robertson test transition temperature (53).

A number of Fracture Appearance Tests are used to determine the transition temperatures by estimating the per cent of the fracture that is fibrous and that is cleavage. The 10 per cent and 50 per cent fibrous fracture are the most common.

Ductility Temperature Transition Tests

The Kinzel Test is a slow bend test designed to represent the combination of weld zone and base plate as it appears in a structure in service (31). It measures the transition temperature as based on one per cent lateral contraction. The test can be used for measuring changes in notćh toughness produced by changes in welding variables or with given welding conditions, measure toughness produced by changing the steel or its condition.

A Reversed-Bend Test has been developed using very sharply bent beams to explore the influence of environment on the borderline between ductile and brittle behavior (28). Brittle fractures have been obtained from this test, although few correlations have been obtained thus far.

The Naval Research Laboratory Drop Weight Test permits laboratory determination of the temperature at which a given steel loses its ability to develop more than a minute amount of deformation in the presence of a sharp crack-like defect (47, 50). A weld overlay with low impact properties is deposited on a small specimen and a saw cut notch put on the tensile surface. A weight is then dropped on the specimen which is constrained so that it can only deflect 0.3 inch which is, however, sufficient to initiate cracking in the brittle weld deposit and propagate into the underlying material. The break to no-break performance of the test specimen usually occurs within a 10°F temperature span.

The temperature determined in this test is defined as the nil-ductility transition (NDT) temperature. It is the highest temperature for initiation of brittle fracture for a given steel. It has also been determined that at temperatures above NDT + 60°F (FTE), stresses higher than yield stress are required to maintain propagation. At temperatures above NDT + 120°F (FTP) fractures are entirely shear and the stress required for fracture approximates the tensile strength of the steel (27).

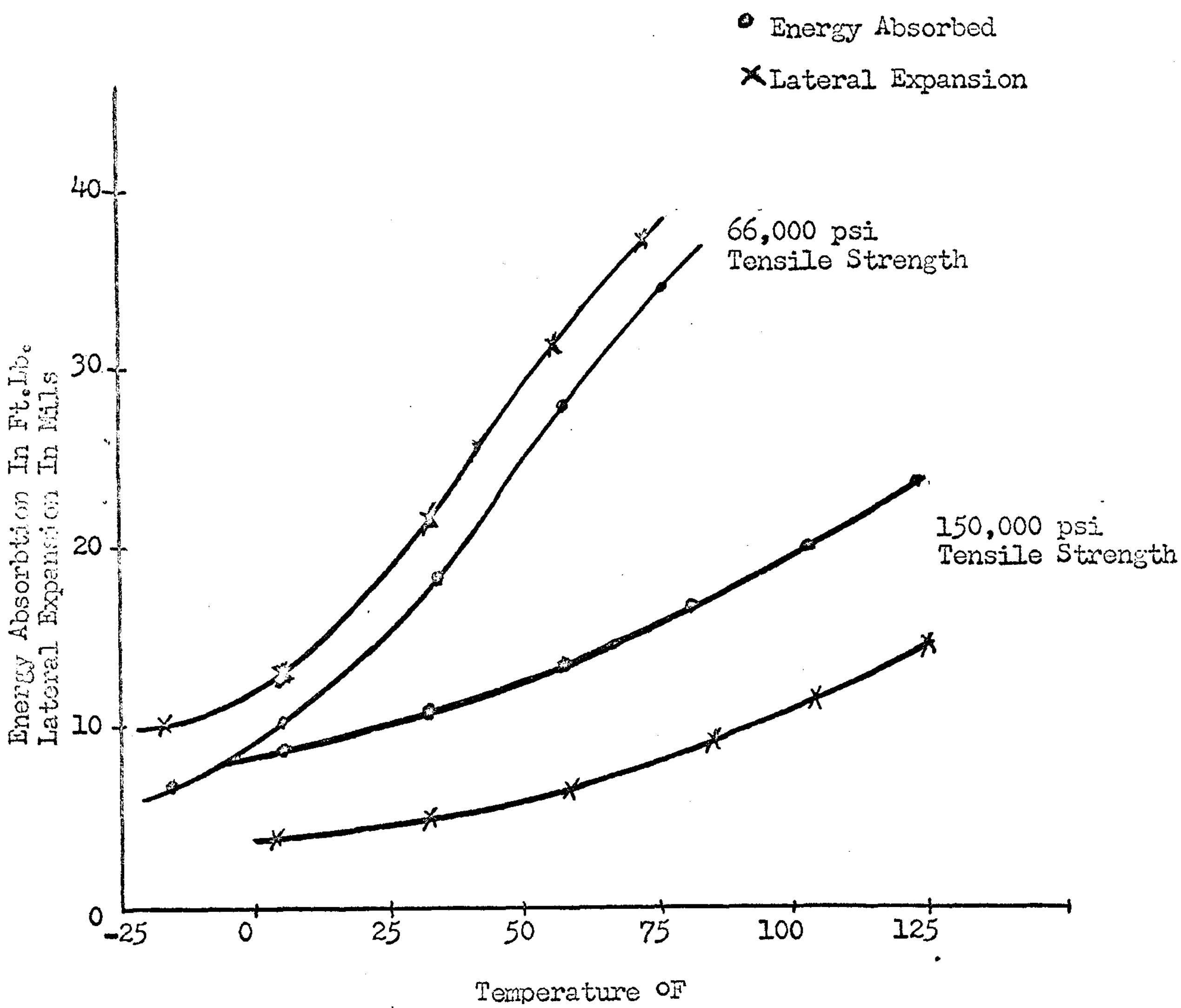
This test has been widely accepted and an ASTM Standard has been published for it (6). A procedure has also been set up for normalizing the test using different size specimens (46). The effect of welding the crack starter bead on the specimen is small if the welding procedure permits the weld metal to cool slowly to drop the weld hardness appreciably. In steels where shear can be developed under the weld bead, the NDT is not completely independent of the influence of the heat affected zone (31).

The <u>Charpy V-Notch</u> and <u>Charpy Keyhole Tests</u> are impact energy tests where the energy absorbtion prior to fracturing of the specimen is recorded. They are the most widely used and perhaps the oldest of the tests used to measure resistance to brittle fracture. The test results are reported as impact energy to cause failure of notched specimens versus temperature. Notch configuration of the specimens is the major difference between these two tests.

One problem in the use of these tests is that energy absorption is influenced by the strength level of the steel (20). Therefore, energy data for different steels must be corrected for the difference in strength before any ductility comparison can be made.

A better index of ductility can be obtained from the Charpy V-Notch Lateral Expansion Test. In this variation of the Charpy test, the lateral expansion of the bar is measured at the compression side of the bar directly opposite the notch. Tests have shown that expansion bears a linear relationship with energy absorption. A transition curve of the usual shape is obtained when lateral expansion is plotted against testing temperature, see Figure IV (20). The ductility component of energy absorption of the Charpy V-Notch test can be evaluated by measuring the lateral expansion, and therefore, it is more logical to adopt a ductility measurement wherein that is the property that is of the most interest.

Another variation in the Charpy tests is the Charpy



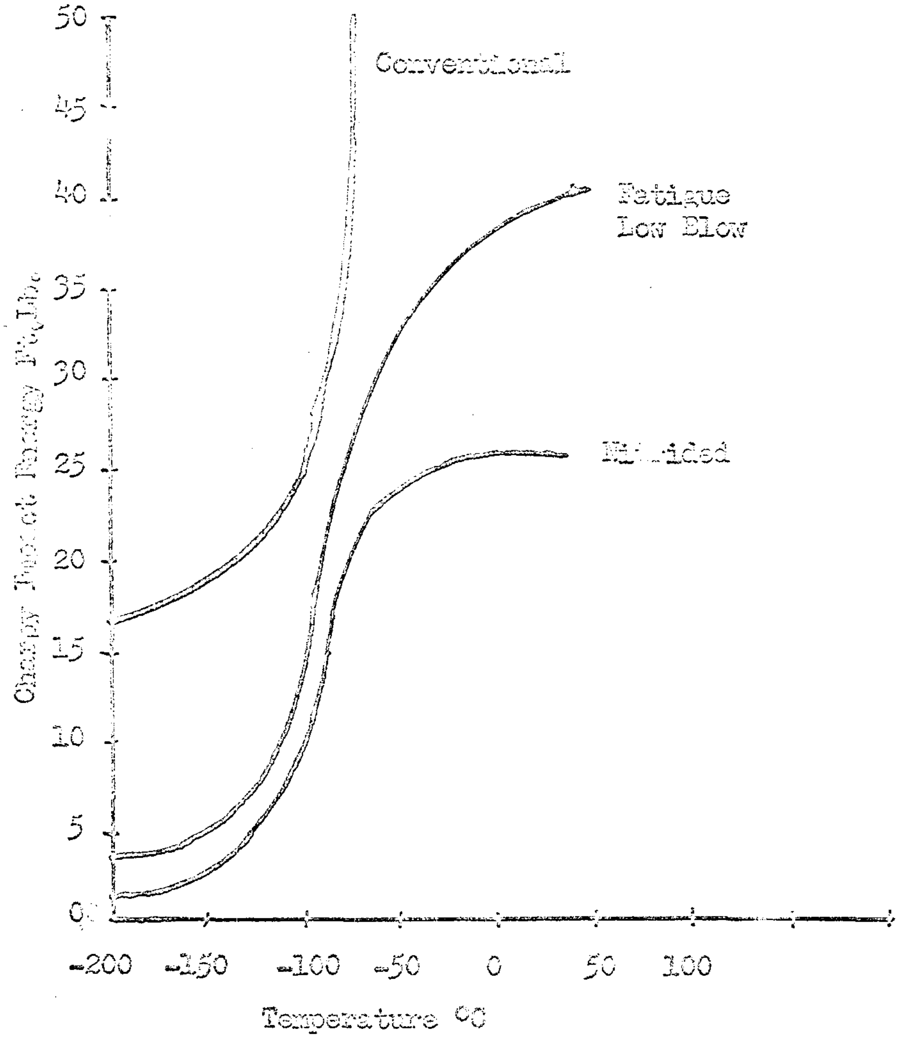
INFLUENCE OF TENSILE STRENGTH ON RELATIVE POSITION OF ENERGY ABSORBTION AND LATERAL EXPANSION TRANSITION CURVES

FIGURE IV (20)

Low Blow Transition Temperature Test. This test permits the separation of the crack initiation and crack propagation stages of the fracture process (40). The technique requires initiation of a crack by means of a low energy blow and propagation of the crack by a full capacity blow of the impact-machine pendulum.

The transition temperature obtained from this test is believed to be the maximum temperature at which an initiating crack can become self-propagating in a thick plate where the energy required to produce shear lips is small compared with the elastic energy available for crack propagation. Specimen size and notch geometry seem to have little effect, within limits, on the transition temperature obtained (39). However, standard Charpy V-Notches are used with precracking done well above the transition temperatures.

One source of difficulty in using notched bend and tensile tests is the difficulty in initiating brittle fracture. Small plastic strains near the notch give abnormally high energy values. This can be overcome by nitriding the surface near the notch (59). These tests have been termed "Brittle Boundary" Impact Tests. Figure V (59) shows a comparison between nitrided, conventional Charpy V-Notch, and Charpy fatigue cracked low-blow tests. A temperature called the fibrous initiation



COMPARISON BETWEEN DATA OBTAINED WITH CONVENTIONAL CHARPY V-NOTCH TESTS AND BRITTLE NITRIDED, LOW BLOW AND FATIGUE CRACKED CHARPY TESTS

FIGURE V (59)

transition temperature, FITT, is derived from this test. It is believed that above this temperature, low strength brittle fracture is very unlikely.

CHAPTER IV

BRITTLE FRACTURE TEST CORRELATIONS

A great deal of work has been done in an effort to correlate brittle fracture tests with actual service experience and to develop relationships between the various tests. These correlations are useful when setting up steel specifications and when trying to evaluate data on steels resulting from differents tests. However, two important facts should be kept in mind. The first being that there is no single test which can predict the transition temperature of a specific structure since tests cannot evaluate structure design and fabrication procedures. And secondly, correlations should be based upon either ductility or fracture criteria, not a mixture of both. Extensive correlation studies between tests have often resulted in contradictory conclusions brought about by the indiscriminate use of totally different criteria. The NRL Drop Weight Test and the Charpy V-Notch Tests, both being ductility criteria tests, are used as the major correlation medium.

Drop Weight Test Correlations

Plain carbon and low alloy steels from various ship and non-ship brittle fractures were investigated by the Drop Weight Test (47, 22, 43, 27). The nil-ductility temperatures obtained were demonstrated to correlate with the service performance of all the materials which were investigated. All failures occurred below the NDT temperature predicted by the test. For fully killed and low-alloy steels the NDT correlates best, while for rimmed and semi-killed steels there is more scatter in the data. The only area in which there is any real difficulty is where tough heat-affected zone structures influence the results.

These tests also indicated that above the NDT + 60°F (fracture transition elastic) it required a stress greater than the yield stress to maintain propagation of a brittle fracture. Assuming a nominal stress level of one-half the yield stress, brittle fractures are arrested at about the NDT plus 30-35°F. At the NDT + 120°F (fracture transition plastic) brittle fracture cannot occur.

The nil-ductility temperature should not be considered an absolute measure of service performance, but more as a relative test of different steels. It still has to be placed in the same category of other laboratory brittle fracture tests.

The nil-ductility temperature obtained by the Drop Weight test or <u>Crack-Starter Bulge</u> test are approximately the same (41). Limited Crack-Starter Bulge test data also generally confirm the FTE and FTP relationship offered by Pupak et. al. (43).

The Kinzel 1% contraction temperature and the Drop Weight test NDT show an acceptable correlation under conditions where the Kinzel test transition temperature is controlled by the ability of the base plate to arrest a cleavage crack (22). Departures occur mainly in alloy steels (31). Very poor results are obtained when the Kinzel test is influenced by a notch-tough heat affected zone.

A comparison between nil-ductility temperature and crack arrest data from many tests on thick, low carbon pressure vessel steels shows that the NDT + 60°F (FTE) is similar to but somewhat more optimistic than the Robertson isothermal crack arrest criterion (16). However, studies at the Naval Research Laboratory (27) demonstrate that the Drop Weight test can be used to establish the crack arrest temperature well enough to eliminate the need for large scale crack arrest tests. Even though the nil-ductility temperature can be used to predict crack arrest, it must be remembered that the Drop Weight test is more closely related to a crack-initiation criteria (50).

Charpy V-Notch Correlations

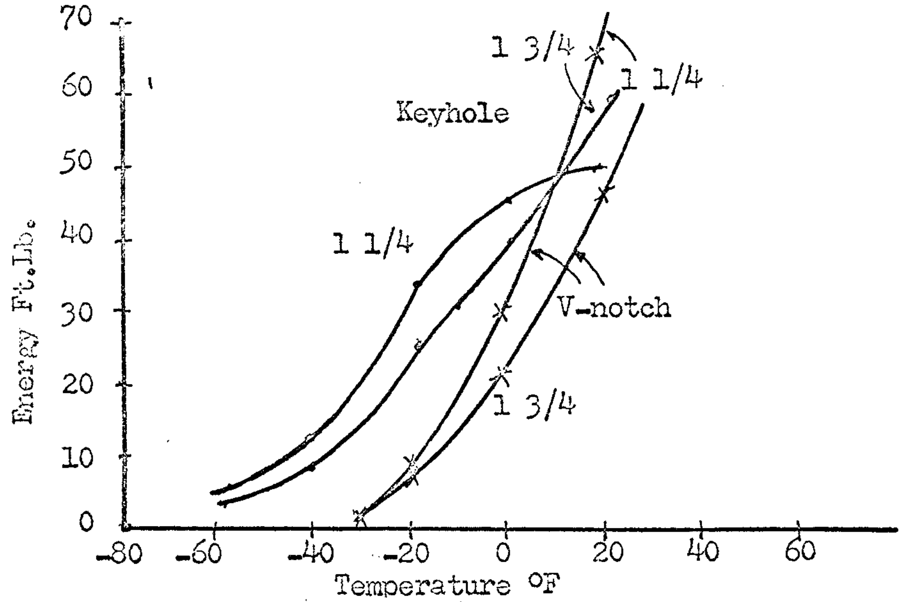
The Charpy V-Notch test is the most generally used test. Good correlation of Charpy-V energy data with ship fracture performance has been obtained (47). The range (3-10 ft.-lb.) and the average (6.2 ft.-lb.) correlations of Charpy-V energy with nil-ductility temperature are in fair agreement with those reported for the failure temperatures of the ship fracture source plates (range of 3-11 ft.-lb. and an average of 7.4 ft.-lb.). Because of this correlation it became common to specify steels having a 15 ft.-lb. energy at the expected minimum service temperature. The energy data at about the 15 ft.-lb. level was considered to provide a measure of the ductility transition temperature.

While a correlation with performance of carbon structural steel was demonstrated, considerable evidence has been advanced to show that other grades of steel, particularly killed plain carbon and low alloy depart from these correlations unless higher levels of energy absorbtion are selected to match Charpy transition temperature to actual service failures (20). This occurs because the test is influenced by both steel strength and ductility. Since the well established Charpy V-Notch test also has been successful in correlating with ship service experience, many attempts were made to correlate it with other tests and with variations of the basic Charpy V-Notch test.

The Charpy Keyhole test was used for many years as a test for brittle fracture susceptibility and a 15 ft.-lb. limit was placed in codes at one time. However, Charpy V-Notch results are believed to provide a better indication of service behavior because of the correlations developed between Charpy V-Notch test data and ship performance. Both tests provide about the same relative ranking of steels (22).

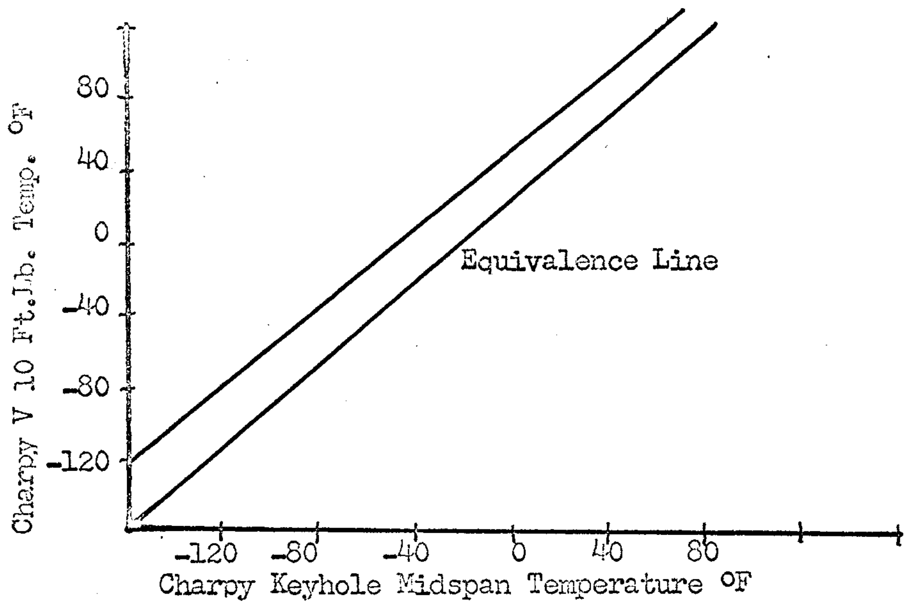
The Charpy Keyhole data tend to have more scatter, and the 15 ft.-lb. criterion has not provided an assurance of safety since a number of failures have occurred with steels that had a keyhole value above 15 ft.-lb. at the failure temperature. A comparison of the Charpy Keyhole Notch and Charpy V-Notch for an ABS Class C Steel is shown in Figure VI (53). The Charpy V-Notch shows a much lower evergy level for the same testing temperature. Figure VII (22) shows the relation of Charpy V-Notch 10 ft-lb.energy with that of the Charpy Keyhole midspan temperature. They show a fair correlation but it would be necessary to add 30°F to the Keyhole midspan temperature to make it equivalent to the 10 ft.-lb. Charpy V-Notch temperature, which in itself is marginal in providing freedom from brittle fracture.

The <u>Charpy V-Notch Lateral Expansion</u> test correlates with energy absorption, but if an expansion criterion is used, the problem of adjusting the energy absorptions as the strength of the steels changes is eliminated (40, 18). A transition curve of the usual shape is obtained when lateral expansion is plotted against testing temperature. The validity of this expansion criterion still must be



KEYHOLE-NOTCH CHARPY AND V-NOTCH CHARPY DATA ON AN ABS CLASS C STEEL 1 1/4 & 1 3/4 PLATE

FIGURE VI (53)



CHARPY V-NOTCH 10 Ft.Lb VERSUS CHARPY KEYHOLE

FIGURE VII (22)

established by correlation with service performance.

A correlation between the Charpy V-Notch transition temperature and the 50 per cent shear fracture temperature shows a separation of about 40°F (22). The slope of correlation curve does not show a one-to-one relation.

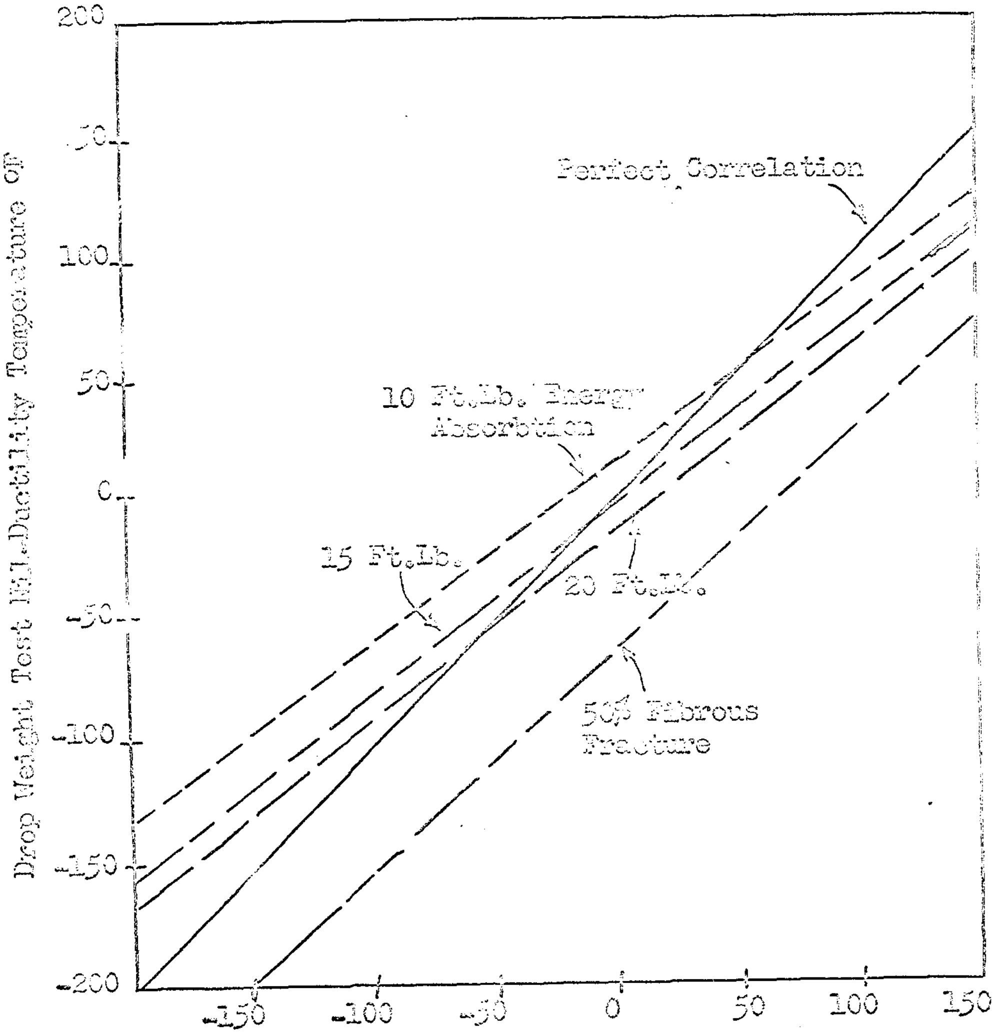
The Charpy Low Blow transition temperature has been ahown to correlate with some service failures. Since this test provides more of a crack arrest type criterion it shows a good correlation with wide plate crack arrest tests (40).

For standard semi-killed and rimmed steels, the SOD Brittle Fracture transition temperature correlates with the Charpy V-Notch 15 ft.-lb. transition temperature. Fully killed fine-grained steels correlate better with the Charpy V-Notch 30 ft.-lb. transition temperature.

Drop Weight Versus Charpy V-Notch Tests

A general linear correlation exists between the Drop Weight nil-ductility temperature and the notch toughness, notch ductility and fracture appearance Charpy V-Notch transition temperatures. There is the normal scatter observed in any brittle fracture test correlation.

Figure VIII(18) illustrates the relationship between the nil-ductility temperature and various notch toughness



ORTHOGONAL REGRESSION LINES RELATING DWT NDT TO VARIOUS NOTCH TOUGHNESS C/V TRANSITION TEMPERATURES

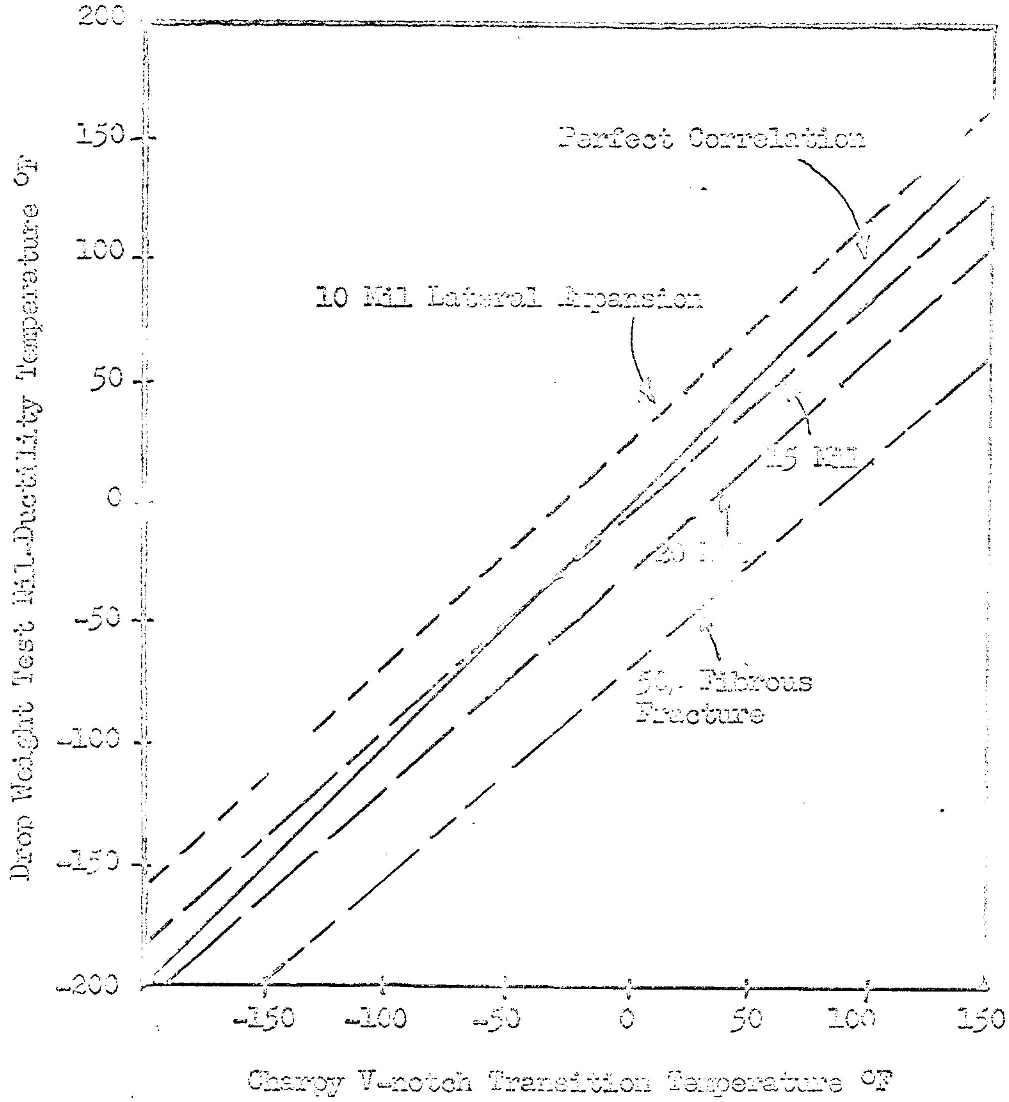
FIGURE VIII (18)

tests (10 ft.-lb., 15 ft.-lb. and 20 ft.-lb. Charpy V-Notch and 50 per cent fibrous fracture V-Notch). The slopes of the correlations are nearly parallel, but are much less than unity. Of this group of tests, the 15 ft.-lb. Charpy V-Notch shows the best correlation and the 50 per cent fibrous fracture the worst. However, even the 15 ft.-lb. test shows increasing disparity as you leave the area of -50 °F.

This disparity is removed considerably if the Charpy V-Notch test is evaluated as a ductility test. Figure IX (18) is a plot relating nil-ductility temperature with notch ductility tests (10 mil, 15 mil, and 20 mil Charpy V-Notch lateral expansion). The 50 per cent fibrous fracture is also included for comparison. All these curves are parallel lines with slopes similar to the one-to-one correlation line. Correlation with the 15 mil expansion line is the best.

Lateral expansion is believed to be a direct measure of notch ductility in the Charpy V-Notch test, and the Drop Weight test is considered a test for ductility transition behavior. Therefore, a correlation between the two is to be expected providing a notch ductility rather than a notch toughness criterion is used.

Orthogonal-regression was used to determine the



ORTHOGONAL REGRESSION LINES RELATING THE DWT TO VARIOUS NOTCH DUCTILITY TRANSITION TEMPERATURES

FIGURE IX (16)

equations of the correlation lines. The following are the equations of the best of each set:

15 ft.-lb	NDT ($^\circ$F) = 0.76 [15 ft.-lb. CVN $^\circ$F] − 6°F
15 mil	NDT ($^\circ$F) = 0.94 [15 mil CVN $^\circ$F] − 1°F

The Charpy V-Notch Low Blow transition temperature has been shown to correlate with the nil-ductility temperature within about 20°C. However, it was usually on the high side (40).

CHAPTER V

PRESENT DAY SPECIFICATIONS TO AVOID BRITTLE FRACTURE

Two basic methods have been used in preparing steel specifications designed to minimize the chance of brittle fracture. The first is that of specifying chemical composition and steelmaking practice along with the customary requirements of tensile strength, yield point and elongation. The other method is by the specification of suitable test requirements that demonstrate the toughness or impact resistance of a steel at its lowest anticipated operating temperature.

Until about 1948, the normal practice in the United States was to specify the melting process and ordinary tensile and bend test requirements. In 1948, the American Bureau of Shipping revised their specifications for steel plate by requiring Class B steel for ½ inch to 1 inch plate and Class C for plate thicker than 1 inch. For Class B and C steels, in addition to mechanical test requirements and a limit on impurities, a range for manganese and a limit for carbon was specified. In addition, Class C steel had a silicon specification and an added requirement that the steel be made to fine grain practice (49). It was not considered practical to include impact test requirements at that time. Later revision, in 1955, specified that plates over 1 3/8 inch thick should be normalized, set up more rigid chemical composition and bend test requirements, and specified that all steels be made by the open hearth or electric furnace practice. The chemical composition specification of a typical ship steel, ASTM A 131-61, is shown in Table II (5).

The ASME Boiler and Pressure Vessel Code, Section VIII (4) in 1962 still did not require an impact test for steels operating above -20°F. However, full X-rays of welds must be made on all plates thicker than 1¼ inches. Below -20°F it requires pressure vessel steels to be impact tested and that the minimum average Charpy Keyhole value of three specimens be 15 ft.-lb. with a minimum of 10 ft.-lb. permitted for one of the specimens. Charpy Keyhole or V-Notch tests may be used. Stress relief and normalizing are required for operation below -20°F. The code also cautions that it should be recognized that fabricating processes, such as welding and forming, may affect the impact properties of the steel and the plate may differ considerably from the plate "as tested".

The chemical composition of a pressure vessel steel which will give satisfactory low temperature (-50°F min) performance is shown on Table III (5). It is an ASTM A-201 steel with an ASTM A-300 requirement for operation at low temperature. The plates must be made in an open hearth

	Grade A	Grade B	Grade C
Plate Thickness	up to ½ in.	½ in. to 1 in.	1 in. to 2 in.
Carbon, max. %	----	0.21	0.23
Manganese, %	----	0.80-1.10	0.60-0.90
Phosphorus, max. %	0.04	0.04	0.04
Sulphur, max. %	0.05	0.05	0.05
Silicon, %	----	----	0.15-0.30
Tensile Strength min. psi	40,000	44,000	42,000
Yield Point min. psi	22,000	27,000	23,000

CHEMICAL REQUIREMENTS FOR ASTM A-131 STEEL (5)

(LADLE ANALYSIS)

TABLE II

	Grade A	Grade B
Carbon, max. %		
Plates under 1 in.	0.20	0.24
1 in. to 2 in.	0.24	0.27
2 in. to 4 in.	0.27	0.30
4 in. to 8 in.	0.31	0.35
8 in. to 12 in.	0.35	----
Manganese, max. %	0.80	0.80
Phosphorus, max. %	0.04	0.04
Sulphur, max. %	0.05	0.05
Silicon, %	0.15-0.30	0.15-0.30
Tensile Strength psi	55,000 to 65,000	60,000 to 72,000
Yield Point min. psi	30,000	32,000

CHEMICAL REQUIREMENTS FOR ASTM A-201 STEEL (5)

(LADLE ANALYSIS)

TABLE III

or electric furnace and if 2 inches or more thick, must be treated to produce grain refinement by normalizing or heating uniformly for hot rolling. A Charpy type impact test with 15 ft.-lb requirement at the lowest service temperature is also specified.

Esso Research and Engineering Company has set up special requirements for selecting and testing steels operating at temperatures between -20°F and +60°F (15). It supplements the ASME Codes. For temperatures -20°F to +30°F any head, shell or pressure weldment exceeding ½ inch in thickness must meet the impact requirements of an ASME Code steel operating below -20°F. For the temperature range of +31°F to +60°F, a fully killed or semi-killed steel must be used. An impact test is not required for a fully killed steel.

The 15 ft.-lb. Charpy Keyhole test criteria was widely used in Codes both in the United States and abroad for specifying steels to avoid brittle fracture. However, the Charpy-V Notch is now supplanting the Keyhole test based on recent test work. The Charpy Keyhole was much too optimistic, and several failures occurred. With the increased use of fully killed and alloy steels, it is becoming apparent that the Charpy V-Notch 15 ft.-lb. criterion is also not sufficient.

Clark (11) has established Charpy V-Notch minimum energy requirements for various types of steel considering whether fracture initiation or propagation is the most important. Table IV (11) shows the suggested values for pressure vessel steels.

The nil-ductility temperature +60°F has been widely used because of its protection against large flaws in critical services. Lange, et.al. (27) in the fracture analysis diagram approach, has proposed increasing the number of degrees added to the NDT depending on how critical the application is. His four design criteria are:
(a) NDT-where protection is needed against brittle fracture initiation due to small flaws in locally stressed areas.
(b) NDT + 30°F- guards against fracture propagation if the stress is less than one-half the yield stress.
(c) NDT + 60°F- protects against fracture propagation up to the yield stress of the material.
(d) NDT + 120°F- Only full shear fractures can occur; applicable to submarine and other military uses.

A procedure (27,15) for hydrostatic test conditions, designed to eliminate the possibility of brittle fracture, has been put into extensive use. When shell thicknesses are 3/4 inch or greater, the water must be a minimum of 100°F unless the transition temperature of the steel is

Type of Steel	Min. Energy, ft.-lb. Charpy-V: To Prevent Fracture Initiation	To Prevent Propagation
Rimmed and semi-killed	10	15
Fully killed fine grain	15	25
High strength	25	35
Quenched and tempered	30	45

VARIATION OF CHARPY V-NOTCH MINIMUM ENERGY CRITERION WITH TYPE OF STEEL (11)

TABLE IV

known. If the transition temperature is known, the water temperature should be at least 10°F above it. This requirement is particularly important for vessels which have been designed to operate at high temperatures.

Many fabrication and design procedures have been developed in an effort to improve workmanship and reduce flaws as an aid in preventing brittle fracture. However, the elimination of flaws on a consistent basis cannot be assured so that the only way to be sure of protecting a structure is to specify a material as brittle fracture resistant as possible.

CHAPTER VI

CONCLUSIONS

Engineering structures are susceptible to catastrophic brittle fracture at all temperatures up to about 100°F. Measures must be taken both in steel specification and fabrication practice to prevent the occurrence of brittle fracture.

A considerable amount of work has been done in the past number of years in determining the factors affecting brittle fracture and in developing tests to measure the resistance of a steel to brittle fracture. Chemical composition is a major factor which affects the transition temperatures and hence the toughness of steels. Low carbon content (less than 0.30 per cent), the addition of manganese and silicon, and restriction of sulphur and phosphorus to no more than 0.05 per cent improve the transition temperature. Carbon content has a greater effect on fracture initiation than on propagation.

Fully killed steel has the best fracture resistant properties. Rimmed and semi-killed steels have higher transition temperatures and require more restrictive tests to assure freedom from brittle fracture. Normalizing is very helpful but should be followed by liquid spray quenching to impart the best properties. Fine grain size lowers the transition temperature, but by itself has little direct effect on fracture. The thicker the plate, the greater is the susceptibility to brittle fracture.

There is still controversy over the effect of residual stress on fracture initiation and propagation. Based on the results of many studies, it is felt that residual stresses do not cause fracture by themselves, but are additive to other stresses in their effect. What is important is the plastic strain history and aging in the region of a notch or defect and the effect it has on the ductility of the steel. Thermal stress relief will both reduce residual stresses and improve ductility.

Almost all brittle fracture service failures originated at a flaw, void, or structural discontinuity where stress concentrations exist. Fabrication procedures are important in reducing flaws. The greater the amount of cold forming, the more susceptible a structure is to brittle fracture. Heat treatment, at high enough temperatures will restore ductility lost in fabrication.

Fractures in welds only occur where defects exist or weld metal is very brittle. The use of weld preheat and post-treatment improve the quality of a weld.

No single notch toughness test can predict the transition temperature of a specific structure since these tests cannot evaluate design and fabrication criteria. Nor has one test, even with modification of criteria, been proved to give equally consistent results for all types and strengths of steels.

Most notch toughness tests agree in their evaluation of chemical composition. The Charpy Keyhole and Charpy V-Notch are the tests most often used, with the Charpy V-Notch specimen displacing the Keyhole because of its better agreement with service performance. The Charpy V-Notch transition temperature and the Drop Weight test nil-ductility temperature show good correlation with service failures. There is a general correlation of Charpy notch toughness, notch ductility, and fracture appearance transition temperatures with the nil-ductility temperature, but the Charpy lateral expansion (15 mil) provides the most direct correlation.

For most rimmed and semi-killed steels, a Charpy V-Notch value of 15 ft.-lb. at the lowest service temperature is satisfactory. However, for fully killed and low alloy steels, the NDT correlates best with service experience. For these steels any Charpy V-Notch specification should be based upon demonstrated specific correlations to the NDT for the steel type in question. For critical applications, the NDT seems to be a good guide, but for less critical situations, the NDT philosophy is unduly conservative since it assumes the existence of crack like defects in an area of high stress concentration.

Most steels are specified using ASTM and ASME codes as a basis, with additional requirements requested by some companies. However, the code requirements for impact testing of steels for service below -20°F appear to be inadequate. In addition, they don't provide guidance for the prevention of brittle fracture at temperatures above -1[illegible]°F.

CHAPTER VIII

RECOMMENDATIONS

The following recommendations are made for the prevention of brittle fracture in common engineering structures which operate above -50°F. In determining whether to use all of these recommendations, consideration should be given to the consequences of failure.

Chemical composition should be controlled to the specifications shown in Table V. Steel should be manufactured by the open hearth or electric furnace process and normalized if the service temperature is below 60°F and the plate thickness is greater than one inch. Fine grain practice should be used for thickness above ½ inch when the temperature is below 30°F.

For rimmed and semi-killed steels, a minimum Charpy V-Notch energy of 15 ft.-lb. at the lowest anticipated temperature is required. Fully killed, high strength, and low alloy steels should have nil-ductility temperatures below the lowest service temperature. Additional degrees should be added to the NDT depending on how critical the application is. A NDT + 30°F is satisfactory for most situations.

The Charpy V-Notch test can be used in place of the

Chemical	Per cent
Carbon, maximum	
under 1 inch	0.15
1 in. to 2 in.	0.20
over 2 inch	0.25
Manganese	0.80-1.20
Silicon	0.15-0.25
Phosphorus, maximum	0.04
Sulphur, maximum	0.05
Arsenic, maximum	0.2

CHEMICAL COMPOSITION REQUIREMENTS FOR A BRITTLE FRACTURE FREE STEEL

TABLE V

Drop Weight test to evaluate the NDT if a suitable correlation exists for the steel being tested. In lieu of such correlation, a minimum energy of 25 ft.-lb for fully killed fine grain, 35 ft.-lb for high strength, and 45 ft.-lb. for quenched and tempered steels should be used.

Vessels and structures operating below -20°F should be stress relieved. Weld preheating to 200°F minimum and thermal stress relief should be used for critical applications where temperatures may go below 30°F. Welds should be spot x-rayed below one-inch thickness and fully x-rayed for one-inch and above. Hydrostatic tests should be conducted at temperatures at least 10°F above the transition temperature or at 100°F minimum if the transition temperature is not known.

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