

GENERALIZED PROCEDURES FOR THE USE OF PLANE STRAIN AND ELASTIC PLASTIC FRACTURE MECHANICS OPTIONS IN THE MODERNIZATION OF NUCLEAR STANDARDS

F.J. LOSS, J.R. HAWTHORNE, L.E. STEELE, W.S. PELLINI
Naval Research Laboratory, Washington, D.C. 20390, U.S.A.

SUMMARY

In the design of nuclear power plants and the selection of related structural materials, the assurance of reliability in operation is an essential consideration. The need for analytical criteria for defining the adequacy of fracture toughness is particularly acute for pressure vessel materials.

A recent revision to the ASME Boiler and Pressure Vessel Code (Section III) has adopted linear elastic fracture mechanics methods as a means of assuring fracture safe operation for vessels and components. This fact has suggested a danger that fracture mechanics may be misunderstood to signify a limited use involving solely plane strain (brittle) metals. Thus, in the modernization of nuclear codes, there is a need to include the full range of fracture mechanics options for system design, that is, elastic-plastic and fully plastic fracture mechanics as well as the linear elastic procedures. The choice of a particular toughness regime for the metal (e.g., plane strain or elastic plastic) can then be made by the designer or regulatory body. It is clear that this decision will have a major implication on the selection of nuclear structural materials. For example, it must be realized that acceptance of a plane strain design criterion permits the material to exhibit brittle behavior even though the metal may not be considered as being brittle by the one using this criterion.

This paper describes recent developments in the means for defining the full range of plane strain, elastic plastic, and plastic fracture mechanics options available to the designer. Comparisons are made between these options and the fracture toughness requirements of the U.S. Atomic Energy Commission and those of the ASME Nuclear Code. Existing plane strain $K_{I,d}$ data for structural metals are analyzed in concert with dynamic tear (DT) test trends. The limited temperature region of $K_{I,d}$ applicability for these materials is shown to presage the elastic plastic regime through which sharply increasing stress is required for fracture propagation until a leak-before-fail condition is ultimately attained. This phenomenon highlights the need to extend the analytical capabilities for fracture assurance into the non-brittle regime. The DT test is an effective engineering tool which, like the COD concept, can be used to define the elastic plastic and plastic constraint transitions. This test procedure is fully rationalizable in terms of section size parameters and can be used independently or together with the $K_{I,d}$ -temperature trend to predict the onset of the elastic plastic and plastic regimes as a function of temperature and section thickness.

1. Introduction

Various codes and standards are in use for the design, materials selection and fabrication of commercial nuclear power plants. In view of the potentially serious consequences associated with the failure of a nuclear component, particularly the primary pressure vessel in water-cooled plants, these codes should offer methods for failure prevention in operation. This fact was recognized at the inception of the nuclear power industry in the USA. Consequently, the U. S. Atomic Energy Commission (AEC) invoked the requirement that primary pressure retaining components must be operated in the ductile regime. Fracture-safe assurance in this regime was predicated on Fracture Analysis Diagram (FAD) [1] procedures that reflected service failure correlations. At that time the ASME (American Society of Mechanical Engineers) Boiler and Pressure Vessel Code offered essentially no guidelines with respect to fracture safety; yet it was, and still is, the most widely used code in the world for pressure vessel design.

The need for revision of the AEC fracture toughness criteria became apparent as a result of research sponsored by the AEC Heavy Section Steel Technology (HSST) Program. This research effort clarified the role of thickness in the evolution of the constraint transition from plane strain to fully plastic behavior. Partly as a result of this effort the ASME code recently adopted rules for fracture-safe assurance. These rules are embodied in Section III, Appendix G [2] of the code and are based primarily on linear elastic fracture mechanics (LEFM). It should be noted that specific criteria are presented for fracture safety during normal operations. The code also recommends that LEFM principles be used to consider emergency conditions but leaves the formulation of criteria for this case to the user. The AEC also prepared fracture toughness requirements [3] that are identical in many respects to those of the ASME code. The AEC rules, however, relate only to normal plant operations, and provisions for fracture safety during an accident or emergency situation are not treated.

The adoption of fracture toughness requirements based on LEFM principles has suggested a danger that fracture mechanics may be erroneously considered to apply only to plane strain (brittle) metals and, furthermore, that this is the consensus among engineers in the USA. It is the intent of this paper to clarify this state of affairs and to emphasize the need for modernization of nuclear codes to encompass the full range of fracture mechanics options for system design. Code revisions must include elastic plastic and fully plastic fracture mechanics as well as linear elastic methods. Procedures for accomplishing this within the current state of the art will be described.

2. Necessity for Full Range Toughness Characterization

It has become clear that no single toughness criterion is adequate for all applications. The LEFM methods can provide a quantitative assessment of the critical flaw size and stress level for fracture initiation, but this method pertains only to brittle metals. On the other hand, one is generally required to operate critical elements of a nuclear plant, such as the primary

pressure vessel, in the ductile regime. A requirement such as this is highly desirable since it will give the assurance that a certain degree of (unanticipated) plastic deformation will not result in catastrophic failure which could have severe ramifications, both economic and political. Clearly the designer should have the option of choosing the level of toughness deemed appropriate for a particular component; yet the current codes generally do not give him this option.

The use of LEFM is a first line of defense in that the structure is considered lost once propagation is initiated. On the other hand, it is generally conceded that structural metals are not homogeneous and isotropic and that initiation is a distinct possibility, and so other reliability criteria are needed. In spite of its limitations, LEFM technology has provided valuable insight to the fracture problem and has suggested a logical three-part toughness categorization for structural metals, namely, linear elastic, elastic plastic, and plastic. This division of fracture behavior can be used to define the different design philosophies that are appropriate for general engineering application:

- The objective of providing protection against fracture initiation for brittle metals requires control of the critical crack size and the use of LEFM principles.
- The objective of providing fracture control for specified nominal elastic stress levels in the presence of flaws of unspecified (large) size necessitates the use of elastic plastic materials. An arrest philosophy is called for in this case such that the parent metal can accept local crack instabilities that continue through the section thickness without further propagation (i.e., leak-before-break).
- If maximum protection from fracture is required for any anticipated service condition, then only metals capable of plastic deformation (in the presence of a flaw) are acceptable. Under this reliability criterion, a flaw can exhibit rapid extension solely under the action of gross plastic overloading.

Only after the designer or regulatory body has determined which of the above reliability criteria are required can the structural material be chosen. It must be emphasized that the metal properties dominate the design philosophies that are used to achieve specific reliability levels. For example, it should be clear that leak-before-fail protection generally cannot be achieved through the use of metals that can exhibit brittle behavior. This fact relates to the existence of regions of high stress in most structures that precludes the existence of large, through thickness flaws that are associated with leakage.

The necessity to evolve quantitative assessments of the elastic plastic and plastic regimes is clear. Unfortunately, quantitative analysis procedures, similar to LEFM, are not presently available. Research toward this goal is continuing on approaches such as the J-integral, crack opening displacement (COD), precracked Charpy-V (C_v), and equivalent energy. However, a development effort is still required to achieve engineering application of these techniques.

The Dynamic Tear (DT) test, on the other hand, can be used without further development work to characterize the low and intermediate strength steels used in nuclear construction. This test procedure is fully rationalizable in terms of section size parameters so as to define the constraint transition from linear elastic to plastic behavior. The techniques for using the DT test to define the three toughness regimes are described in the following section.

3. Procedures for Full Range Toughness Characterization

Conservative fracture-safe design requires protection from dynamic flaw initiation, whether due to a localized flaw instability such as a popin or due to full section dynamic load, e.g., impact or shock loading. The LEFM K_{Id} values have been used to achieve a flaw size/stress level relationship for plane strain metals. Figure 1 illustrates the general trend in K_{Id} (and K_{Ic}) with temperature for low and intermediate strength steels. Of prime importance is the sharp fracture state transition with increasing temperature that characterizes the low alloy structural steels used in water-cooled nuclear plants. This fracture state transition is the result of constraint relaxation induced by increasing ductility on a microscale. The practical result for the structure as a whole is a large increase in deformation capability within a small temperature increment above the limiting temperature for plane strain applicability.* This behavior is reflected by the sharp increase in the large specimen DT energy curve illustrated in Fig. 1 and discussed elsewhere [4].

From Fig. 1 it is apparent that determination of the upper range of K_{Id} values requires large specimens. Also, these values can no longer be measured at temperatures significantly above the Drop Weight-NDT temperature. This correspondence is consistent with the sharp constraint transition from plane strain to plastic behavior. In order to give the designer the option of specifying structural reliability criteria at a toughness above the level of plane strain (K_{Id}), it is essential to develop procedures that translate the significance of the fracture state transition in terms of structural behavior. A description of this translation procedure, as based on the DT test and K_{Id} corrections, follows.

An analysis of the constraint transition requires an understanding of several concepts based on LEFM behavior. The first is the sharp rise of the K_{Id} values with temperature above the NDT temperature index as illustrated in Fig. 2. This curve is based on 8-in. (203 mm) thick K_{Id} tests of A533-B steel conducted by Westinghouse [5], but the trend is believed to be characteristic of all low and intermediate strength steels (see, for example, K_{Id} trends measured by Shoemaker and Rolfe on seven structural steels [6]). Only Westinghouse data are described because the existence of other dynamic K_{Id} data from very thick specimens is not known. Secondly, note that the temperature scale in Fig. 2 can be alternatively expressed in terms of the ratio of

*The limit of plane strain applicability for a section of thickness B has been defined by ASTM Committee E-24 as $B \geq 2.5 (K_{Ic}/\sigma_{ys})^2$ for static testing. The same relationship, using dynamic properties (K_{Id} , σ_{yd}), is assumed to apply for dynamic loading.

K_{I_d}/σ_{yd} * (hereafter referred to simply as the "ratio" or R) and that this ratio increases sharply with increasing temperature. Thirdly, note that the NDT temperature may be indexed at a ratio of approximately 0.5. This index value has been confirmed on both theoretical and experimental grounds [6,7].

The K_{I_d} curve in Fig. 2 is now used to establish two important index scales for thickness denoted as L and YC. The L scale refers to a plane strain limit thickness. In other words, there exists a maximum plane strain ratio, R, that can be experimentally determined with a given thickness, B, specimen as defined by ASTM Committee E-24 (i.e., $B \geq 2.5 R^2$). A ratio in excess of this value, for the given thickness, relates to the onset of elastic plastic behavior. For example, to measure a ratio of 1.0 $\sqrt{\text{in.}}$ (ratio scale) requires a thickness of 2.5 in. (L-scale). Entering the L scale of Fig. 2 at 2.5-in. thickness translates to a temperature of about 90°F (50°C) above the NDT. In other words, plane strain measurements are not possible at temperatures higher than 90°F above NDT for a 2.5-in. thick specimen whose material exhibits the K_{I_d} -temperature trend illustrated. The YC thickness scale in Fig. 2 is used to determine the yield criterion for a material of thickness B that contains a sharp flaw. In this case the relationship between thickness and ratio is given as $B = 1.0 R^2$. Thus for a 2.5-in. thick plate (i.e., 2.5 in. on the YC scale), the yield condition is obtained at a temperature of approximately 120°F above the NDT. Consequently, a 2.5-in. section of this steel undergoes a fracture transition from plane strain (L) to plastic (YC) behavior in only 30°F (17°C).

The identification of the YC condition as $1.0 R^2$ was first expressed by Irwin [8] as an approximation of the midrange toughness for the fracture mode transition for sheet material (i.e., Irwin's $\beta_{Ic} = 1$, where $\beta_{Ic} = R^2/B$). Later, Rolfe and Barsom [9] concluded that this criterion defines the condition at which considerable through-thickness yielding begins to occur in the notch vicinity, and further, considered it to reasonably approximate the conditions required in leak-before-break behavior. Finally, Pellini [10] interpreted the toughness values lying between the ratios of $R = \sqrt{B/2.5}$ and $R = \sqrt{B/1.0}$ (i.e., $L = 0.63 \sqrt{\text{in.}}$ and $YC = 1.0 \sqrt{\text{in.}}$ for 1-in. thickness) as defining the limits of elastic plastic behavior for material at the upper shelf level† toughness condition. This concept has been expressed graphically in terms of the Ratio Analysis Diagram (RAD) shown in Fig. 3 for 1-in. (25 mm) thicknesses. Here the region between the ratios of 0.63 and 1.0 $\sqrt{\text{in.}}$ has been designated as "elastic plastic". The RAD is extremely useful to define the structural reliability criterion that can be imposed with a given choice of material. For example, the choice of any 1-in. thick steel at a strength level over

* For the steel shown in Fig. 2 the dynamic yield stress, σ_{yd} , is approximated by the addition of 30 ksi (21 kg/mm²) to the static yield stress, σ_{ys} .

† Upper shelf level toughness refers to the temperature region corresponding to the upper plateau of the DT curve for a given thickness as illustrated in Fig. 1.

230 ksi (161 kg/mm²) in Fig. 3 will permit only the use of a plane strain reliability criterion, whereas steels having a yield stress below 100 ksi (70 kg/mm²) will generally exhibit plastic behavior at the shelf level toughness regardless of the reliability criterion imposed. Thus, the controlling influence of the choice of materials in relation to a desired reliability criterion can be readily visualized from the RAD.

It now appears reasonable to extend this definition of the elastic plastic regime to encompass the fracture state transition that characterizes low and intermediate strength structural steels. The objective here is to relate the structural significance of a particular fracture state (elastic, elastic plastic, or plastic) to the stress level that may be imposed on the structure. This is accomplished in Fig. 4 through the use of the K_{Ic} vs temperature curve for a given steel and the definitions of the L and YC index points.

The L and YC index temperatures are first entered on a K_{Ic} vs temperature curve that has been obtained for the material in question (Fig. 4, bottom) The procedure is as follows:

- Plot the ratio scale on the temperature axis by computing K_{Ic}/σ_{yd} at a given temperature; assume $\sigma_{yd} = \sigma_{ys} + 30 \text{ ksi (21 kg/mm}^2\text{)}$.
- Enter the ratio scale at values of $R = (B/2.5)^{1/2} \sqrt{1 \text{ in.}}$ and $R = (B/1.0)^{1/2} \sqrt{1 \text{ in.}}$ and project down to the K_{Ic} curve, thereby locating the respective values of L and YC. Note that these index temperatures are thickness-dependent and will shift accordingly.

Next, the temperatures corresponding to L and YC are used to construct a plot of stress vs temperature (Fig. 4, top). The YC temperature is located at yield stress loading (by definition) and the L temperature is entered at $0.3 \sigma_{ys}$. As a limit of plane strain applicability, the L index is defined as the highest temperature at which plane strain conditions apply for a through-thickness crack of length (2a) equal to approximately three times the thickness. This logic provides a conservative (lowest) stress level that may be tolerated in the presence of a large flaw corresponding to leak-before-break behavior. With this flaw in a tension plate the following relationship for a Griffith crack applies

$$\frac{K_{Ic}}{\sigma_{ys}} = \frac{\sigma}{\sigma_{ys}} \sqrt{\pi a} \tag{1}$$

For any thickness B that satisfies the condition for plane strain constraint, i.e., $B \geq 2.5 (K_{Ic}/\sigma_{yd})^2$, it can be shown that $\sigma/\sigma_{ys} > 0.3$. Thus, a conservative value of stress corresponding to the L index temperature is $0.3 \sigma_{ys}$.

In Fig. 4, top, the allowable stress vs temperature relationship for a through-thickness flaw in a 4-in. (102 mm) thick section is formed by connecting the L and YC points with a straight line; a second line is formed between $0.3 \sigma_{ys}$ at the L temperature and zero stress at absolute zero. To consider flaws smaller than the through-thickness flaw, the K_{Ic} vs temperature relation may be used to plot a family of curves for a semielliptic surface flaw in a tension plate (Fig. 4, top). The semielliptic flaw may be

treated with the following equation:

$$\frac{K_{Ic}}{\sigma_{ys}} = 1.1 \frac{\sigma}{\sigma_{ys}} \sqrt{\frac{\pi a}{Q}} \quad (2)$$

where a is the flaw depth, σ is the applied stress, and Q is a dimensionless shape factor [11]. Equation (2) applies only in the plane strain regime, that is, at temperatures below the L-index temperature.

Figure 4 provides a convenient analysis diagram for the designer in that it illustrates the required minimum structural temperatures that must be maintained for certain applied stress levels in the presence of a flaw. For example, consider a small surface flaw (1-in. or 25 mm deep) residing in a region of yield stress (peak) loading. For the 4-in. (102 mm) thickness illustrated in Fig. 4, it is seen that the temperature of the structure must be maintained above the L index value which, by definition, requires operation in the elastic plastic regime. When this same flaw is loaded at the usual design stress level (i.e., 0.2 to 0.4 σ_{ys}) in uniform sections, operation below the L-index temperature is possible. However, a somewhat larger flaw of 2-in. (51 mm) depth will require operation in the elastic plastic regime.

In theory, Fig. 4 provides an ideal method to achieve fracture-safe design for a structure. Unfortunately, the required K_{Id} curve is difficult to obtain because large specimens must be tested and no standard procedure for dynamic K_{Id} measurement has been evolved. Note that the previous examples have cited a necessity to operate the structure in the elastic plastic regime. In this regime the LEFM methods do not apply and analytical elastic plastic approaches have not been well developed.

The DT test offers an alternative procedure which may be used by itself or in conjunction with the K_{Id} test to evolve Fig. 4. The philosophy behind this procedure is that the fracture state transition is associated with a change in the ratio of K_{Id}/σ_{yd} . The ratio exhibits a sharp increase with temperature above the NDT; the increase in DT energy with temperature therefore can be expressed in terms of the ratio. This analysis procedure is illustrated schematically in Fig. 5 for high shelf level steels. For these steels it has been shown that the mid-energy of the DT curve approximates a yield condition [4]. This behavior is therefore associated with the YC-index temperature previously defined.

Figure 5 illustrates the correspondence of the DT and K_{Id} curves for a 1-in. (25 mm) thickness. The YC temperature from the mid-energy* of the DT

*The criterion of using the DT mid-energy to define a YC-index temperature is generally valid for steels of less than 100 ksi (70 kg/mm²) yield strength. This is due to the high shelf level energies exhibited by these steels and narrow temperature range corresponding to the constraint transition. A sufficient shelf energy for this purpose is 4000 ft-lb from the 1-in. RAD in Fig. 3. Steels exhibiting a shelf energy lower than this value must be treated separately. Generally, the DT energy index for these steels is determined from the lower boundary of the "plastic" region in Fig. 3.

curve is projected downward to the ratio scale at $1.0 \sqrt{\text{in.}}$. Likewise, the $0.5 \sqrt{\text{in.}}$ ratio associated at NDT temperature* is projected from the lower toe region of the DT curve to the ratio scale. The remainder of the ratio scale between 0.5 and $1.0 \sqrt{\text{in.}}$ may be interpolated without excessive error, keeping in mind the characteristic shape of the K_{Id} vs temperature curve. In this way the stress vs temperature plot of Fig. 4 is obtained in a straightforward manner.

3.1 Thick Section Analysis Procedures

In the case of nuclear vessels, fracture safe assurance requires consideration of thick sections. However, thick section testing for toughness properties is expensive, and it can be assumed that very little of this testing will ever be accomplished. Consequently, the use of small specimens to project large specimen behavior takes on special significance. Figure 6 illustrates a way in which small DT specimens ($5/8$ to 1 -in. thick) can be used to predict the behavior of sections an order of magnitude larger. Research conducted at NRL in conjunction with the HSST Program [4] has suggested that a thick section DT curve may be obtained by translating the smaller curve by an increment of temperature at the YC energy level as shown in Fig. 6 (both DT curves are normalized on the basis of upper shelf energy). The YC entry on the small specimen curve is an index of metal quality, similar to the NDT, whereas the temperature translation of YC from the thin section curve to the thick section curve is believed to be primarily a mechanical effect and should not be unique to the A533-B steel investigated.

In Fig. 6 the ratio scale has been entered using the data of Fig.1. However, without the large specimen K_{Id} data, the location of the scale can be approximated using two YC ratio values from the small and large DT curves plus the $0.5 \sqrt{\text{in.}}$ index corresponding to NDT. As long as the material exhibits a sharp constraint transition as confirmed by the thick section DT curve, this indexing procedure for the ratio scale should result in minimal error as opposed to computing the exact ratio scale using thick section K_{Id} tests. Finally, the L and YC ratio temperatures may be projected to a stress vs temperature plot (Fig. 6, bottom) to achieve the thick section analysis diagram equivalent to Fig. 4.

*The NDT temperature may be easily determined with the Drop Weight specimen. It has also been shown [4,7,12] that the NDT temperature consistently lies at the toe region of the $5/8$ -in. DT curves.

4.0 Comparison of Code Criteria and DT Analysis Procedures

The fracture toughness requirements for the coolant pressure boundary of water-cooled reactors in the USA is governed by AEC criteria [3]. However, a significant portion of the AEC criteria is referenced to the ASME Code (Section III and Appendix G) [2]. Salient features of these criteria for pressure vessels are presented here for discussion purposes. The ASME criteria postulates the existence of a surface flaw having the dimensions of 0.25 B by 1.5 B (depth and length respectively) for thicknesses of 4 to 12 in. (102 to 305 mm); a 1-in. (25 mm) deep flaw is taken for thicknesses less than 4 in. The applied K_I level is assumed to consist of a component due to pressure or primary stress (K_{Ip}) and a component due to thermal stress (K_{It}). To permit vessel operation, the following inequality must be satisfied.

$$2 K_{Ip} + K_t < K_{IR} \quad (3)$$

where K_{IR} is considered a lower bound curve of existing K_{Ic} and K_{Id} data for pressure vessel steels. This curve is compared with the K_{Id} curve for HSST plate* in Fig. 7, bottom, and is referenced to the NDT temperature of the particular steel. The AEC criteria define the minimum operating temperature at all power levels (in excess of 5% of maximum rated power) as the higher of: (a) 40°F (22°C) above the minimum allowable temperature obtained using the ASME rules (eq. 3), or (b) NDT + 160°F (89°C).†

An example of the application of these criteria for a 6-in. (155 mm) thick vessel wall is presented in Fig. 7. The top portion of the figure illustrates the stress vs temperature relation for both a surface flaw and a through-thickness flaw. The expected levels of these stresses during normal operation are indicated by the horizontal lines. The curves were derived using the K_{Id} trends and the equations shown for a yield stress of 70 ksi (49 kg/mm²). Thus for a small (1-in. or 25 mm deep) flaw in the nozzle at yield stress loading, the metal temperature must be maintained at approximately 150°F (83°C) above NDT** for material exhibiting a " K_{IR} -type" curve; use of "HSST-type" material permits a somewhat lower temperature. To prevent propagation of a through-thickness flaw in the shell region for K_{IR} -type metal, Fig. 7 shows that the temperature must be maintained above NDT + 160°F (89°C) for an assumed shell stress of 0.3 σ_{ys} . Note that these temperature limitations relate only to plane strain reliability requirements.

Within this framework, the minimum operating temperatures obtained with the ASME/AEC criteria and the DT procedures are now examined. For the ASME criteria, eq. (3) is computed for a flaw in the cylindrical section of a

*Note that the HSST curve has been considered for all of the analysis procedures described in this paper.

†NDT + 60°F (33°C) is substituted whenever the core is critical at power levels below 5% of maximum rated power.

**The equation for the nozzle in Fig. 7 is approximate; refined methods of calculations are presented in reference 13.

6-in. (152 mm) and a 10-in. (254 mm) vessel. For these vessels, respective values for K_{It} of 4 and 10 ksi $\sqrt{\text{in.}}$ are assumed [13] along with a shell stress level of 20 ksi at the operating pressure.* The minimum allowable temperatures using eq. (3) and the K_{IR} curve are 112°F (62°C) and 140°F (78°C) above the NDT for wall thicknesses of 6-in. (152 mm) and 10-in. (254 mm) respectively. The AEC criteria requires the addition of 40°F (22°C) to these minimum temperatures, that is, 152°F (84°C) and 180°F (100°C) above NDT for 6- and 10-in. thicknesses respectively. The DT indexing procedures may likewise be used to project fracture safety. The question of required metal toughness level is one which can be arbitrarily set by the regulatory agency. However, the authors are of the opinion that a YC level of toughness is the minimum acceptable value for a critical structure such as the primary pressure vessel. From the 12-in. (305 mm) thick DT data for HSST-type material (Figs. 1 and 6), the YC temperature from the DT midrange is approximately 175°F (97°C) above NDT. Had K_{IR} -type material been tested, the DT mid-energy undoubtedly would have been somewhat higher as suggested by the shifts in the HSST and K_{IR} curves in Fig. 10, bottom. Considering the displacement of the K_{IR} curves in Fig. 7, a YC temperature for the latter steel is estimated to be 215°F (102°C) or 40°F (22°C) higher than for HSST-type material.

The above comparisons lead to the conclusion that neither the ASME nor the AEC criteria will consistently provide a YC criterion. The AEC criteria is the more conservative of the two and potentially will provide a higher level of toughness at power levels over 5% by virtue of the NDT + 160°F (89°C) limitation, especially during startup and shutdown of the plant when the K_{Ip} of eq. (3) may be small. In cases where the actual material exhibits a K_{Id} curve lying above the K_{IR} curve (e.g., HSST curve in Fig. 7), then the AEC criteria could provide YC-type fracture toughness. If on the other hand, the material exhibited K_{IR} behavior, then the AEC criteria would be perhaps 40 to 50°F (22 to 27°C) below the YC as estimated for this material. With respect to the temperature region of constraint transition, the significance of operating only 40 to 50°F below the YC temperature is readily apparent and can translate to a crucial difference in terms of structural reliability level. For example, the computed L and YC ratios for a 6-in. (152 mm) thickness are 1.55 and 2.45 $\sqrt{\text{in.}}$ respectively. It can be seen from the ratio scale in Fig. 7 that this L-to-YC transition evolves in less than 50°F (28°C). Hence the metal could behave in a plane strain manner using the AEC criteria whereas a yield stress loading would be exhibited for fracture propagation at a temperature less than 50°F higher. The message from the above example can be stated in simple terms. Basically, the constraint transition evolves within a small temperature increment; any margin of error in choosing an operating temperature

* This stress level has been calculated for commercial pressurized water reactors (PWR) from the tabulations of Whitman [14]. The shell stress due to pressure in large PWR exceeds 22 ksi; this corresponds to 0.3 to 0.4 σ_{ys} for the unirradiated material.

within this increment signifies a large change in fracture toughness and therefore a large change in fracture safe assurance for a given flaw and loading condition. In view of this expression of the nature of pressure vessel material, it would appear prudent to operate at a temperature regime where yield loading can be tolerated. This philosophy could help to account for errors in computing the K levels for eq. (3), such as the failure to include residual stresses in the welded portions of the vessel.

The sharp transition in fracture behavior with temperature is also significant to data scatter that leads to variation in K_{Id} curves from different heats of the same material. Consider the K_{Id} curves in Fig. 7 to represent those obtained with two different heats of A533-B steel. Note that at 160°F the ratio for K_{IR} material is 1.5 $\sqrt{\text{in}}$, whereas that for HSST-type material is approximately 2.5 $\sqrt{\text{in}}$. Also note that this variation in ratios at a given temperature corresponds to the L-to-YC transition (i.e., plane strain to yield performance) for a 6-in. thickness.

5.0 Summary

Fracture-safe operation of commercial nuclear power plants must be achieved through compliance with various codes and standards as set forth by regulatory agencies. The AEC fracture toughness requirements have recently been rewritten to reflect improved methods of toughness characterization. Significant portions of the current requirements are based on LEFM methods as described in the 1972 ASME Code revision. This fact presents an apparent inconsistency with the best material performance that is attainable. On the one hand it is desirable to achieve fracture safety knowing that the metal can withstand some degree of gross plastic strain in the presence of a flaw; this provides a built-in safety margin against unforeseen circumstances. Yet, LEFM, per se, cannot provide this assurance since this method is applicable only to plane strain (brittle) metals.

Clearly, an expansion of existing codes is required in order to give the designer and regulatory agency the option of choosing the reliability level of the structure. Three broad reliability levels have been outlined on the basis of fracture mechanics (plane strain, elastic plastic, and plastic) that reflect the fracture state transition with temperature that characterizes nuclear structural metals. Thus, if the designer requires the assurance of leak-before-fail behavior, a toughness level in the elastic plastic regime is required; plane strain metals will not suffice. This fact emphasizes the dominant role which must be assigned to the choice of material in achieving a particular reliability level.

The modernization of nuclear codes and standards must incorporate the full range of fracture mechanics options that includes elastic plastic and fully plastic fracture mechanics as well as linear elastic procedures. Different criteria should then be formulated for the different levels of performance desired. In this way the risks associated with the structure can be logically related to the probability and consequences of failure.

Interpretative procedures based on the DT test and the K_{Id}/σ_{yd} ratio

have been illustrated to define the full range of toughness associated with the fracture state transition. Emphasis was placed on a ratio definition of the limit of plane strain applicability (L) and also a yield criterion (YC) related to the upper limit of the elastic plastic regime. These index ratios have a definite meaning in terms of structural performance and can be defined with the DT test. It should be realized that a change in ratio bears a fixed relationship to toughness variations resulting from changes in temperature so that specification of one is identical to specification of the other. In addition, a small DT specimen (5/8-in. or 16-mm thick) is all that is required to index the metal quality; a temperature-translation of this curve then can be used to define the mechanical constraint imposed by thick sections, thereby obviating the need to conduct large size tests such as would be required to establish the K_{Id} vs temperature curve.

The current AEC and ASME fracture toughness criteria have been examined on the basis of the reliability levels they can project. The AEC criteria are more conservative than those of the ASME; however, neither one consistently specifies a YC-type of fracture toughness. This may be partly attributed to the fact that the AEC requirements are applied only to normal operation and not to accident situations where plastic overloads may be encountered. Use of these criteria, as based on LEFM principles, implies that the structure will exhibit brittle behavior under the appropriate circumstances. It is pointed out the toughness generally increases sharply with increasing temperature so that elastic plastic or plastic fracture characteristics can be achieved with the addition of small temperature increments to current ASME/AEC criteria. However, this small temperature increment translates to a large increase in ratio and thus a large increase in reliability level. Finally, statistical (heat to heat) variations in toughness can have a major influence on the fracture behavior. For a given set of conditions, one heat may result in plane strain behavior while another gives a leak-before-fail reliability. Use of the ASME- K_{IR} curve could result in YC-type performance but there is no way to take advantage of this toughness level within the LEFM framework. The specific requirement of a YC performance level, on the other hand, would provide a much higher reliability level than is called for under current AEC requirements and, more importantly, could assure a consistent level of ductile behavior in an accident situation, a condition to which current AEC criteria have not been addressed.

REFERENCES

- [1] PELLINI, W. S., and PUZAK, P. P., "Fracture Analysis Diagram Procedures for the Fracture-Safe Engineering Design of Steel Structures," Welding Res. Council Bull. 88, 1963.
- [2] ASME Boiler and Pressure Vessel Code, Sec. III, Nuclear Power Plant Components, Summer 1972 Addenda, 30 June 1972.
- [3] Fracture Toughness Requirements, Appendix G, 15 Feb 1973 (draft), Title 10, Code of Federal Regulations, Part 50.
- [4] LOSS, F. J., "Effect of Mechanical Constraint on the Fracture Characteristics of Thick-Section Steel," Nucl. Engr. Des. 17(#1), 16-31 (Aug. 1971)
- [5] SHABBITS, W. O., "Dynamic Fracture Toughness Properties of Heavy Section A533 Grade B Class 1 Steel Plate," WCAP-7623, Westinghouse Electric Corp. Dec. 1970.
- [6] SHOEMAKER, A. K., and ROLFE, S. T., "The Static and Dynamic Low-Temperature Crack-Toughness Performance of Seven Structural Steels," Eng. Fracture Mech. 2(#4), 319-340 (June 1971).
- [7] LOSS, F. J., and PELLINI, W. S., "Coupling Fracture Mechanics and Transition Temperature Approaches to Fracture-Safe Design," Practical Fracture Mechanics for Structural Steel, Chapman and Hall, London, Aug. 1969, pp. J1-J35.
- [8] IRWIN, G. R., "Relation of Crack Toughness Measurements to Practical Applications," The Welding Journal, 519s-528s, Nov. 1962.
- [9] ROLFE, S. T., and BARSOM, J. M., "A Fracture-Toughness Criterion for Steels," U. S. Steel Applied Research Laboratory Report No. 89.018-020(3), 30 June 1969.
- [10] PELLINI, W. S., "Criteria for Fracture Control Plans," NRL Report 7406, 11 May 1972, Naval Research Laboratory, Washington, D. C.
- [11] IRWIN, G. R., et al, "Basic Aspects of Crack Growth and Fracture," NRL Report 6598, Nov. 1967; Whitman, G. D., Robinson, G. C., Jr., and Savolainen, A. W., editors, "Technology of Steel Pressure Vessels for Water-Cooled Nuclear Reactors," ORNL-NSIC-21, Oak Ridge National Laboratory, Dec. 1967.
- [12] LOSS, F. J., HAWTHORNE, J. R., and SERPAN, C. Z., JR., "A Reassessment of Fracture-Safe Operating Criteria for Reactor Vessel Steels Based on Charpy-V Performance," Trans. ASME, J. Basic Engr., 93(Ser.D #2), 247-258, June 1971.
- [13] PVRC Recommendations on Toughness Requirements for Ferritic Materials, Welding Research Council Bulletin No. 175, Aug. 1972.
- [14] WHITMAN, G. D., "Technology of Steel Pressure Vessels for Water-Cooled Nuclear Reactors," Nucl. Engr. Des. 8, 7-21 (1968).

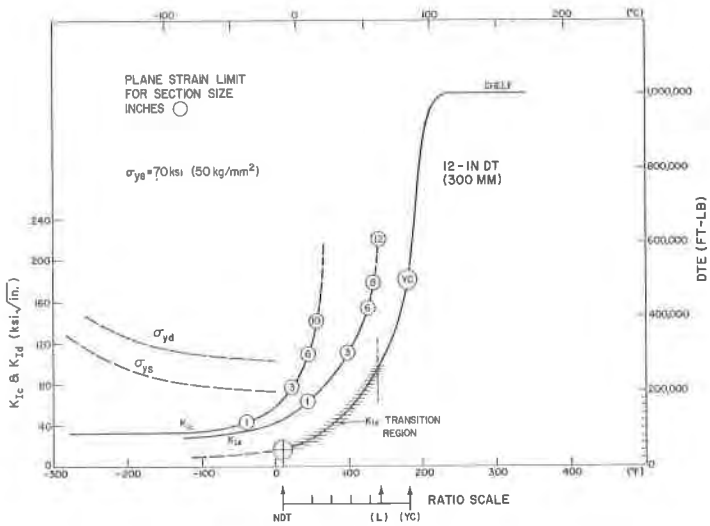


Fig. 1-General trend of K_{Ic} and K_{Id} with temperature for A533-B steel as defined by Westinghouse Corp. data. The sharp increase in K with temperature reflects the beginning of the constraint transition whose full extent is defined by the DT curve.

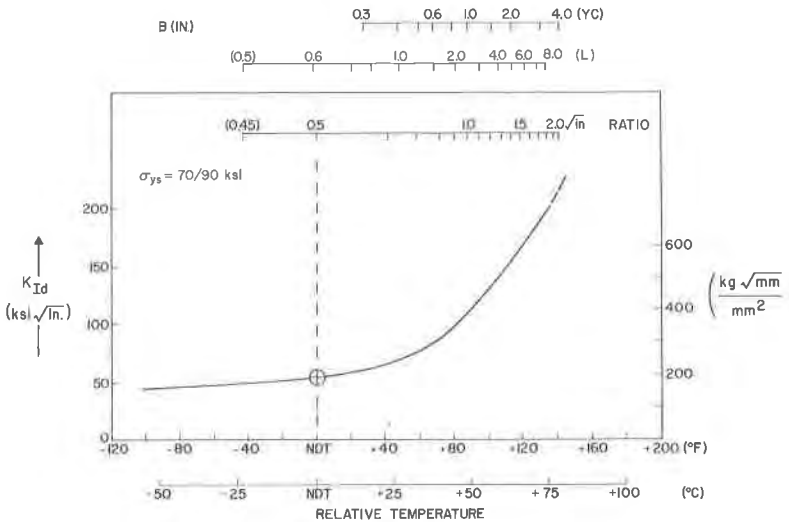


Fig. 2-The K_{Id} vs temperature curve of Fig. 1 is used to compute the K_{Id}/σ_{yd} ratio scale. This scale forms the basis for the L and YC scales for this steel. Note that the values on the L and YC scales are in terms of thickness and not ratio.

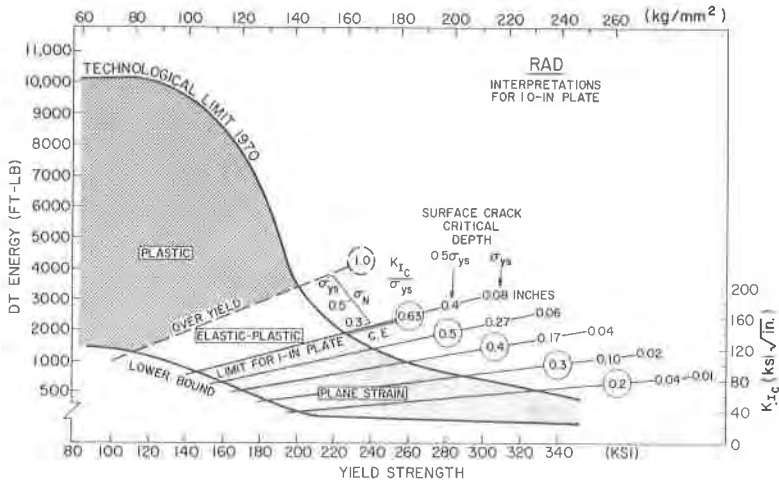


Fig. 3-The Ratio Analysis Diagram for 1-in. (25 mm) thicknesses is used to project fracture behavior for various yield strength steels on the basis of the upper shelf level energy or K_{Ic} level. The depth of critical surface flaws is given in terms of the nominal stress level ($0.5 \sigma_{ys}$ and σ_{ys}) in a tension plate. The boundaries of the elastic-plastic region are defined by the L and YC ratios for a 1-in. thickness and the stress ratios here refer to a through-thickness crack.

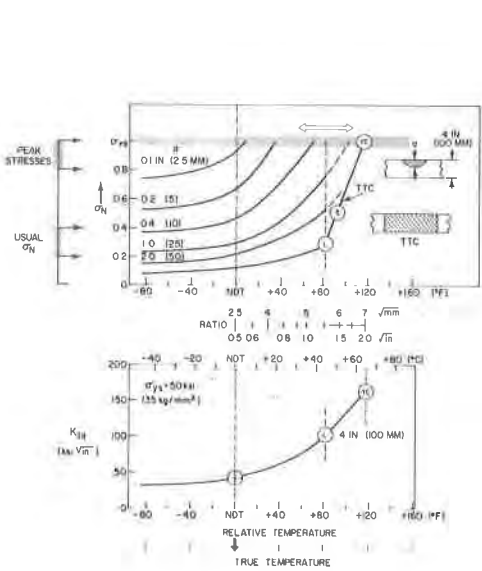


Fig. 4-The L and YC index ratio values for a 4-in. (102 mm) thickness are used to define a stress vs temperature boundary for look-before-fail behavior for a through-thickness crack (lowest curve-upper figure). The family of curves defines the behavior of a smaller, surface crack.

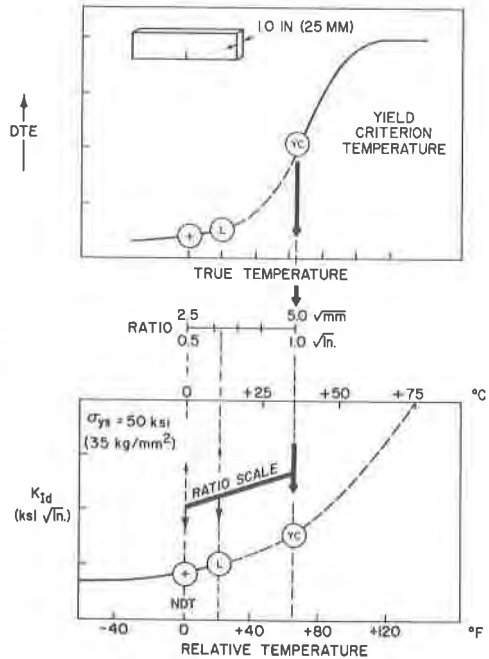


Fig. 5-Correspondence of DT and K_{Ic} curves for purposes of indexing the L and YC ratios. The mid-energy of the DT curve may be used to define the YC temperature; likewise the NDT temperature corresponds to the toe region of the DT curve or can be defined with the Drop Weight test.

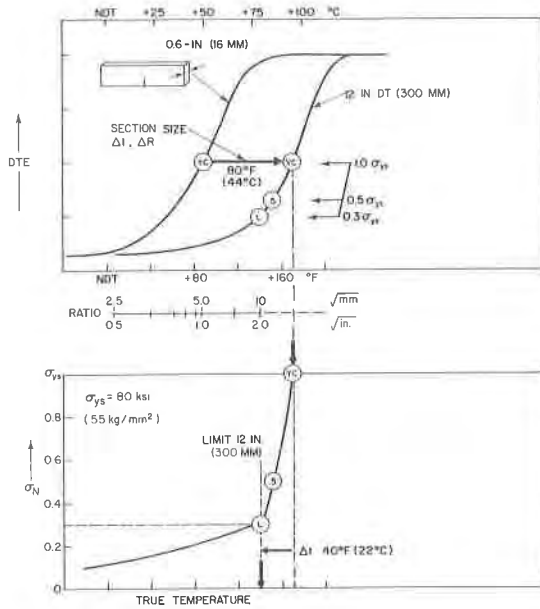


Fig. 6-The small size (0.6 in.) DT curve is employed to establish the YC temperature for a larger section thickness using a temperature translation of the YC index. These index values are used to construct a stress vs temperature analysis diagram for the thick section.

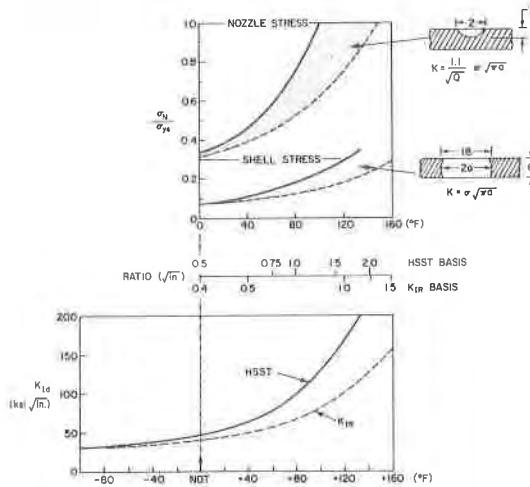


Fig. 7-The K_{Ic} curves defined by the ASME Code (K_{IR}) and by data from the HSST plate (HSST) were used to compute the flaw size vs temperature correspondence for two types of flaws. The ratio scale was computed by assuming a dynamic yield stress of 100 ksi (70 kg/mm²). The intersection of the shaded area with the horizontal line (indicating the expected stress level) defines the lowest temperature permitted in the plane strain regime.