A PROCEDURE FOR
DETERMINING BOUNDING VALUES ON
FRACTURE TOUGHNESS K_{Ic} AT ANY
TEMPERATURE

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OCTOBER 1972

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FOREWORD

This work has been sponsored by the Heavy Section Steel Technology (HSST) Program. The HSST program is a USAEC-sponsored effort at Oak Ridge National Laboratory (ORNL) for investigating the effects of flaws, material inhomogeneities and discontinuities on the strength and structural reliability of present and contemplated water-cooled nuclear reactor pressure vessels. The cognizant engineer for the USAEC is J. R. Hunter. At ORNL the program is under the Pressure Vessel Technology Program. The work discussed in this report was summarized at the Fifth National Symposium on Fracture Mechanics, University of Illinois, Urbana, Illinois, August 31-September 2, 1971. This report is designated Heavy Section Steel Technology Program Technical or Programmatic Manuscript No. 19.

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NOMENCLATURE*

a	general symbol for crack depth in calculation of K_Q or K_{Ic} (see Ref. 9), in.
a_d	particular value of crack depth in a compact tension specimen of thickness d , in.
b, e	volumetric energy ratios, dimensionless
B	general symbol for thickness of a compact tension specimen in calculation of K_Q or K_{Ic} (see Ref. 9), in.
d, p, t	particular values of thickness of compact tension specimens as specified, in.
E	modulus of elasticity, psi
$E()$	area under the load-displacement curve of a compact tension specimen up to point (), in.-lb
$f(\frac{a}{W})$	shape factor for compact tension specimens (see Ref. 9), dimensionless
G_{Ic}	critical value of the elastic strain energy release rate, in.-lb/in. ²
J_{Ic}	critical value of the J-integral for fracture (see Ref. 18), in.-lb/in. ²
K_{Ic}	static linear elastic fracture toughness (see Ref. 9), psi $\sqrt{\text{in.}}$
K_{Icd}	lower bound static linear elastic fracture toughness obtained from a compact tension specimen of thickness d , psi $\sqrt{\text{in.}}$
K_Q	potential static linear elastic fracture toughness (see Ref. 9), psi $\sqrt{\text{in.}}$
P_Q	general symbol for load used in calculating K_Q or K_{Ic} (see Ref. 9), lb
P_{Qi}	load arbitrarily chosen on linear portion of load-displacement curve of a compact tension specimen; in particular, P_{Q1} represents $1/b^2$ times the fracture load P_Q for a hypothetical specimen of thickness bd , lb

*This nomenclature applies specifically to this report; several of the terms listed below have definitions applicable to other than compact tension specimens.

$r_{p,d}$	ratio of corresponding dimensions of two geometrically similar compact tension specimens of thicknesses p and d ; numerically it is p/d , dimensionless
$s_{d,p}$	volumetric energy ratio between a specimen of thickness d and a geometrically similar specimen of thickness p ; that is, the normalized energy to maximum load for the specimen of thickness d divided by the normalized energy to maximum load for the specimen of thickness p , dimensionless
W	general symbol for width of a compact tension specimen (see Ref. 9), in.
W_d	width of a compact tension specimen of thickness d , in.
ν	Poisson's ratio, dimensionless

PERTINENT DEFINITIONS

Fracture toughness (K_{Ic}): critical stress intensity factor which is the unique property of a material that governs its brittle fracture behavior; it varies only as a function of temperature (see Refs. 8 and 9).

Lower bound fracture toughness: a number numerically less than or equal to the fracture toughness K_{Ic} of the exact material for which the lower bound value is determined.

Normalization: a procedure for comparing the load response behavior of geometrically similar specimens; corresponding energies are compared by dividing each particular energy quantity of a specimen by the third power of any particular dimension; corresponding loads are compared by dividing each particular load quantity of a specimen by the square of any particular dimension; corresponding displacements are compared by dividing each particular displacement quantity of a specimen by any particular dimension; such comparisons are said to utilize the principles of dimensional analysis.

Volumetric energy ratio: see definition of $s_{d,p}$ given above.

A PROCEDURE FOR DETERMINING BOUNDING VALUES ON FRACTURE TOUGHNESS K_{Ic} AT ANY TEMPERATURE

F. J. Witt and T. R. Mager¹

ABSTRACT

With the increasing need to insure quantitative margins of safety in structures which might contain flaws, it is becoming necessary to demonstrate more than just that fracture toughness K_{Ic} is high or unobtainable because of insufficient thickness of the particular product forms of interest for determining K_{Ic} . This problem comes particularly to the fore when attempting to determine K_{Ic} for irradiated water reactor pressure vessel steels such as ASTM A 533, grade B, class 1 plate steel. Here the problems of reactor space, fluence gradients, gamma heating and economics for large fracture toughness specimens tend to limit the size of specimens, to limit the number of such specimens which can be irradiated and to confound the final results.

In this report a method using compact tension specimens is proposed for determining upper and lower bounds on the fracture toughness of a material at any temperature of interest. First, the existence of K_{Ic} at all temperatures is explored. Using the equivalent energy approach to fracture the formulation of the bounding value equations is set forth and discussed. Lastly, bounds on K_{Ic} for ASTM A 533, grade B, class 1 steel are presented from temperatures above which valid K_{Ic} 's cannot be determined to 550°F.

INTRODUCTION

Quantitative methods of fracture prediction of flawed structures have become major items of research within the past few years. Much of this emphasis has come about because of the urgent need to assure quantitative and adequate margins of safety in the large thick primary containment

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pressure vessels of the nuclear central power stations which are becoming quite numerous throughout the United States. Almost all of the pressure vessels of interest are fabricated from ASTM A 533, grade B, class 1 steel plate and/or the equivalent forging grade steel ASTM A 508, class 2.¹ Typical wall thicknesses of such vessels are between 6 and 12 in.

The two nuclear power systems commercially accepted throughout the United States and, in more general terms, throughout the world are the boiling water reactor system (BWR) and the pressurized water reactor system (PWR). Of these two systems, the pressure vessels of the PWR systems are generally conceded to receive a considerable amount of fast neutron bombardment during service life such that significant irradiation embrittlement occurs in the core belt line of the vessel. Thus for the PWR systems, at least we have the added problems of assessing margins of safety when the parameter of irradiation has been added.

The test results presented and discussed in this report are limited to compact specimens of the ASTM A 533, grade B, class 1 plate steel, longitudinal orientation only. Although data are available or are being obtained on other materials, it is this plate steel which has been by far the more extensively investigated. The other investigations completed or in progress support the conclusions reached in this paper.

Linear elastic fracture mechanics is the most universally accepted method of fracture calculation by quantitative means; however, as shown by Shabbits, Pryle and Wessel², the static fracture toughness K_{Ic} of the ASTM A 533, grade B, class 1 steel is obtainable only up to about 50°F even when using specimens as thick as 12 in. oriented in the longitudinal direction. Shabbits³ and Crosley and Ripling⁴ have demonstrated that under dynamic and arrest conditions fracture toughness values can be measured at temperatures over 100°F. Nevertheless, it has become infeasible if not impossible to measure directly toughness levels in the range of temperatures most pertinent to reactor pressure vessel service life (that is, temperatures from 200 to 550°F). Thus, while high loads and/or large flaw sizes are considered to be the necessary conditions to promote fractures at temperatures of interest, the margins of safety either in load or strain most often cannot be obtained by linear elastic fracture mechanics methods in a quantitative manner. While irradiation

lowers the fracture toughness, current data indicate that here too the fracture toughness becomes quite high at reasonably low temperatures (say 200°F) and high fluence levels (say 5×10^{19} n/cm², E > 1 MeV, irradiated at 550°F).⁵ Thus, the same dilemma of establishing realistic quantitative safety margins exist as before but perhaps to a lesser degree.

The problem of irradiation is a particular challenge since it has already been demonstrated by Mager⁵ that, for the irradiated conditions of interest, specimens with thicknesses of 4 in. or greater must be tested to attain a fracture toughness K_{Ic} of 100,000 psi $\sqrt{\text{in.}}$. Here then we face a different problem than for the unirradiated plate where we could test specimens in full plate thickness. The problems of reactor space, fluence gradients, gamma heating and economics for irradiating specimens 4 in. thick or greater tend to limit the number of such specimens which can be irradiated and tested as well as confound the degree of quantification of the results. Thus, we see an urgent need to develop a method to determine, if not the fracture toughness exactly, at least quantitative bounding values for the fracture toughness.

The basis for the method described in this paper is the equivalent energy concept as set forth by Witt.⁶ This concept has proven fairly successful for predicting the general elastic-plastic fracture behavior of specimens (structures) fabricated from the ASTM A 533, grade B, class 1 steel.

One of the parameters discussed in Ref. 6 is the quantity identified as K_{Icd} (see Ref. 7 for an extensive discussion of this quantity). It is the intent of this paper to explore further the significance of this measurement as related to fracture toughness K_{Ic} . Data will be presented which lend support to the existence of K_{Ic} at all temperatures of interest to reactor pressure vessels and procedures will be presented for calculating upper and lower bound values for such K_{Ic} 's at any temperature. Using data from compact tension specimens of various thicknesses, upper and lower bounds on K_{Ic} are calculated at temperatures up to 550°F.

THE EXISTENCE OF K_{Ic}

A question pertinent to this paper is "Does K_{Ic} exist at all temperatures of interest for the pressure vessel steels?" Since K_{Ic} is a material constant,⁸ establishing the existence of such a quantity is quite apart from determining its value. From the discussion presented below we shall conclude that K_{Ic} does indeed exist at all temperatures.

First, let us recall that Shabbits, Pryle and Wessel² obtained K_{Ic} values at 50°F for the ASTM A 533, grade B, class 1 steel in the longitudinal direction by testing 10-in.-thick (10 T) specimens. Almost valid data were obtained at 75°F. However, specimens 1/2-, 1-, 2-, 4- and 6-in.-thick have also been tested at these temperatures. A plot of the load-deflection curves of these specimens up to maximum load normalized to a 1 T specimen is shown in Fig. 1. Here normalized means using the principles of dimensional analysis to compare the load response curves of geometrically similar structures. Thus each specimen's behavior is compared to a particular size specimen. Normalized crack depths for each specimen are given so as to account for slight discrepancies observed in the curves. Some of the discrepancies are also due probably to slight material differences, to testing procedures, and to the gage lengths of the measured displacements. We may conclude that each specimen obeyed the laws of geometric similitude up to maximum load for that particular specimen. We also note that as thickness increased the specimens reached a lower maximum load and indeed for the specimen 10 in. thick tested at 50°F, a K_{Ic} was obtained. Thus it would appear that thickness alone has accounted for the possibility of obtaining K_{Ic} at 50°F.

We shall now introduce the concept of volumetric energy ratio as discussed in Ref. 6. The volumetric energy ratio is simply the normalized energy (area under the normalized load-deflection curve, see Fig. 1) of one specimen tested to maximum load divided by the corresponding normalized energy of another geometrically similar specimen tested to maximum load. For example, in Fig. 1 the volumetric energy ratio between the 1 T specimen tested at 50°F and the 6 T specimen tested at 50°F is the area under the curve for the 1 T specimen up to maximum load divided by the corresponding area for the 6 T specimen. It is to be noted that the

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Fig. 1. Normalized Load-Deflection Curves to Maximum Load for a Series of Compact Tension Specimens Tested at 50°F and 75°F (only for the 1/2 T specimen was a correction made for the displacement gage length).

areas compared are normalized areas with dimensions of energy per unit volume. For compact tension specimens the front face load-displacement curve as specified in Ref. 9 will be used as a basis for comparison (in particular, each curve in Fig. 1, before normalization, was such a curve). In terms of geometric similitude, then, if two geometrically similar specimens behave in a similar manner up to the same maximum load, the volumetric energy ratio is unity.

In Fig. 1 then we see that, at a given temperature, as thickness increases the volumetric energy ratio obtained by normalizing the load-displacement curves to a 1 T specimen increases. That is to say, the specimen behavior diverged with increasing thickness from a volumetric energy ratio of unity; so much so that in fact at 50°F the fracture toughness K_{Ic} was obtained.

We now pose the question "Is the behavior exhibited at 50°F and 75°F typical at all temperatures up to 550°F say?" In Fig. 2 normalized load-deflection curves are shown for the compact tension specimens in thicknesses from 1 to 9 in., tested at 200°F and 550°F. Here we note a behavior similar to that shown in Fig. 1. Thus there is a trend that suggests the conclusion that if one had been able to obtain and test a very thick specimen (say 100 in. thick or greater) at these temperatures of exactly the same material, then a fracture toughness K_{Ic} might have been determined.

Observations similar to those noted in Figs. 1 and 2 have been previously made. Loss^{10,11} noted a divergence from geometric similitude as thickness increases. Witt and Berggren^{12,13} agree with Loss in that the behavior in terms of energy diverges from geometric similitude as thickness increases. Finally Begley and Toolin¹⁴ have reported upper shelf fracture toughness for a higher strength forging grade steel using specimens 8 in. thick.

The question of crack extension prior to maximum load may be raised. If such crack growth occurred it would tend to discount to a degree the application of the laws of similitude at maximum load. However, for the monotonically increasing loads as applied in the testing of compact tension specimens, the engineers performing the tests are reported to have observed no such growth prior to maximum load on any specimens tested.

Fig. 2. Normalized Load-Deflection Curves for 1 T (1-in.-thick), 6 T and 9 T Compact Tension Specimens Tested at 200°F and 550°F (ASTM A 533, Grade B, Class 1 Steel, HSST Plate 03, longitudinal orientation).

In summary let us consider further the behavior depicted in Fig. 2. If the decrease in load as a function of thickness approaches a limit, then as this limit is approached two geometrically similar specimens would approach geometrically similar behavior in energy-absorbing capacity. This behavior is incongruous with the behaviors discussed by Loss^{10,11} and Witt and Berggren.^{12,13} We conclude then that the specimens as a function of increasing thickness will never behave, even in the limit, in a geometrically similar manner.

On the basis of the above discussion, it would appear to follow that frangible behavior satisfying the condition for calculating K_{Ic} will eventually occur as thickness increases.

On the basis of this discussion, we conclude that K_{Ic} exists for the ASTM A 533, grade B, class 1 steel (even though possibly not obtainable) at all temperatures of interest, in particular up to the operating temperatures of water reactor pressure vessels.

THE FRACTURE TOUGHNESS PARAMETER K_{Icd}

In Ref. 6, a fracture toughness parameter K_{Icd} is defined. Further, Witt and Mager⁷ have presented such values obtained from 1 T compact tension specimens up to 550°F. We shall review the manner in which this parameter is calculated and its relationship to fracture toughness K_{Ic} .

First, let us assume a compact tension specimen of thickness d , width W_d and crack length a_d , has been tested at some temperature which does not product K_{Ic} . Let us take the curve in Fig. 3 as an example. Here we have the load displacement curve obtained from a longitudinally oriented 1 T compact tension specimen (nonsurface material) of ASTM A 533, grade B, class 1 steel tested at 250°F. For this discussion, however, the specifics of the test conditions and specimen size (referred to as having thickness d in the following discussion) are immaterial. In Fig. 3, the maximum load was obtained at Point A. We now ask how many times thicker than the thickness d of the specimen tested would a specimen have to be to reach maximum load at Point D on the linear portion of the curve. It is not at this time obvious that K_{Ic} would be found for the specimen failing at Point D. (Later we shall see that for calculating K_{Icd} it is immaterial where Point D is selected as long as it is

Fig. 3. Load-Displacement Curve of a 1 T Compact Tension Specimen Tested at 250°F (Ref. 7).

on the linear portion of the curve.) If we knew how thick the specimen would have to be to fail at Point D then we could calculate K_Q and check to see if it were K_{Ic} as outlined in Ref. 9. Since we do not know the thickness, then we use the one quantity we do know, the volumetric energy ratio between the specimen which would reach maximum load at Point D and the specimen tested with maximum load at Point A. This number is simply the area under the curve to Point A divided by the area under the curve to Point D. Let us call this ratio b . We now calculate K_{Icd} by simply calculating K_Q for a specimen of thickness bd which is assumed to fail at Point D at a load of P_{Q1} normalized to the specimen of thickness d . From Ref. 9

$$K_Q = \frac{P_Q f\left(\frac{a}{W}\right)}{B \sqrt{W}} \quad (1)$$

where P_Q is the load on the specimen at fracture, a is the crack length, W is the width and B is the thickness. For the case at hand then $P_Q = P_{Q1} \cdot b^2$, $B = bd$, $a = ba_d$, and $W = bW_d$. Thus,

$$K_{Icd} = \frac{P_{Q1} \sqrt{b} f\left(\frac{a_d}{W_d}\right)}{d \sqrt{W_d}} \quad (2)$$

We now ask how K_{Icd} calculated by Eq. (2) differs from K_{Ic} . First, let us see if the selection of Point D has affected the calculation. We shall use the notation $E(\)$ to indicate the area under the curve up to Point () (for example, E_D is the area under the curve up to Point D). In Fig. 3 we now select Point F other than Point D, on the linear portion of the curve which gives a load of P_{Q2} . Let us define $E_A/E_F = e$ (note that $E_A/E_D = b$). Using Point F to calculate K_{Icd} we have

$$K_{Icd} = \frac{P_{Q2} \sqrt{e} f\left(\frac{a_d}{W_d}\right)}{d \sqrt{W_d}} \quad (3)$$

However, $E_D/E_F = E_D/E_A \cdot E_A/E_F = e/b$ and from similar triangles, $E_D/E_F = (P_{Q1}/P_{Q2})^2$. Thus, $P_{Q1} \sqrt{b} = P_{Q2} \sqrt{e}$ and Eqs. (2) and (3) are identical.

Hence we see we can choose any point on the linear portion of the curve and obtain the same value for K_{Icd} .

We now note that both $P_{Q1} \sqrt{b}$ and $P_{Q2} \sqrt{e}$ are simply the load obtained by extending the linear portion of the load-deflection curve until it encompasses an area equal to the area under the actual load-deflection curve at maximum load.

We shall now derive the relationship between K_{Icd} and K_{Ic} . In Fig. 3 let us assume that a specimen of thickness t would fail at Point D and give K_{Ic} . In this case the specimen is t/d times thicker than the specimen of thickness d which was tested; in particular, the load P_{Q1} must be multiplied by $(t/d)^2$ to give P_Q , etc. Thus,

$$K_{Ic} = \frac{P_{Q1} \cdot \sqrt{\frac{t}{d}} f\left(\frac{a_d}{W_d}\right)}{d \sqrt{W_d}} \quad (4)$$

We note that Eq. (4) differs from Eq. (2) by the factor $\sqrt{\frac{t/d}{b}}$. Now t/d is the ratio of the dimensions and b is the volumetric energy ratio between the specimens (that is, $b = E_A/E_D$). Thus we have

$$K_{Ic} = K_{Icd} \sqrt{\frac{\text{ratio of dimensions}}{\text{volumetric energy ratio}}} \quad (5)$$

where the thicker specimen gives K_{Ic} . For the case where K_{Ic} is unobtainable, perhaps due to restrictions on thickness, we can obtain K_{Icd} from a smaller specimen which can be tested and observe how the ratio under the radical in Eq. (5) varies.

While we have focused our attention on how K_{Ic} is related to K_{Icd} , it is perhaps well to generalize Eq. (5) by noting that for a specimen of thickness p (see Ref. 6)

$$K_{Icp} = K_{Icd} \cdot \sqrt{\frac{r_{p,d}}{s_{d,p}}} \quad (6)$$

where $r_{p,d}$ is the ratio of dimensions, p/d , and $s_{d,p}$ is the volumetric energy ratio between the specimen of thickness d and the one of thickness p . (Note: These double subscripted quantities are ratios: the first

subscript denoted the numerator quantity, the second, the denominator quantity.)

Series of compact tension specimens were tested at temperatures up to 550°F with thicknesses of from 1 in. (1 T) to 9 in. (9 T). The specimens considered here were longitudinally oriented and machined from the inner 9 in. of a 12 in. quenched and tempered plate of ASTM A 533, grade B, class 1 plate identified as HSST Plate 03.¹⁵ A summary of results from these tests is given in Table 1. Considerably more data on 1 T specimens from a similar plate (HSST Plate 02) are reported in Ref. 7.

In Fig. 4 we see plotted the volumetric energy ratios versus thickness as a function of temperature for the data given in Table 1 together with the results from tests made at 50°F and 75°F as shown in Fig. 1. Some data from 1/2 T specimens are also plotted (see Refs. 16 and 17). It may be noted in Fig. 4 that for 100°F and above and at a given temperature, the volumetric energy ratios from smaller to larger specimens have always been less than the ratios of the dimension. The exceptions have been in the cases where the volumetric energy ratios were about equal to the ratios of the dimensions, such as we have at 50°F and 75°F in Fig. 4. Here, however, the variations are well within the variational range generally observed for K_{Ic} .² Thus, we conclude in general that

$$\frac{r_{p,d}}{s_{d,p}} \geq 1 \quad (7)$$

with the following exception. For reasons discussed in Refs. 12 and 13 we can hypothesize that there may be a lower limit on d somewhere between 0.25 and 0.5 in. Thus above this limit we may now claim that in general

$$K_{Ic} \geq K_{Icd} \quad (8)$$

Assuming the data shown in Fig. 4 for 100°F and above are typical of the general behavior for the steel being investigated we note that a straight line connecting the points for any two thicknesses falls generally on the point for a still greater thickness. Based on the discussion

Table 1. Summary of the K_{Icd} and Volumetric Energy Ratio
Results for ASTM A 533, Grade B, Class 1 Steel
(HSST Plate 03, longitudinal orientation)

Test Temperature (°F)	K_{Ic1} ksi $\sqrt{\text{in.}}$	K_{Ic6} ksi $\sqrt{\text{in.}}$	$s_{1,6}^{b,c}$	K_{Ic9} ksi $\sqrt{\text{in.}}$	$s_{1,9}^{b,c}$
100	202	232	4.6		
130	312 ^a	374	4.15		
200	246, 254	408	2.24	447	2.81
550	196, 212	362	1.91	394	2.41

^aThis value was the one obtained at 125°F from Ref. 7.

^bThe average of the K_{Ic1} values, where more than one was obtained, was used in the calculation.

^cThese values were obtained from the K_{Icd} data using Eq. (6).

Fig. 4. Variations of Volumetric Energy Ratios as a Function of Thickness at Different Temperatures Normalized to a Value of 1 for a 1 T Specimen.

of the previous section, we would actually expect the straight line determined by two thicknesses to fall below the point for a still greater thickness. If this is the case, we conclude that the linear extension of a line connecting the points for any two thicknesses will always produce a result which is nonconservative; that is, the linear extension gives a tougher behavior than actually observed for thicker specimens. Sufficient data is not available however to demonstrate clearly this behavior. In particular, the 9 T specimens were slightly tougher than might be projected. However, the 9 T specimens contained material within 1 1/2 in. of the original plate surface which is generally accepted to be a little superior to center plate material.

If the above noted behavior is correct, we select point $(t, s_{d,t})$ on the linear extension for the line connecting two data points at a given temperature from Fig. 4. Hence the $\lim_{t \rightarrow \infty} r_{t,d}/s_{d,t}$ when substituted into Eq. (5) will always give an upper bound on K_{Ic} regardless of what thickness is required to obtain K_{Ic} , that is

$$K_{Ic} \leq K_{Icd} \lim_{t \rightarrow \infty} \sqrt{\frac{r_{t,d}}{s_{d,t}}} \quad (9)$$

If two geometrically similar compact tension specimens then are tested at the same temperature with d the thickness of the smaller and p the thickness of the larger, and with a volumetric energy ratio of $s_{d,p}$, we can determine the limit in Eq. (9) directly. By normalizing the data to the specimen of thickness d we have

$$\lim_{t \rightarrow \infty} \sqrt{\frac{r_{t,d}}{s_{d,t}}} = \sqrt{\frac{(p-d)}{d(s_{d,p}-1)}} \quad (10)$$

and Eq. (9) becomes

$$K_{Ic} \leq K_{Icd} \sqrt{\frac{p-d}{d(s_{d,p}-1)}} \quad (11)$$

For $d = 1$

$$K_{Ic} \leq K_{Ic1} \sqrt{\frac{p-1}{s_{1,p}-1}} \quad (12)$$

In summary

$$K_{Icp} \leq K_{Ic} \leq K_{Icd} \sqrt{\frac{p-d}{d(s_{d,p}-1)}} , \quad p > d \quad (13)$$

where p and d are thicknesses of geometrically similar compact tension specimens. We may now note that if the linear behavior exhibited in Fig. 4 is general, then the upper bound is indeed really K_{Ic} .

Using K_{Icd} as a lower bound for K_{Ic} is equivalent to assuming the specimen from which the number was obtained exhibits frangible behavior. Under this assumption the slope of the line becomes $s_{1,d}/d$ for greater thickness and goes through (0,0). Note in Fig. 4, that at 100°F and above, the point for a greater thickness always lies below the linear extension of a line through (0,0) and the point for any lesser thickness.

We now ask why calculate K_{Icd} as a lower limit, why not just take K_Q (see Ref. 9) as obtained perhaps from the load at deviation from linearity, or the secant offset load or the ultimate load. There are several reasons for using K_{Icd} . First, as shown by Witt and Mager⁷ we establish a much higher lower bound in the transitional and tough regimes than obtained by using the loads suggested above. Secondly, if one knows with confidence the volumetric energy ratio for the condition of interest, perhaps obtained from other types of specimens, then only a single specimen needs to be tested. It is also perhaps well to note that the K_{Icd} values obtained from compact tension specimens, used in conjunction with the pertinent volumetric energy ratios, have potential applications in rather general equivalent energy fracture calculations.⁶

Looking further at Eq. (7), we note that for the equality, one of the conditions for frangible behavior for two geometrically similar specimens has been met. Indeed the equality has not been observed for other than frangible or near frangible behaviors. (Note: As seen in Fig. 4,

the equality is rather closely approximated by all the specimens for thicknesses greater than 1 in. tested at 50°F and 75°F.) One now asks if a situation could exist such that

$$\frac{r_{p,d}}{s_{d,p}} \leq 1 \quad (14)$$

with the equality holding for frangible behavior. The inequality would hold, if at all, then for transitional and tough behavior. In this case we find the bounding procedure reversed. That is, referring to Eq. (13)

$$K_{Icd} \sqrt{\frac{p-d}{d(s_{d,p}-1)}} \leq K_{Ic} \leq K_{Icp}, \quad p < d \quad (15)$$

For the various specimens of ASTM A 533, grade B, class 1 steel tested to date no such behavior as expressed by Eq. (14) has been exhibited except for the equality.

The existence of a material behaving as suggested by Eq. (14) is being further explored and some careful tests will be run on other materials. The bounding methods discussed in this report will be much more meaningful and useful if Eq. (14) holds only for the equality (frangible behavior).

GENERAL BEHAVIOR OF K_{Icd}

A considerable number of compact tension specimens have been tested in thickness from 1/2 in. to 9 in. (see Table 1 and Refs. 2, 7, 16 and 17). These data, although not from the same plate, are summarized in Fig. 5. It may be observed that up to 50°F all the data fall within the same general scatter band. Above this temperature the data from the smaller specimens begin to deviate below the data from the larger specimens. This general behavior is neither surprising nor unexpected. In Fig. 6 we have plotted K_{Icd}^2/E in units of ft-lb/in.² versus temperature where E is the elastic modulus. The behavior is quite similar to the behavior exhibited in the dynamic tear tests data as discussed by Loss

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Fig. 5. Variation of K_{Icd} as a Function of Temperature and Thickness.

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Fig. 6. Energy Release Rate as a Function of Thickness and Temperature.

when plotted using the same dimensions based on total energy to fracture.^{10,11} The energy density, however, for the compact tension specimens to maximum load is about 1/8 of that for the dynamic tear specimens in the same thickness and at the higher temperatures.

BOUNDS ON K_{Ic} AND G_{Ic} UP TO 550°F

We shall now use the data in Table 1 to calculate the upper bounds on K_{Ic} up to 550°F. The lower bounds are, of course, the K_{Icd} for the largest specimen tested.

Using results from 1 T and 9 T specimens, we shall first present an example calculation for the upper bound on K_{Ic} at 200°F. From a 1 T specimen, the average K_{Ic1} is 250,000 psi $\sqrt{\text{in.}}$ while for the 9 T, $K_{Ic9} = 447,000$ psi $\sqrt{\text{in.}}$ The energy ratio $s_{1,9}$ is 2.81. Using Eq. (13), we have

$$447,000 \leq K_{Ic} \leq 250,000 \cdot \sqrt{\frac{9-1}{2.81-1}} = 525,000 \quad .$$

Thus, K_{Ic} is bracketed between 447,000 and 525,000 psi $\sqrt{\text{in.}}$

Using the same procedure as above, we also have obtained the bounds on K_{Ic} at 100°F, 130°F and 550°F. These results are given in Table 2. The upper bound has been calculated using all combinations of the available data. The upper bound is seen to be defined within $\pm 6\%$ in all cases.

The complete curve for K_{Ic} as measured by Shabbits, Pryle and Wessel² and as extended in this report up to 550°F is shown in Fig. 7. It is perhaps significant to note that the ratio of the lower bound (K_{Ic9}) values at 200°F and 550°F is only 1.13 as compared to a factor of almost 1.5 as obtained from 1 T specimens (see Ref. 7).

It is also interesting to note that at both 200°F and 550°F a specimen well over 100 in. thick would be required to obtain a valid K_{Ic} . Also, as may be observed in Fig. 4, we see that as temperatures increase the volumetric energy ratios at a given temperature when compared to a lower temperature decrease, indicating an improvement in relative fracture behavior with temperature. Counteracting this behavior is a decrease in K_{Icd} at the higher temperature from a maximum value.

Table 2. Upper and Lower Bounds on K_{Ic} from 100°F to 550°F for ASTM A 533, Grade B, Class 1 Steel (HSST Plate 03, longitudinal orientation)

Test Temperature (°F)	Lower Bound	Upper Bound
100	232 (6T) ^a	238 (1T-6T) ^b
130	374 (6T)	393 (1T-6T)
200	447 (9T)	500 (1T-6T), 525 (1T-9T), 560 (6T-9T)
550	394 (9T)	480 (1T-6T), 485 (1T-9T), 490 (6T-9T)

^aIndicates thickness from which the lower bound value was obtained.

^bIndicates thickness for defining d and p ; see Eq. (11).

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Fig. 7. Upper and Lower Bounds on K_{Ic} for ASTM A 533, Grade B, Class 1 Steel (HSST Plate 02 to 75°F , HSST Plate 03 from 100°F to 55°F , longitudinal orientation).

If we define

$$G_{Ic} = \frac{(1 - \nu^2) K_{Ic}^2}{E} \quad (16)$$

where G_{Ic} is the strain energy release rate for frangible behavior, ν is Poisson's ratio and E is the elastic modulus, then we may obtain upper and lower bounds on G_{Ic} . Such a plot obtained from Fig. 7 is shown in Fig. 8. Since $G_{Ic} = J_{Ic}$, the value of the J-integral¹⁸ for frangible behavior, then the data in Fig. 8 are also the bound for J_{Ic} .

SUMMARY

Since the prevention of frangible fracture of in-service reactor pressure vessels is a necessity, the need to obtain fracture toughness K_{Ic} throughout the operating temperature range of nuclear reactors, especially for irradiated conditions, is readily apparent. This report has been written in response to this need.

The existence of K_{Ic} is discussed. Data are presented which suggest that if compact tension specimens of sufficient thicknesses could be tested then the fracture toughness K_{Ic} could be obtained. Since specimens in such thicknesses often cannot be obtained, a procedure for finding upper and lower bound values on K_{Ic} from testing smaller specimens is suggested. The procedure applies the equivalent energy concept using the fracture toughness parameter K_{Icd} . In particular, it is shown that K_{Ic} is equal to K_{Icd} times the square root of the ratio of dimensions divided by the volumetric energy ratio. By characterizing the pertinent ratio it is shown that both an upper bound and a lower bound on K_{Ic} can be obtained by testing two geometrically similar but different thickness compact tension specimens. Unfortunately, specimens, even though tested in thicknesses up to 9 in., have not been tested in thicknesses sufficient to show that K_{Ic} is substantially less than the upper bound value.

The applicability of the lower bound fracture toughness to linear elastic fracture mechanics calculations must be understood. For instance, the lower bound value calculated from a small specimen may be a factor of

Fig. 8. Upper and Lower Bounds on G_{IC} (J_{IC}) for ASTM A 533, Grade B, Class 1 Steel (HSST Plate 02 to 75°F, HSST Plate 03 from 100°F to 550°F, longitudinal orientation).

two or three less than K_{Ic} . However, if the use of a lower bound toughness yields a conclusion that frangible fracture cannot occur, then surely it will not occur. On the other hand, if the lower bound value indicates fracture can occur, then the result is inconclusive that actual fracture will occur depending on the proximity of the lower bound value to K_{Ic} .

Upper and lower bounds on K_{Ic} (as well as for G_{Ic} and J_{Ic}) for unirradiated ASTM A 533, grade B, class 1 plate, longitudinal orientation, are calculated at 100°F, 130°F, 200°F and 550°F. These results confirm that large flaws and over design loading conditions are necessary to cause fracture to occur in the operating temperature range of nuclear reactors (200°F to 550°F). This conclusion lends further support to similar conclusions based on less quantitative data. A decrease in toughness with temperature, once the maximum value is reached, is confirmed; however, the toughness still remains very high up to 550°F.

It is to be noted that the results and conclusions reported here have been obtained from compact tension specimens and one product form. However, the method set forth for determining bounds on K_{Ic} has been or is currently being investigated for other materials and by other laboratories. The results of compact tension specimen tests from these investigations support the conclusions reached in this report.

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