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Analysis of Radiation-Induced Embrittlement Gradients on Fracture Characteristics of Thick-Walled Pressure Vessel Steels

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13. ABSTRACT

The fracture behavior of thick-walled nuclear vessels is considered for the case of a radiation-induced toughness gradient through the wall which characteristically results from neutron attenuation by the wall material itself. Fracture-safe design analyses based on linear elastic formulations or extrapolations of these formulations to the elastic-plastic regime are not sufficiently developed to characterize the integrated behavior of a wall whose toughness can range from brittle at the inner surface to highly ductile at the outer surface. Solutions to the problem in the foreseeable future will be obtained only by experimental means. The present approach uses the Fracture Analysis Diagram (FAD) together with a new interpretative method for fracture extension resistance based on modified dynamic tear specimens as the tools for gradient assessments. With these techniques the significance of the toughness gradient through the wall is assessed in terms of thick section mechanical constraint, and fracture characteristic of the complete wall are predicted.

Characterization of a hypothetical 8-in. vessel wall is based on measured through-thickness fluence levels; this behavior is correlated with fracture toughness degradation for steels of varying sensitivity to irradiation using the FAD. This analysis indicates that major portions of the vessel wall remain above the FTE temperature, which dictates yield stress loading requirements for fracture, when the wall temperature is maintained at the limiting value, NDT + 60°F, for the inside surface as suggested by current AEC criteria.

Fracture extension resistance measurements based on data from a 3-in.-thick plate having a metallurgically induced toughness gradient suggest that nuclear vessels with analogous gradients will not fracture in an unstable fashion and will not generate missiles capable of breaching the containment system. Additional research is necessary to fully develop the approach for application to the individual reactor vessel.

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PROBLEM STATUS

This is an interim report on one phase of the problem; work on other phases is continuing.

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ANALYSIS OF RADIATION-INDUCED EMBRITTLEMENT GRADIENTS ON FRACTURE CHARACTERISTICS OF THICK-WALLED PRESSURE VESSEL STEELS

INTRODUCTION

For thick-walled reactor pressure vessels the neutron flux emanating from the fuel core is attenuated appreciably in passing through the vessel thickness and results in decreasing levels of embrittlement toward the outer surface. Subsequently, the wall develops a gradient in toughness with the poorest properties exhibited at the inside surface. Material comprising the outside surface of the vessel wall, away from the core, may retain its preirradiation toughness characteristics, depending on the fluence level and the radiation embrittlement sensitivity of the particular steel. The resultant fracture behavior of the vessel, as a unit, is governed by the composite of toughness levels.

It is of great importance to determine if a nuclear vessel having a toughness gradient can fracture in an unstable fashion, and principally if missile generation capable of breaching the containment system is highly probable. Commercial nuclear pressure vessel steels as a whole exhibit ductile behavior even after moderate amounts of irradiation. Because of this, linear elastic fracture mechanics (LEFM) methods for frangible materials are of little use in the analysis of the fracture behavior. This is especially true of a vessel gradient case where a popin may originate at the inside wall surface if the fluence is very high. LEFM treats conditions for fracture initiation only (e.g., popin). The fact that a popin, per se, exists does not imply extensive crack propagation. In other words, it cannot be assumed that popin and complete rupture are synonymous as is implied by plane strain fracture toughness (K_{Ic}) testing of frangible materials.

An analytical analysis of the fracture behavior of ductile material involving significant amounts of plasticity does not exist and furthermore there are no indications that it will be developed in the immediate future. Near-term solutions to the problem thus must be evolved through empirical methods relying on laboratory tests and correlations.

Consistent with the above projections, this report examines the nature of fluence attenuation in thick-walled reactor vessels as determined from recent experimental evidence and translates this attenuation into notch ductility gradients reflecting individual steel sensitivity to radiation-induced embrittlement. The significance of the toughness gradient is assessed in terms of thick section mechanical constraint and the fracture characteristics of the complete wall using Dynamic Tear (DT) test energy and the Fracture Analysis Diagram (FAD). A new method of defining fracture extension resistance R for nonfrangible metals, using DT specimens, is employed to characterize the case of a toughness gradient where the material is not all of uniformly high ductility.

REFERENCE FRACTURE CRITERIA AND NOTCH DUCTILITY RELATIONSHIPS

The FAD (1) for fracture-safe design, in Fig. 1, lends itself well as an analytical tool for investigation of the gradient case. The Fracture Transition Elastic (FTE) temperature and the drop weight nil-ductility transition (NDT) temperature are two primary

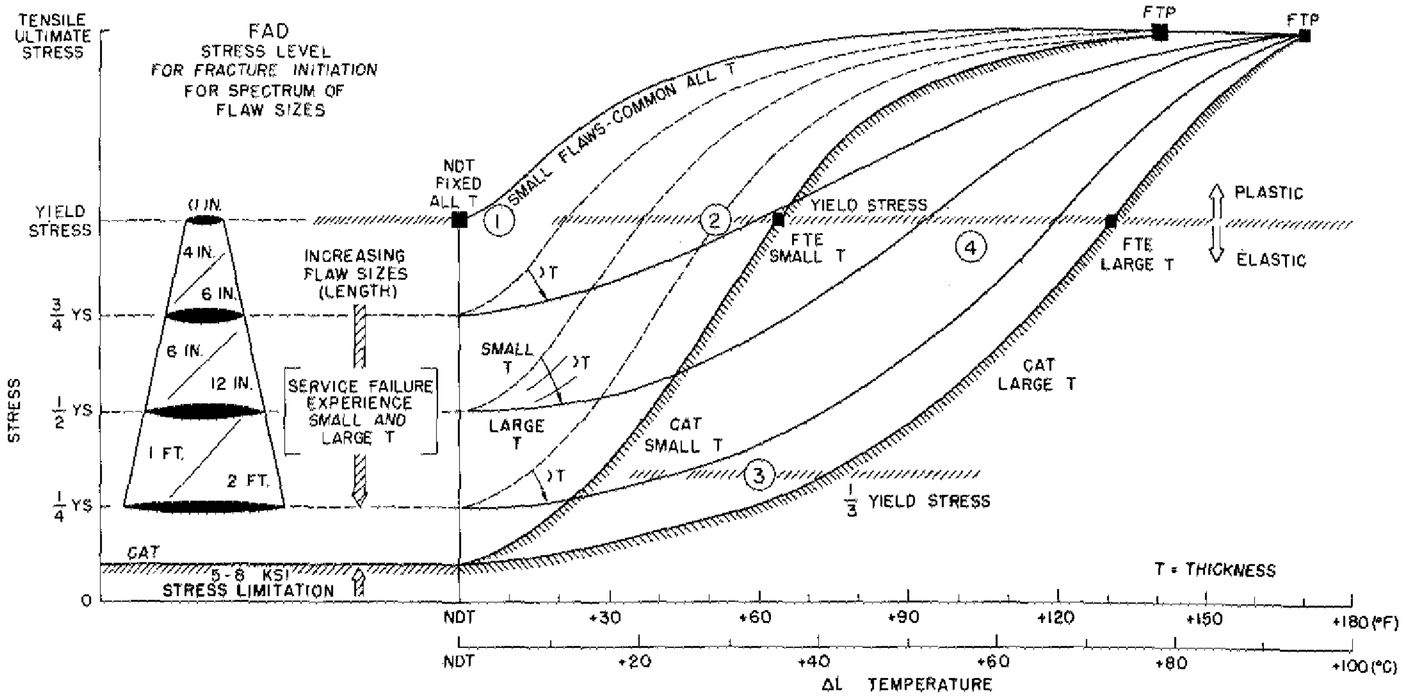

Fig. 1 - Fracture Analysis Diagram (FAD) for flaws residing in sections of small and large thickness (Ref. 1)

indexes of the FAD and they are used to index the crack arrest temperature (CAT) curves shown in the figure. The FTE is that tempeature above which stresses in excess of yield are required to propagate a "large" flaw. Nuclear reactor vessels, at present, are generally operated at temperatures in excess of NDT + 60°F, determined at the inside wall surface. This limiting condition defines the FTE temperature for relatively thin sections (≤3 in.) as derived from service failure correlations. For high shelf level* steels in general, the mid-energy range transition temperature defined experimentally by a given thickness DT test determines the FTE temperature for that section (2). In this context, recent NRL studies (3) on unirradiated A533-B steel have shown that the FTE temperature for thick sections (6 in. or more) is elevated on the order of 70°F (39°C) above that for thin sections by the thickness-induced mechanical constraint. Cognizance of this must be taken in applying FAD procedures to thick sections; a revised FAD illustrating the FTE for thick sections has been developed (2) in which the FTE is indexed as NDT + 130°F. All reference to the FTE temperature in this paper is to that FTE associated with the thickness being considered, namely thick sections. The NDT + 60°F temperature, therefore, will be called a reference temperature associated with existing criteria.

Throughout this discussion, it must be kept in mind that while irradiation serves to elevate the FTE temperature by varying amounts through the thickness, it also lowers the upper shelf energy level as determined by the Charpy-V (C_v) or DT tests. With high fluences, the shelf level can be lowered sufficiently to eliminate the benefits of operation above the FTE temperature. Operation above the FTE results in requirements of stresses in excess of yield only if the material is capable of exhibiting this level of toughness. (See Ref. 4 for a discussion of this subject). It is assumed for the ensuing analysis that the upper shelf energy for the irradiated material is sufficiently high to assure ductile behavior with operation above the FTE temperature.

Important to this study, indications of transition temperature increase (ΔT) with irradiation provided by C_v, drop weight NDT, and DT test methods for A302-B and A533-B steels are similar. For example, the C_v 30-ft-lb transition temperature increase has been shown to compare well with the increase in NDT temperature with irradiation (5). Separately, good agreement has been reported for C_v and DT mid-energy range transition increase with neutron exposure (4). On the basis of these observations, it is felt reasonable to project FTE temperature elevations from radiation effects data not only on DT transition behavior but also on C_v or NDT behavior with progressive radiation exposure.

Trends in C_v 30 ft-lb transition temperature increase with increasing fluence ($n/cm^2 > 1$ MeV) for the 550°F (288°C) exposure condition are illustrated in Fig. 2 for two A302-B steel plates from different commercial production melts that are considered in the gradient analysis. From comparisons with several production plates of nickel-modified A302-B steel (A533-B) (6), the ASTM A302-B reference plate is regarded as having average sensitivity to radiation embrittlement. The plate identified as the Yankee reactor vessel surveillance material is considered to have higher-than-average sensitivity to radiation effects. Minor differences in chemical composition between the plates are believed responsible for the observed differences in irradiation response. Residual copper and phosphorus, for example have been shown to have a particularly detrimental effect on irradiation response characteristics of the steels of interest (7, 8). Apparent radiation embrittlement sensitivity has a major bearing on the nature and significance of gradients in through-thickness properties, as shown below.

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*A high shelf level steel is one requiring gross plastic deformation in the vicinity of a crack to propagate a fracture.

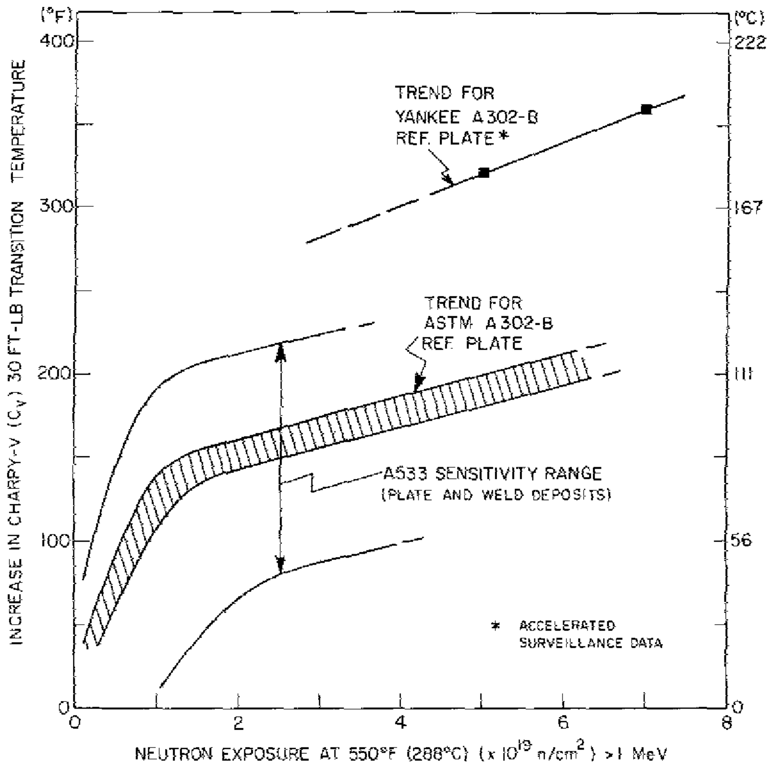

Fig. 2 - Increase in Charpy-V 30-ft-lb transition temperature with fission spectrum fluence at 550°F (288°C) for the 6-in. ASTM A302-B reference plate and the 8-1/8-in. Yankee reactor surveillance plate. A data band illustrating the degree of variability in radiation embrittlement sensitivity of A533 steel plate and weld metals is also shown.

NEUTRON FLUENCE ATTENUATION THROUGH A THICK VESSEL WALL

Neutron fluence attenuation through an 8-in.-thick steel vessel, expressed as a percentage of the inner wall neutron exposure ($n/cm^2 > 1$ MeV) is shown in Fig. 3 and defined by thickness position in Table 1. This idealized wall thickness gradient is adequate to represent both pressurized water and boiling water reactor vessels currently in service.

Through-wall fluence attenuation was derived from measurements in simulated pressure vessel wall radiation experiments and verified through reactor physics spectrum calculations (9). The vessel mock-up experiments (10, 11) provided for determination of both fluence attenuation and corresponding C_v 30 ft-lb transition temperature increase for individual thickness positions. Results, when compared against known trends in C_v transition temperature increase with fluence, showed close agreement. Thus, properties trends from conventional test reactor (or reactor vessel surveillance) experiments can be used with confidence to project through thickness embrittlement behavior. Reactor physics calculations supporting Fig. 3 were transport theory calculations of flux decrease through a thick steel wall. In addition to the pressure vessel wall experiments (10, 11) these calculations have been applied successfully to the Yankee reactor (12) and the Big Rock Point reactor (13) vessels.

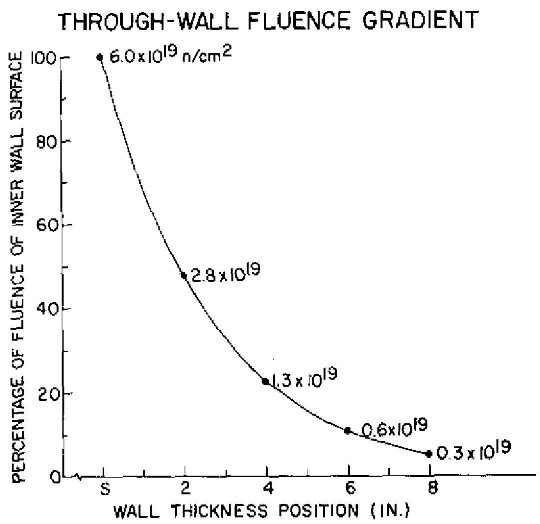

Fig. 3 - Fluence attenuation through an 8-in. pressure vessel wall expressed as a percentage of the fluence received by the inner wall surface nearest the fuel core.

Table 1
Neutron Fluence Attenuation as a
Function of Distance Through a Reactor Vessel Wall

Distance into Vessel Wall (in.)	Neutron Fluence (n/cm^2 >1 MeV) Relative to Surface (%)	Neutron Fluence Φ_s = 6.0 x 10^{19} n/cm^2 >1 MeV (calculated spectrum)
0 (Inside Surface)	100	6.0 x 10^{19}
1	69	4.1
2	47.5	2.8
3	32.5	2.0
4	22.5	1.3
5	15.5	0.9
6	10.5	0.6
7	7.2	0.4
8	5.0	0.3

Neutron fluence values shown in Fig. 3 and Table 1 are given in terms of a calculated spectrum for n/cm^2 >1 MeV. The fluence decrease in 8 in. is noted to be 95%. By comparison, the fluence decrease, n/cm^2 > 1 MeV, based on a fission spectrum, would be about 98% in 8 in. By either criterion, the fluence is reduced by one half at a point 2 in. into the vessel thickness and decreases to one quarter of the incident value at a 4-in. wall depth.

AVERAGE RADIATION EMBRITTLEMENT SENSITIVITY CASE

Figure 4 presents schematic CAT curves for various thickness positions within an 8-in. thick vessel wall for the case of a surface fluence of 1.5 x 10^{19} n/cm^2 >1 MeV and

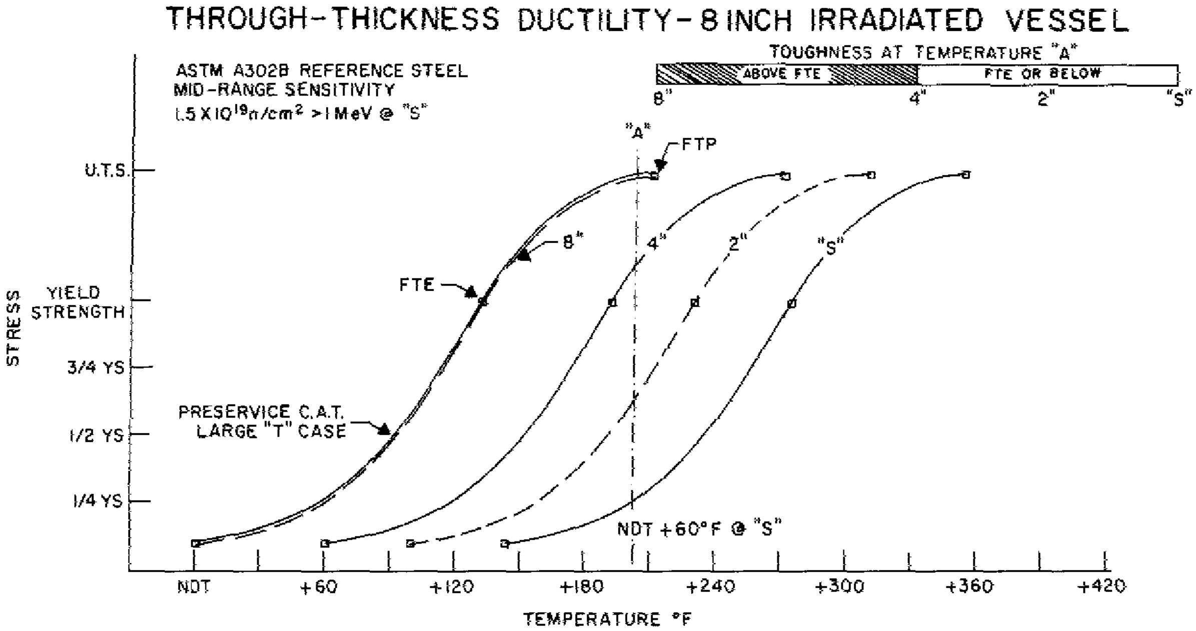

Fig. 4 - Crack arrest transition (CAT) for surface and interior positions of an 8-in.-thick steel vessel having an inside surface fluence of 1.5×10^{19} n/cm^2 > 1 Mev. Radiation embrittlement sensitivity of the vessel material is depicted based on trends exhibited by the ASTM A302-B reference steel (midrange sensitivity). Diagram insert indicates that at least half of the wall thickness would exhibit above-FTE performance at the NDT + 60°F temperature indicated. This temperature corresponds to the lowest permissible vessel wall temperature permitted by current AEC fracture-safety criteria.

average radiation embrittlement sensitivity.* Irradiation response in this example is based on the performance of the ASTM reference plate. The family of curves was developed by first ascertaining the fluence attenuation for each thickness position (see Fig. 3), then determining the corresponding transition temperature increase for each position from the C_v trend in Fig. 2. The CAT curves for a given thickness location were then determined by translating the lowest CAT curve in Fig. 1 by an amount equal to the radiation-induced increase in C_v transition temperature. Figures 5 and 6 depict relative CAT curve positions for two higher inside surface fluences, 3.0 and 6.0×10^{19} n/cm^2 > 1 MeV, respectively.

The position of the NDT + 60°F reference temperature for the irradiated inside surface layer is indicated on each figure. Comparing individual FTE temperatures for the various thickness positions against this reference temperature, it is possible to ascertain the minimum thickness position exhibiting FTE performance when the uniform wall temperature is equal to the surface reference temperature. For example, in Fig. 5 the reference temperature for the surface layer is 225°F (107°C). At this temperature thicknesses below 4 in. from the inside surface exhibit FTE performance.

*Uniform preirradiation properties are assumed through the thickness even though quenching can result in superior properties of the plate surfaces. However, these properties cannot be assumed in every case and the analysis is also intended to apply to submerged are weldments which exhibit essentially uniform toughness through the thickness.

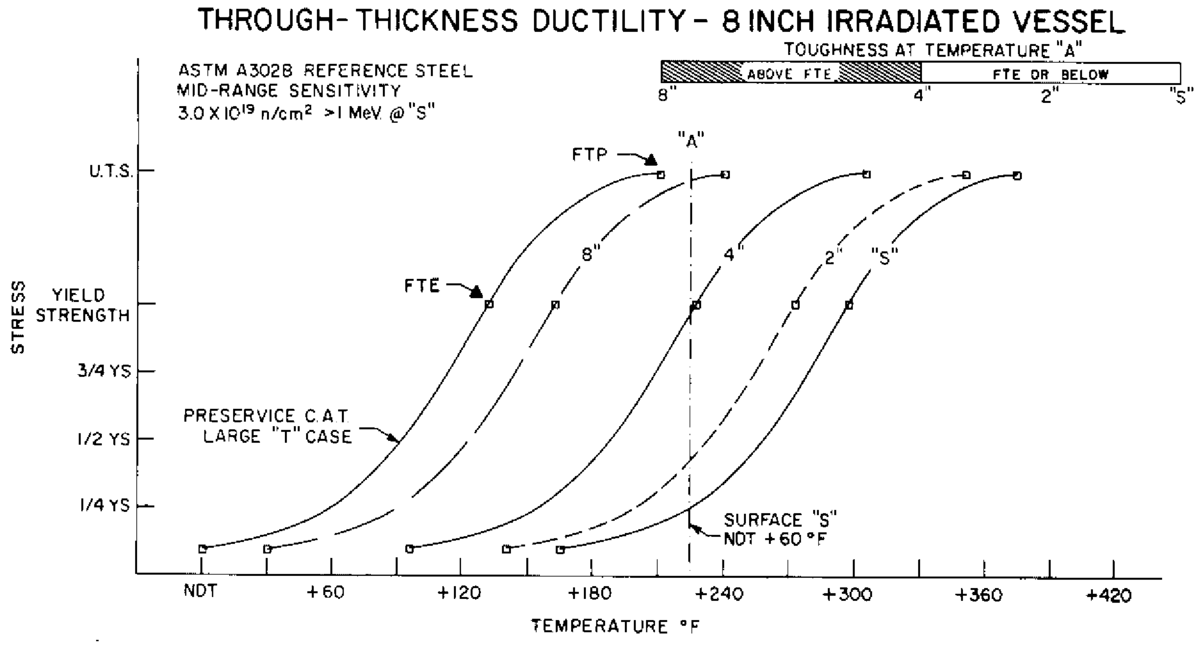

Fig. 5 - Crack arrest transition (CAT) for surface and interior positions of an 8-in.-thick steel vessel having an inside surface fluence of 3.0 x 10^{19} n/cm^2 > 1 MeV based on trends exhibited by the ASTM A302-B reference steel (midrange sensitivity case).

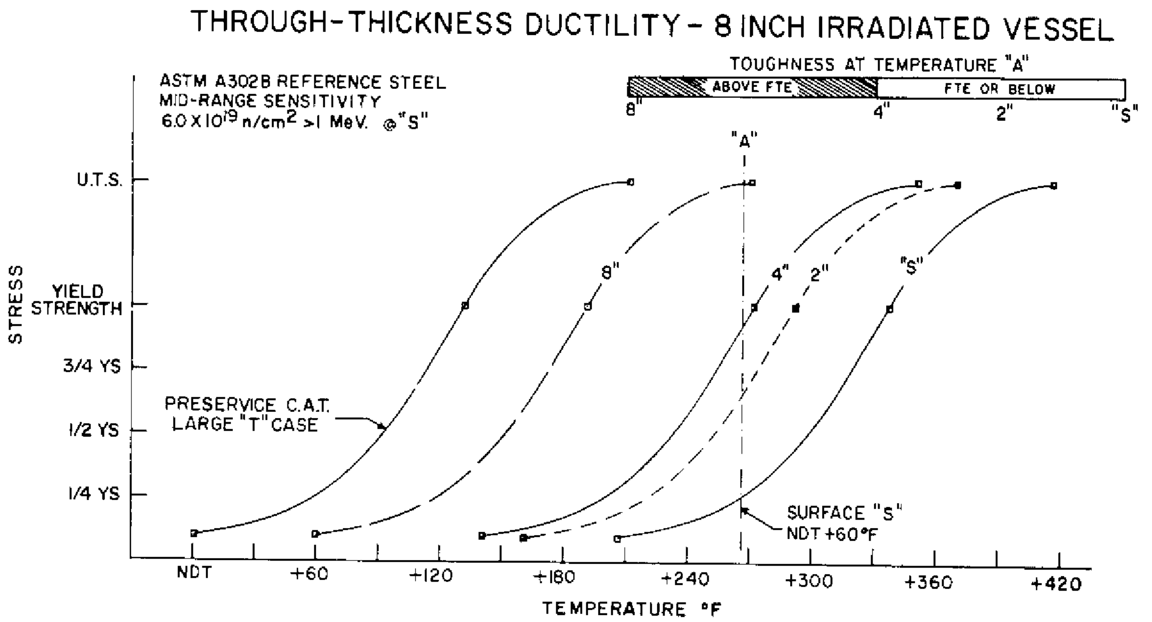

Fig. 6 - Crack arrest transition (CAT) for surface and interior positions of an 8-in.-thick steel vessel having an inside surface fluence of 6.0 x 10^{19} n/cm^2 >1 MeV based on trends exhibited by the ASTM A302-B reference steel (midrange sensitivity case).

HIGHER-THAN-AVERAGE RADIATION EMBRITTLEMENT SENSITIVITY CASE

Projected CAT curve relationships for the condition of above average sensitivity to radiation embrittlement are shown in Figs. 7 and 8. Indicated inside surface fluence conditions are 3.0 and 6.0 x 10^{19} n/cm^2 > 1 MeV, respectively. Relationships in this instance follow observations for the Yankee reference steel given in Fig. 2. For the surface reference temperature condition, FTE behavior in this case is established at a depth of less than 2 in. below the inside surface.

Figure 9 summarizes gradient projections for both steel types for the range of surface fluence conditions evaluated. The effects of above-average radiation sensitivity to embrittlement are quite obvious. Not only are transition temperature shifts greater for a given fluence condition but also the gradient in properties through the thickness is more pronounced. Two observations are of major importance. First, the wall depth for FTE performance at a uniform wall temperature equal to the inside surface reference temperature appears fairly independent of fluence exposure once the surface fluence reaches 3 x 10^{19} n/cm^2 >1 MeV or more for either steel. Secondly, the FTE position is closer to the inside vessel surface for steel having the higher radiation embrittlement sensitivity and, in turn, the higher through-thickness properties gradient. In fact, a steel represented by the Yankee material has approximately 80% of the thickness exceeding FTE performance, whereas a steel represented by the ASTM reference plate has only 50% of its thickness exceeding FTE performance at the reference temperature. The significance of the proportion of material above and below FTE is considered in following sections.

Figure 9 presents an apparent anomaly in that the Yankee steel which is more sensitive to irradiation than the ASTM steel has less of the wall thickness below FTE than does the ASTM steel for the same fluence level. This is *not* meant to imply that the

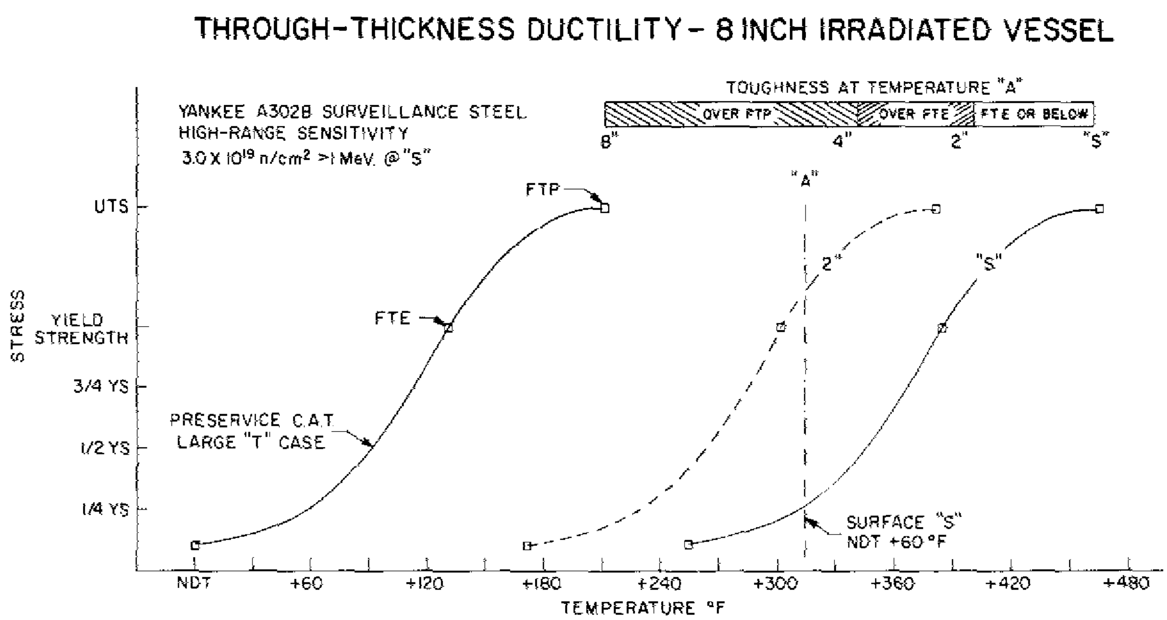

Fig. 7 - Crack arrest transition (CAT) performance of surface and 2-in. depth position of an 8-in.-thick steel vessel for an inside surface fluence of 2.0 x 10^{19} n/cm^2 > 1 MeV (higher-than-average radiation embrittlement sensitivity case). Radiation response is depicted comparable to the Yankee surveillance steel (quarter-thickness position).

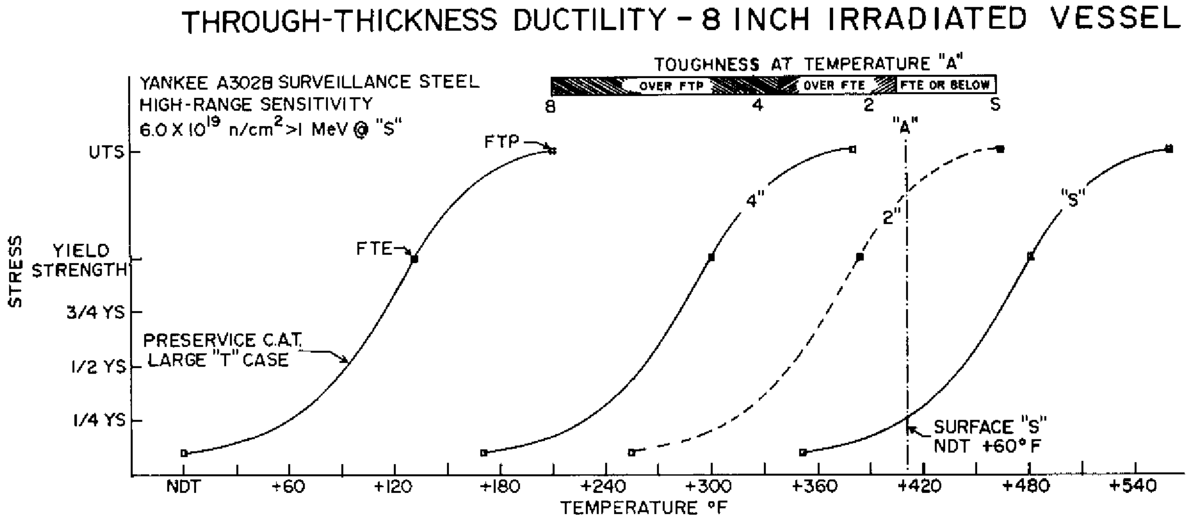

Fig. 8 - Crack arrest transition (CAT) performance of surface, 2-in. and 4-in. depth positions of an 8-in.-thick steel vessel for an inside surface fluence of 6.0 x 10^{19} n/cm^2 > 1 MeV based on trends exhibited by the Yankee surveillance steel (higher-than-average radiation sensitivity case).

Yankee steel is "better" than the ASTM steel because in terms of actual temperature the Yankee steel must be at 400°F (205°C), whereas the ASTM steel need be only at 265°F (129°C) to achieve the conditions shown in the figure for the 6 x 10^{19} fluence level.

The essential point from Fig. 9 is that if sometime in the vessel lifetime, the NDT + 60°F reference temperature at the inside surface can rise to the operating temperature, then the steel which is more sensitive to irradiation is embrittled to a lesser depth than the less sensitive steel in view of the sharper gradient in toughness associated with the former.

FULL-SECTION FRACTURE CHARACTERIZATION FOR THE TOUGHNESS GRADIENT CONDITION

Using currect AEC criteria, reactor vessel operation must be curtailed if the uniform wall temperature drops to NDT + 60°F as determined for the material at the *inside vessel surface*. Similarly, if cognizance is taken of the FTE elevation for thick sections, operation must be curtailed at the more stringent NDT + 130°F limit as discussed previously (3). Neither of these criteria recognizes that large fractions of the wall may still be above the FTE temperature when these limiting conditions are first encountered for the inside surface. The intent of the remainder of this report is to consider the consequences of relaxing the conservatism inherent in the above criteria by permitting operation when the FTE of surface material equals or somewhat exceeds the operating temperature while the FTE temperatures of significant portions of the vessel continue to remain well below the operating temperature.

The significance of a small region of material whose FTE temperature is above the vessel operating temperature (that is material which can fracture unstably) must be assessed in terms of the fracture behavior of the complete wall. At present this relationship can be established only through direct experimental means. Analyzing the consequences of a popin entering material of high toughness is beyond the capability of

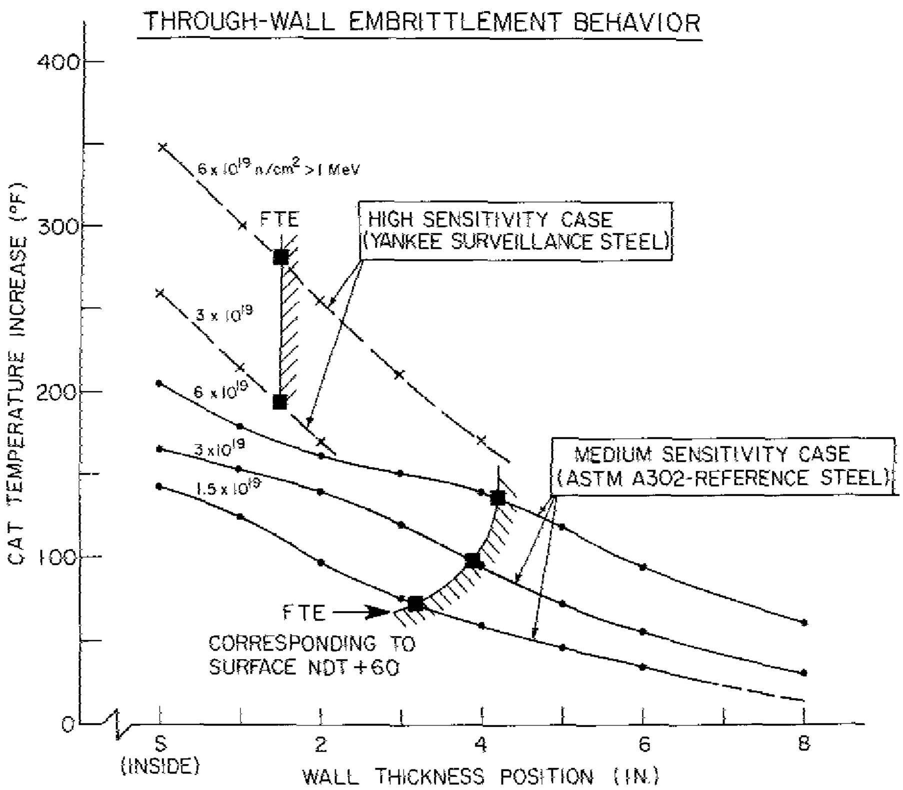

Fig. 9 - Summary of through-thickness notch ductility performance of 8-in.-thick vessel steel comparable to the ASTM A302-B reference (average sensitivity case) or the Yankee surveillance steel (higher-than-average sensitivity case) for inside surface fluences up to $6.0 \times 10^{19} n/cm^2 > 1$ MeV. The loci of the FTE position when the vessel temperature is indicated for each fluence. Note the dependence of FTE position on the radiation embrittlement sensitivity level of the steel.

current analytical approaches, especially when it is remembered that the compliance of the structure must be considered in determining the overall fracture characteristics involving appreciable plastic deformation.

Existing evidence from 12-in. DT tests of A533-B steel (2) indicates that a popin through several inches of brittle weld crack starter is arrested by unirradiated plate material even under gross plastic deformation. One would therefore not expect a popin through a small fraction of the vessel wall to continue through the entire thickness. It may be argued that if popin does not result in penetration of the wall thickness, then the flaw may continue to propagate in a longitudinal direction through the embrittled material near the inside surface and result in a long flaw which, if sufficiently deep, can overload the remaining material. Since the wall is normally loaded to less than half of yield stress, it does not seem likely that this type of propagation could overload and fail the vessel in a ductile manner, even if initiated by a popin to, say, 25% of the vessel thickness. It is assumed herein that popin is arrested very shortly after entering the tough material whose temperature is above FTE and this supposition, of course, must be demonstrated by future studies. The point to be made is that fracture characteristics of structures under consideration must be demonstrated through experimental means because no other acceptable method currently exists.

Having established the background for the toughness gradient and for first event crack conditions (initiation), the resistance of the vessel wall to continued crack propagation is now considered. What must be determined is the relative contribution to overall crack propagation behavior from a tough ligament in the gradient case. In other words, how is the composite behavior influenced by material of varying degrees of toughness ranging from brittel to ductile? This question is explored by considering the energy absorption characteristics of unirradiated material specially prepared to exhibit a toughness gradient.

A 3-in. thick low alloy steel plate having a metallurgically induced property gradient has been examined using the DT test method. The behavior of this material is taken as analogous to that which could be exhibited by irradiated material exhibiting a similar toughness gradient. Standard 1-in. DT tests were performed on plate surface and mid-thickness locations with results shown in Fig. 10. (See Table 2 for individual data.) By elevating the FTE of the 1-in. thick curves to simulate the mechanical constraint associated with 3-in. thicknesses (2), one can project DT performance of 3-in. thick material if composed totally of material comparable to the surface or comparable to the mid-thickness material.* These projected curves, normalized to the same total energy range for 1-in. DT data, are indicated by the dashed curves in Fig. 10. See Table 2 for individual data. A curve depicting full thickness DT test results for the 3-in. composite plate is also shown for comparison. Significantly, actual measurements for the composite coincide with the projection for performance of 3-in.-thick all-surface material from the toe region (NDT temperature) to well past the mid-energy range transition temperature level. Thus, a very significant if not dominant effect from the tough surface ligament is felt by the composite in full section tests. More important, note that the DT curve for the composite rises well past its mid-energy region before any noticeable upsweep in toughness is observed for mid-thickness material alone. Clearly, the FTE temperature (defined by the mid-energy range transition) for the composite tends to mirror the FTE for the tough surface ligament in preference to the FTE for mid-thickness material. In further illustration of this relationship, data for 1-1/2-in. tests representing one-half of the plate thickness (surface to mid-thickness) are shown in Fig. 11. (For clarity, the dashed lines of Fig. 10 for the 1- to 3-in. constraint correction have been omitted in Fig. 11.) Notice the agreement between the 1-1/2-in. and the 3-in. composite test behavior. For reactor vessels, the properties gradient would tend toward that shown by one-half of the shaded region, that is, an asymmetric gradient with the radiation-embrittled inner wall surface layer being comparable to the 3-in. thick plate mid-thickness material and the outer wall surface layer being comparable to the 3-in. plate surface material.

FRACTURE-EXTENSION RESISTANCE FOR THE GRADIENT CASE

There exists no universal method for assessing the fracture characteristics, after initiation, of a material having a severe gradient in toughness. Analytical methods based on elastic or elastic-plastic behavior deteriorate rapidly as the toughness of the metal approaches high ductility and new approaches based on experimental observations are required. It is known that ductile or semiductile materials exhibit slow stable flaw growth. In some cases this slow growth terminates with an instability and, in others, slow tearing continues until complete separation unless prematurely terminated by a

*One expects the trend of a 3-in. DT curve of all surface material to be the same as the trend of the 3-in. composite material in the lower toe region where the gradient is not displayed (i.e., all the material is frangible). Using this fact, the resultant 20°F translation of the 1-in. DT curve of surface material corresponds with a similar type of elevation displayed between 1-in. and 3-in. DT curves from another material having no gradient (2).

Table 4
Fracture Energy Values For a 3-in.-Thick Low-Alloy Steel Plate
Exhibiting a Metallurgically Induced Toughness Gradient

Specimen Designation		3-in.* (Full Thickness)	CR†= 1.67	1-1/2-in.* (Surface to T/2)	CR†= 3.0	1-1/2-in.* (Surface to T/2)	CR†= 3.0	1-in.* (Surface)	CR†= 3.0	1-in.* (Surface)	CR†= 1.0	1-in.* (Mid Thickness)	CR†= 3.0	1-in.* (Mid Thickness)	CR†= 1.0
Temperature °F	°C	Energy (ft-lb)	R** (ft-lb/in.^{2})	Energy (ft-lb)	R** (ft-lb/in.^{2})	Energy (ft-lb)	R** (ft-lb/in.^{2})	Energy (ft-lb)	R** (ft-lb/in.^{2})	Energy (lb-lb)	R** (ft-lb/in.^{2})	Energy (ft-lb)	R** (ft-lb/in.^{2})	Energy (ft-lb)	R** (ft-lb/in.^{2})
-120	-84							580	193	440	440				
-100	-73	4350	290					1985	661						
-80	-62			2,300	341	1150	511	3120	1080	1040	1040	645	215		
-60	-51	12,850 11,400	857 760	5,950	881	1440	640	2415 3810	805 1270			585	195	430	430
-40	-40			6,100	905	1950	867	4850 6850	1615 2380	1105	1105	920 980	306 327	450	450
-30	-34	16,475 12,700	1098 847												
-20	-29			13,700	2030	2500	1110	7515	2510	1107	1107	1585	528	650	650
0	-18	29,700	1980	17,200	2548	3245	1440	7425	2400	1285	1285	3185 4535	1061 1510	860	860
20	-7			21,100	3120	2830	1260	7545	2530	1265	1265	4010	1340	835	835
30	-1	35,950 37,550	2397 2503					7265	2420			5045	1680		
40	4			18,100	2681	3070	1365								
80	27	40,600	2707	15,950	2360	3175	1410					5575	1860	1140	1140

*Specimen Thickness
**Fracture Extension Resistance (R) = Energy ÷ Fractured Area
†Relative Crack Run (CR) = Length of Fractured Ligament ÷ Thickness

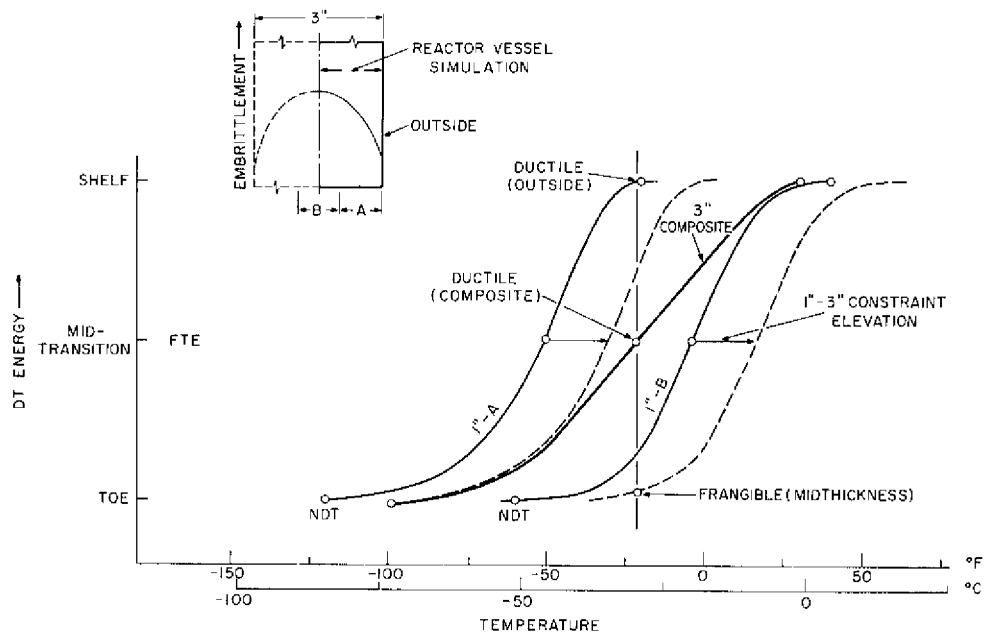

Fig. 10 - Dynamic tear (DT) energy trends for a 3-in.-thick low-alloy plate having a metallurgically induced toughness gradient. The energy scale has been normalized to accommodate both the 1-in. and 3-in. test results. Similarly, a 20-degree elevation for thickness-induced mechanical constraint is applied (dashed curve) to 1-in. data to project for 3-in. DT results of the same toughness level. The upsweep in toughness for the 3-in. section of composite toughness follows the upsweep of the tough surface material curve (adjusted for 3 in.) rather than the trend for the midthickness material curve (adjusted).

rapid tearing dictated by plastic collapse. This type of slow stable growth for brittle materials has been defined in terms of a crack extension resistance curve, or simply an R curve, in elastic fracture mechanics (14). The R curve is a characteristic of the material. When the curve is plotted vs crack length, the tangent with the crack extension force ($\mathcal{G}$) curve (same units as R, ft-lb/in.^{2}) determines the instability value of $\mathcal{G}$ called $\mathcal{G}_c$. It has been proposed by Pellini and Judy (15) that analogous R curves for ductile materials can be determined by means of energy density* (E/A) measurements for dynamic tear specimens of various geometries. Specifically, for a given thickness, DT specimens having various crack runs** Δa are fractured in the normal manner. If the E/A increases with crack run then the material is one of rising R; if E/A is constant with increasing crack run then the material is termed frangible and E/A must be directly related to $\mathcal{G}_{Ic}$ or K_{Ic}.

The concept of an R curve determined on an energy density basis was formulated only recently and the interpretations are qualitative at this point. A sharply rising R curve represents increasing resistance to fracture extension with increasing crack extension path. The increased resistance is a consequence of the development of a plastic enclave emanating from the DT specimen crack starter region which simulates the

*Energy density or E/A is defined as fracture energy per unit fractured area. This term has the same units as $\mathcal{G}$ and R.

**Crack run is defined as the length of the unbroken ligament in inches.

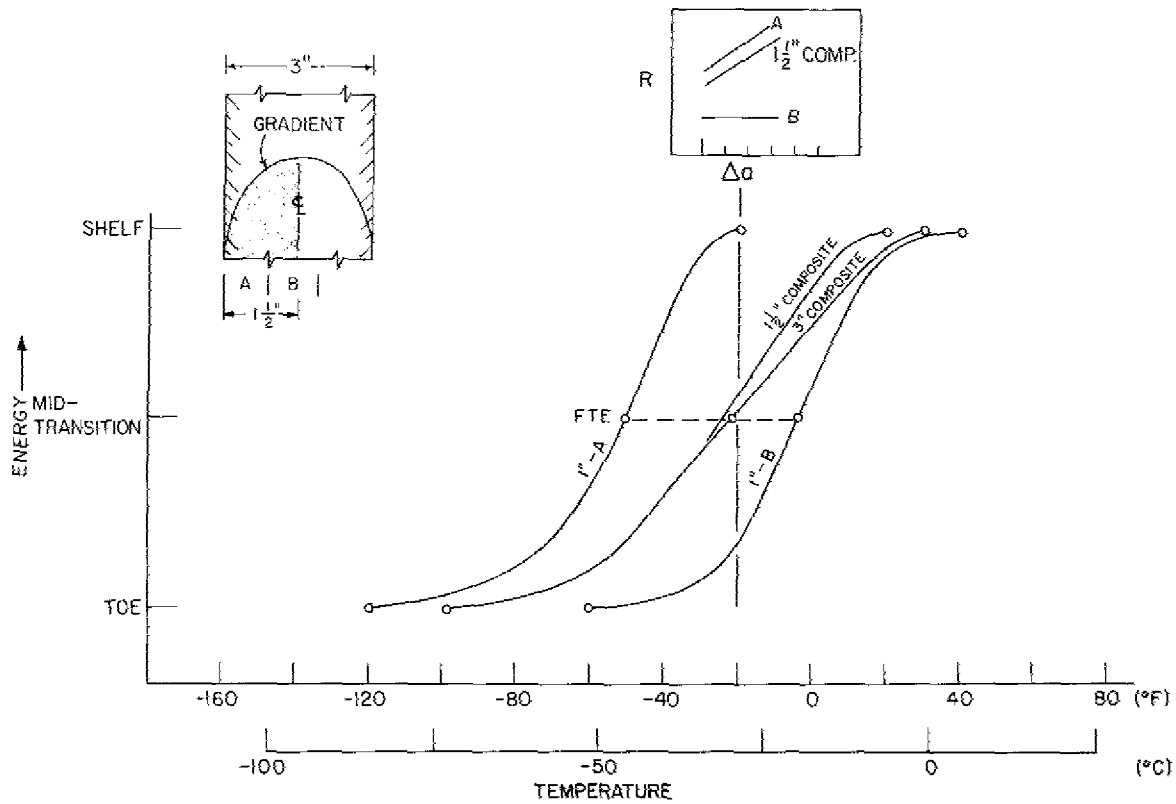

Fig. 11 - Half-plate thickness (1-1/2-in.) vs full-plate thickness (3-in.) DT performance of a low-alloy plate with a toughness gradient. Strong influence of the tough ligament on composite performance is indicated. Insert figure shows a parallel increase in fracture resistance R at -20°F with crack run Δa for surface and 1-1/2 in. composite material but not for mid-thickness material.

extension of a cracklike defect in nonfrangible metals. An R curve which does not rise with increasing crack extension path characterizes a frangible metal that is analyzable with linear elastic techniques. In this case the plasticity associated with the crack tip is fully developed at the instant of fracture initiation and must therefore be of a localized nature. The ranking of materials with rising R curves with respect to those of nonrising R curves is an indication of plastic loading requirements for fracture. The modification of the DT test to include various crack runs thus provides a simple means for assessment of fracture-extension resistance.

In Fig. 11 (insert) the effect of varying the crack run Δa of DT specimens is illustrated schematically for different thickness locations of a 3-in.-thick test plate having a metallurgically induced toughness gradient that is symmetric about the mid-thickness plane (see Table 2 for individual data.) The temperature of -20°F (-29°C) was chosen for comparison of resistance characteristics at shelf temperatures (surface layer) vs toe region temperatures (mid-thickness layer). The ratio of Δa to specimen thickness B was varied from 1 to 3 for 1-in.-thick specimens. A rising R is defined by the DT results for the shelf condition, while a flat R curve is defined for the toe region at -20°F (-29°C), which may be interpreted in terms of the characteristics defined above. Investigations of composite material representing the gradient from the surface to mid-thickness locations were accomplished with 1-1/2-in. DT specimens with relative crack runs Δa/B of 1 and 3. The results indicate rising R features to be consistent with FTE performance at the -20°F test temperature.

The DT behavior of the entire 3-in.-thick plate, shown in Fig. 11, represents a relative crack run of 1-2/3. Similar behavior is depicted for 3-in. and 1-1/2-in. specimens when their differences in crack runs are normalized by plotting individual transition curves relative to a common shelf level.

Figure 12 shows the relationship of the R curves at surface and mid-thickness locations as compared to the 1-1/2-in. composite material at selected temperatures. The rising R curves at -20°F (-29°C) from Fig. 11 are reproduced for comparisons with trends at -40°F (-40°C) and +20°F (-7°C). At -40°F only the surface region is found to have rising R-curve characteristics. This is expected, since only the surface DT material is above the mid-energy transition (or FTE) at this temperature. At 20°F the DT curves from all thickness locations are above their respective DT mid-transitions and consequently exhibit rising R curves.

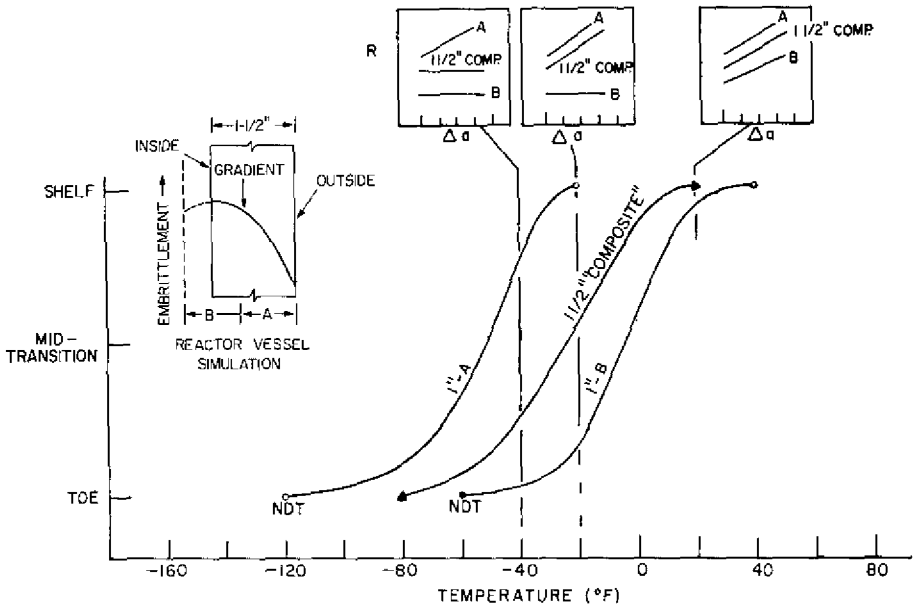

Fig. 12 - Changes in crack extension resistance R with increasing crack run Δa at temperatures of -40, -20 and 20°F. Temperature of rising R for surface, midthickness, and 1-1/2-in. composite materials appears to coincide generally with mid-energy transition temperature defined by DT results (Δa/B = 3).

Consider the case of a pressure vessel wall with a toughness gradient similar to that discussed above and having R curve trends like those at -20°F in Fig. 12. Even with a portion of the vessel wall significantly below the FTE temperature (that is, a flat R curve), the composite behavior is considerably more influenced by the tough outer skin material such that the complete section exhibits toughness commensurate with FTE-type performance. These results suggest an optimistic trend which, if verified by future research, indicate that the overall vessel fracture characteristics may not be markedly degraded if operation is continued with the inside surface at a temperature slightly below the FTE temperature. As a consequence the generation of missiles, associated with frangible behavior, is unlikely. It is thus seen that a toughness assessment by means of R curves can readily indicate when the frangible behavior of the vessel as a unit appears improbable.

SUMMARY

It is known that the self-shielding of a thick-walled nuclear pressure vessel can result in severe attenuation of neutron flux at a given thickness location; this characteristic leads to a gradient in fracture toughness. Current AEC criteria restrict vessel operation to temperatures above NDT + 60°F as determined at the inside surface. When the toughness gradient is borne in mind, it has been considered necessary to determine the consequences of relaxing this conservative criterion to permit the uniform vessel wall temperature to fall below the FTE temperature at the inside surface. This question is germane in that it has been demonstrated herein for a 6-in. A302-B plate and an 8-in. A302-B plate displaying average and higher-than-average sensitivity to irradiation, respectively, that significant portions of both plates would be above the FTE temperature for fluences up to 6×10^{19} at a uniform metal temperature equal to the currently specified limit temperature of NDT + 60°F at the inside surface.

It is of great importance to realize that the answer to the question does not lie in an application of analytical approaches which are founded in linear elastic behavior or in current extrapolations of these methods to the elastic-plastic regime. Only a portion of the problem may consist of a possible linear elastic popin through a limited region of embrittled material. The required sophistication, however, comes in being able to assess the consequences of this popin in predicting the integrated response of the section as a unit, which contains a large portion of material whose toughness remains very high and requires significant amounts of gross plastic deformation to propagate a fracture. The solution to this problem in the foreseeable future must therefore come from experimentally devised correlations of laboratory tests with prototype fracture behavior.

This report has demonstrated that experimental, interpretative methods based on DT tests, the FAD, and the newly formulated R curve approach are quite useful tools to analyze the problem at hand. These methods can be used to determine if unstable fracture is possible for the vessel as a unit and therefore the methods uniquely contribute to the solution of the problem of great urgency. Alternatively, these methods can be used to assess the degree of elevation in toughness above frangible conditions which the gradient material exhibits and thus indicate the toughness reserve prohibiting missile generation.

Experimental demonstration of the above aspects was obtained by assessing the significance of the unit fracture characteristics of a complete vessel wall containing an irradiation-induced gradient using DT investigations of a 3-in. thick low alloy steel having a metallurgically induced gradient. Comparisons of 1-1/2-in.-thick DT specimens, representative of composite behavior, with that of surface and mid-thickness material, show that the composite behavior is strongly influenced by the tough outer skin in that it exhibits FTE-type behavior at a temperature when the mid-thickness region of the plate is in a frangible condition.

The results of the 3-in. plate investigation are characterized in terms of flaw extension resistance measurements analogous to the R-curve determination of linear elastic fracture mechanics. It is shown that the material of high toughness exhibits a rising R curve with increasing fracture ligament in tests of modified DT specimens. This behavior denotes slow stable flaw extension, which, for high levels of R, does not lead to an instability. The composite behavior of the 3-in. steel having a toughness gradient showed a rising R curve at a temperature at which the mid-thickness location is in a frangible condition. From this behavior it is concluded that considerable toughness can be exhibited by a reactor vessel even when the inside wall is slightly below the FTE temperature. Additional research is necessary to extend these observations more directly to the irradiated vessel case, but first indications are that catastrophic vessel failure will not occur for the gradient situation at a uniform wall temperature equal to FTE of the inside surface and that missile generation is not likely.

Qualification of the effect of radiation on R curve characteristics, as identified by modified DT specimen tests, will be an important goal of future research efforts. In particular, the possible degradation of steel characteristics by radiation from high to low R performance obviously will have a significant bearing on the true toughness potential of gradient material and on the weight which can be assigned to the toughness reserve afforded by that portion of a vessel wall less highly embrittled through fluence attenuation. Beyond this initial objective, procedures for the selection or production of materials for high R characteristics from a long-range experimental objective in the interest of reactor materials optimization.

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REFERENCES

1. Pellini, W.S., and Puzak, P.P., "Fracture Analysis Diagram Procedures for the Fracture-Safe Engineering Design of Steel Structures," NRL Report 5920, Mar. 15, 1963; Welding Research Council Bulletin No. 88, May 1963

2. Loss, F.J., and Pellini, W.S., "Coupling of Fracture Mechanics and Transition Temperature Approaches to Fracture-Safe Design," NRL Report 6913, Apr. 14, 1969; "Practical Fracture Mechanics for Structural Steels," Chapman and Hall, London, Aug. 1969, pp. J1-J35

3. Loss, F.J., "Dynamic Fracture Characteristics of Thick Section Steel," Proceedings of Symposium on The Technology of Pressure-Retaining Steel Components, Vail, Colo, Sept. 21-23, 1970, Met. Soc. of Am. Inst. of Mining, Met. and Pet. Engrs., Inc., New York, 1970

4. 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," NRL Report 7152, Sep. 1970; Trans. ASME, J. Basic Engrg. (pending publication)

5. Hawthorne, J.R., "Studies of Radiation Effects and Recovery of Notch Ductility of Pressure-Vessel Steels," Iron and Steel Institute Special Report No. 69, London, Symposium on Steels for Reactor Pressure Circuits, London; Iron and Steel Institute, 1961

6. Hawthorne, J.R., and Potapovs, U., "Initial Assessments of Notch Ductility Behavior of A533 Pressure Vessel Steel With Neutron Irradiation," NRL Report 6772, Nov. 22, 1968; Symposium on Radiation Effects on Structural Metals, ASTM STP 457, pp. 113-134 (1969)

7. Potapovs, U., and Hawthorne, J.R., "The Effect of Residual Elements on 550°F Irradiation Response of Selected Pressure Vessel Steels and Weldments," NRL Report 6803, Nov. 22, 1968; Nuclear Applications 6: No. 1: 27-46 (1969)

8. Hawthorne, J.R., "Demonstration of Improved Radiation Embrittlement Resistance of A533-B Steel Through Control of Selected Residual Elements," NRL Report 7121, May 21, 1970, ASTM STP 484, Niagara Falls, June 1970 (pending)

9. Serpan, C.Z., Jr., "Through-Thickness Neutron Fluence and Embrittlement Gradients in Reactor Pressure Vessels," submitted to Nucl. Appl. Technol. (pending)

10. Serpan, C.Z., Jr., and Hawthorne, J.R., "Through-Thickness Notch Ductility and Tension Properties as a Function of Neutron Exposure to a Simulated Pressure Vessel Wall of A302-B Steel," NRL Report 6575, June 30, 1967; Nucl. Engrg. Design 6 (No. 1): 78-88 (1967)

11. Steele, L.E., et al, "Irradiation Effects on Reactor Structural Materials, Quarterly Progress Report, 1 May-31 July 1970," NRL Memorandum Report 2153, Aug. 15, 1970

12. Unpublished data, Battelle Memorial Institute, Pacific Northwest Laboratories Richland, Wash., private communication from J. A. Ulseth to C. Z. Serpan, Jr., 1967

13. Serpan, C.Z., Jr., and Watson, H.E., "Mechanical Property and Neutron Spectral Analyses of the Big Rock Point Reactor Pressure Vessel," Nucl. Engrg. Design 11 (No. 3): 393-415 (1970)

14. Strawley, John E., and Brown, William F., Jr., "Fracture Toughness Testing Methods," in "Fracture Toughness Testing and Its Applications," ASTM STP 381, pp 133-195, 1965

15. Pellini, W.S., and Judy, R.W., Jr., "Significance of Fracture Extension Resistance (R Curve) Factors in Fracture-Sale Design for Nonfrangible Metals," NRL Report 7187 Oct. 19, 1970