Reactor Pressure Vessels - Is Upper Shelf Operation Necessary?

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ABSTRACT

This paper examines the significance of upper shelf behaviour in the context of ensuring the safety of the Magnox steel reactor pressure vessels in the UK. Nuclear Electric's approach to the safety of these vessels is based on fracture mechanics calculations using the R6 procedures and is described. Problems with the definition of the onset of the upper shelf are discussed. It is concluded that confidence in an assessment is gained by examination of factors on pressure, temperature and toughness relative to uncertainties in the input parameters rather than by a requirement for particular values of any one factor or a requirement to operate on the upper shelf.

1 INTRODUCTION

Over recent years a great deal of attention has been given to the fracture toughness/temperature relationship of pressure vessel steels in relation to the PWR steel pressure vessel (Hirsch 1987). A requirement for operation on the upper shelf of fracture toughness represents a qualitative fracture mechanics approach. This, however, requires a definition of the onset of upper shelf behaviour which is not straightforward as discussed in Section 2.

This paper then goes on to examine the significance of upper shelf behaviour for Magnox reactor pressure vessels made of carbon-manganese steel. The overall approach to assuring the integrity of these vessels is described in Section 3. The use of the R6 fracture assessment procedure (Milne et al. 1986) to obtain deterministic factors or failure probabilities which can be used in a safety case is then described in Sections 4 and 5.

2 DEFINITION OF THE UPPER SHELF

Historically, the concepts of upper shelf behaviour and ductile/brittle transition temperature have been developed from impact tests. The curve of fracture toughness variation with temperature has a similar shape to that for impact energy and is often also described in terms of an upper shelf and a transition curve. Mechanistically, the transition represents a change in crack initiation process from a cleavage (brittle) mode to a microvoid coalescence (ductile) mode with increasing temperature. The change is not sharp, however, and the two processes compete in the upper part of the transition region.

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If materials selection or operating rules are to be based on structures operating on the upper shelf of fracture toughness, then it is necessary to define the onset of upper shelf behaviour. There are a number of definitions and the principal ones are listed below and illustrated in Fig. 1:

(1) attainment of a particular value of fracture toughness;
(2) intersection of an equation describing the transition region with an equation describing the toughness on the upper shelf;
(3) temperature at which there is a complete absence of cleavage;
(4) demonstration of a specified amount of ductile crack growth;
(5) temperature defined from impact testing.

There are problems with these definitions. For example, it is desirable to have a material with a steep resistance curve; but such a material may be unable to demonstrate a specified amount of ductile crack growth in a standard fracture toughness test and could fail criterion (4) for being on the upper shelf. Other definitions suffer from similar illogicalities. If two materials have the same transition curve, the material with the higher upper shelf toughness would be considered the worse material according to criterion (2) because the onset of the upper shelf occurs at a higher temperature; yet it would have the higher toughness at a given temperature.

The definitions listed above suffer from the illogicalities defined in the previous paragraph, from problems of practical measurement, and also do not relate directly to the structure for which a high defect tolerance is required. Although fast fracture can occur in a brittle mode, it can equally occur in a ductile mode if the fracture toughness is low. To demonstrate that a structure has a high defect tolerance, a sufficient level of toughness is required, irrespective of whether that toughness is in the transition or on the upper shelf. Therefore, there is little merit in attempting to closely define the onset of the upper shelf. Instead, it is important to be confident about the value of fracture toughness used in an assessment.

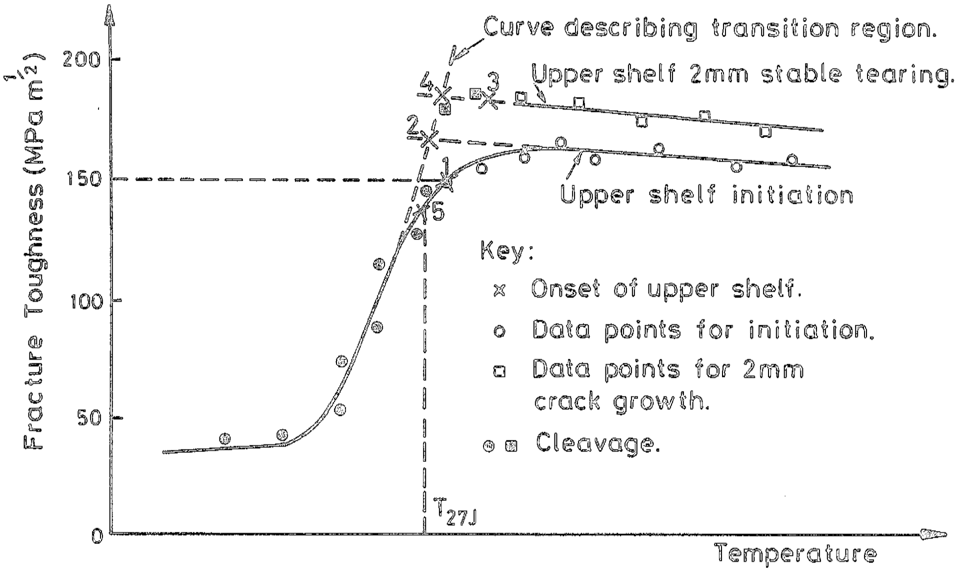

Figure 1. Schematic showing possible definitions of the onset of the upper shelf

3 NUCLEAR ELECTRIC'S MAGNOX PRESSURE VESSEL APPROACH

Safety cases for Magnox steel reactor pressure vessels have been based on quantitative fracture mechanics calculations using R6 (Milne et al. 1986). In the absence of in-service inspection, defects of two sizes are considered, both significantly larger than those which could realistically have escaped the initial pre-service inspection. The first is the largest defect that could have survived the overpressure test made prior to reactor operation. The second is a crack size of 25mm depth. In both cases calculations are made for fully extended defects.

For Magnox vessels the overpressure test was typically 1.65 times the normal operating pressure. For the majority of seam welds, assessments show that operating stresses, and fault pressure conditions, will not cause instability of any defects that had survived the overpressure test. These analyses are based on mean materials properties and allowance is made for effects such as fatigue crack growth and changes in materials properties due to irradiation. It is argued that as pressure reserve factors are greater than unity, the safety case is established.

There are a few locations where, due to high thermal stresses for example, it is not possible to demonstrate pressure reserve factors greater than unity for the proof test defect. In these cases 'windows' of defect sizes are calculated. These are the range of defect sizes at start of life which could have survived the overpressure test and have survived operation to date but which give pressure reserve factors less than unity. Window sizes are generally small and associated with postulated extended defects which are typically half the vessel thickness. Under these circumstances the integrity of the vessel is based upon the improbability of such defects existing.

In addition to calculations based on mean material properties, sensitivity analyses are performed using bounding properties. It is found that the pressure reserve factors can be greater if the start-of-life fracture toughness is assumed low as this leads to smaller defect sizes being able to survive the overpressure test. There are circumstances where the calculated factors with the material operating off the upper shelf can be higher than situations where the material is on the upper shelf. Additional calculations are performed to evaluate the length of a through-wall defect that would lead to leakage at a detectable rate and the limiting length of such a defect calculated using R6.

The above calculations are used to demonstrate that under all phases of normal operation, adequate margins exist based on R6 for the largest credible postulated defect. The approach does not explicitly require the reactor pressure vessels to be on the upper shelf of fracture toughness at full operating pressure. The prime requirement is to use a level of toughness appropriate to service conditions. The principle lying behind the approach is that tolerance to defects is guaranteed by the fracture mechanics methods embodied in R6 given an adequate level of fracture toughness. The calculations do not distinguish between values of toughness on the upper shelf and those in the transition region as it is conceded that fracture at defects can, and indeed does, occur in both ductile and brittle modes.

4 PRESSURE, TOUGHNESS AND TEMPERATURE FACTORS

In the Nuclear Electric approach described above, pressure reserve factors are calculated but requirements for particular values of the factors are not specified. This reflects the advice in R6 that "application of particular numerical factors in fracture analyses can be misleading because of the inherent but variable interdependence of the parameters contributing to fracture behaviour". For operation near the onset of upper shelf behaviour, two factors of interest, defined in R6, are those on pressure and toughness:

$$F^{P} = \frac{\text{the pressure which would produce a limiting condition}}{\text{the applied pressure in the assessed condition}}$$

$$F^{K} = \frac{\text{fracture toughness of the material being assessed}}{\text{fracture toughness to produce a limiting condition}}$$

Here, by "limiting condition" is meant that the pressure or fracture toughness is changed until the assessment point (L_r, K_r) lies on the R6 failure assessment line. As changes and uncertainties in material properties in the transition region are often related to a transition temperature, it is additionally useful to define a reserve factor on temperature ΔT:

$$\Delta T = \text{operating temperature} - \text{operating temperature to produce a limiting condition}$$

For an LEFM analysis of a component loaded only by pressure, the reserve factors on pressure and toughness are identical. For vessel operation in the transition region, these factors are then simply related to the factor ΔT by the dependence of fracture toughness on temperature. However, the interdependence of factors is generally more complex. Fig. 2 illustrates some effects using the elastic-plastic fracture analysis in R6 and these, and other general observations, are listed below.

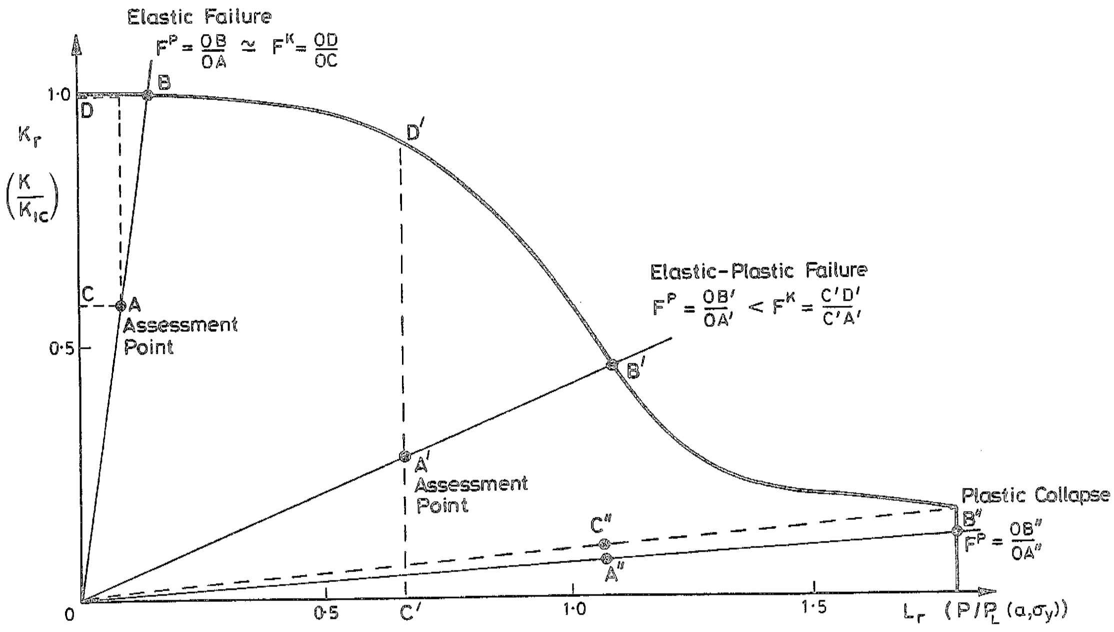

Figure 2. R6 diagram showing the effect of plasticity on the relationship between reserve factors

(a) Plasticity reduces the dependence of the assessment on fracture toughness and, therefore increases the factors on toughness and temperature for a given pressure factor (as for point A' in Fig. 2).

(b) At the extreme of plastic collapse, the assessment may be independent of fracture toughness over a range of values (represented by movement of the point A'' to C'' in Fig. 2). Consequently, imposing specific values for F^K or ΔT would confer no confidence in an assessment.

(c) As reducing temperature tends to lead to an increase in yield stress, the temperature factor for a given F^K is increased by plasticity.

(d) In the LEFM case, the factors on pressure and toughness are not equal in the presence of thermal stress. They are related by

$$F^K = [F^P + K_1^S/K_1^P]/[1 + K_1^S/K_1^P]$$

where K_1^S, K_1^P are the stress intensity factors due to thermal stress and pressure stress, respectively. A given pressure factor corresponds to a lower factor on fracture toughness, and therefore a lower temperature factor, when thermal stresses are present.

(e) As for pressure only, plasticity increases toughness and temperature factors for a given pressure factor in the presence of thermal stresses.

It is clear from the above discussion that the factors on toughness, pressure and temperature are interdependent. This emphasises the importance of a sensitivity analysis to establish the parameters most strongly influencing an assessment, and reinforces the R6 recommendation that reliance should not be placed on specific values of particular factors. In general, the required factors depend on uncertainties in material properties and loading conditions, and on other supporting arguments such as the proof test, leak rate calculations and warm-prestressing, for example.

5 PROBABILISTIC METHODS

The fracture mechanics methods described above are deterministic with potential variations in the input parameters addressed by means of a sensitivity study. An alternative approach is probabilistic analysis. The simplicity of the R6 procedure makes it a suitable basis for probabilistic calculations, and developments over a number of years have recently led to the production of an R6 appendix giving a probabilistic fracture mechanics assessment procedure (Wilson and Ainsworth 1991). This describes an approach considering variations in defect size, fracture toughness and flow stress and a computer code, STAR6, developed to carry out the calculations.

The code STAR6 has recently been applied to typical conditions in Magnox reactor pressure vessels to assess the importance of operating temperatures near the onset of the upper shelf. Fig. 3 shows some results illustrating the variation of failure probability with operating temperature along with the input fracture toughness distributions. The effects of a pre-service proof test and changes in mechanical properties due to irradiation in service are included. More important than the absolute values of failure probability, which are dependent on a variety of assumptions such as that for defect distribution, is the relative variation of failure probability with temperature. It can be seen that failure probabilities are not significantly larger just off the upper shelf than on the upper shelf. Thus the probabilistic calculations support the views expressed in Section 3 that operation on the upper shelf is not a prime requirement as fracture must be conceded both on and off the upper shelf.

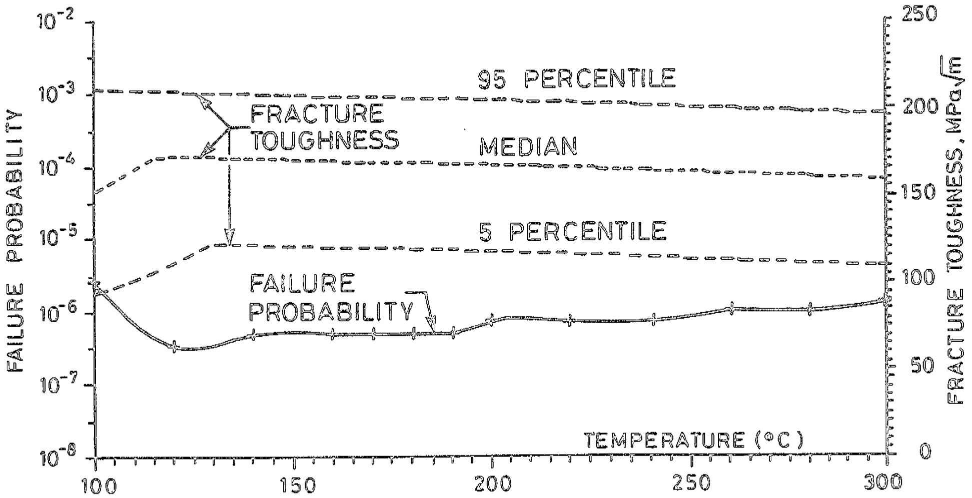

Figure 3. Variation of calculated failure probability and fracture toughness with operating temperature

6 CONCLUSIONS

The Nuclear Electric approach to reactor pressure vessel safety is based on detailed fracture mechanics methods embodied in the R6 procedure. The application of these methods is not limited to vessels that operate on the upper shelf but can be applied to predict fracture at defects in both ductile and brittle modes. Factors on pressure, toughness and temperature can be evaluated using the R6 procedure. Confidence in an assessment is gained by an overall examination of these factors relative to uncertainties in the input parameters rather than by a requirement for a particular value of any one factor or a requirement to operate on the upper shelf. Probabilistic fracture mechanics calculations have been performed to support this view and the results suggest that failure probabilities are not significantly larger just off the upper shelf than on it.

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