PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

# Fracture Mechanics as an Aid to Design and Operation of Nuclear Plant [and Discussion]

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*Phil. Trans. R. Soc. Lond. A* 1981 **299**, 227-236
doi: 10.1098/rsta.1981.0021

*Phil. Trans. R. Soc. Lond.* A **299**, 227–236 (1981) [ 227 ]
*Printed in Great Britain*

# Fracture mechanics as an aid to design and operation of nuclear plant

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Fracture mechanics analyses are an important part of nuclear plant design, supplementing the conventional design protection against failure to cover the possibility of the presence of crack-like defects. The degree of detail and accuracy required for a particular application depends on the possible consequences of a failure and whether the assessment is concerned with plant safety or with aspects of reliability. In the former case, a conservative approach is necessary and the prevention of initiation is the usual criterion. This approach is typified by the safety assessment applied to pressurized water reactor pressure vessels, which is outlined and discussed in relation to elastic plastic approaches and the importance of plant transient conditions, material properties (especially in weldments) and possible defect distributions.

Fracture mechanics can help in defining quality control and quality assurance procedures, including both requirements for mechanical property appraisal and non-destructive testing. The latter aspects extend into operation, in respect of monitoring of plant conditions, surveillance of changes in material properties and the use of periodic inspection and plant condition monitoring techniques. A number of examples are quoted and recommendations made to permit improved fracture mechanics assessments.

## Introduction

Wherever possible, designers of nuclear plants use existing Design Codes and standard specifications, thus taking advantage of successful long-term experience in fabrication and operation. Such an approach provides confidence that failure will not occur provided that crack-like defects are not present. This requirement that a structure is to be free from detectable crack-like defects is made in most Design Codes and is inherent in the design methods used, the confirmation of absence of defects being sought by quality assurance methods and by pre-service inspection. For nuclear plant it is the practice to require fracture mechanics assessments, especially for such structures as those containing pressure where large-scale disruptive failure could lead to loss of reactor coolant. Fracture mechanics assessments of the significance of defects are made in the design stage, in safety assessments and in service. The degree of detail applied is dependent upon the possible consequences of failure and whether the assessment is concerned with plant safety or with aspects of reliability that could produce significant economic penalties.

The application of fracture mechanics leads to additions in design requirements, to specific requirements in quality assurance and quality control, to precise appraisal of the effect of service conditions in terms of transient stresses and environmental effects upon materials and, especially, to great emphasis and reliance being placed upon pre-service and in-service volumetric non-destructive examination. The degree of sophistication required and that which is possible in practice is dependent not only upon the consequences of failure but also upon the acceptance by designers, fabricators and operators of the consequences of requiring fracture mechanics assessments. The requirements currently demanded in design and safety assessments of a pressure vessel for a pressurized water reactor (p.w.r.) contrast with what is achievable when the application of fracture mechanics has not been considered at the outset.

15-2

## Fracture mechanics applied to p.w.r. pressure vessels

### *Outline of procedures*

The integrity of a p.w.r. pressure vessel is a critical feature of the safety of this reactor system, and more effort has been devoted to the application of fracture mechanics to this system than to any other nuclear system. In essence, the safety case is based upon a fracture mechanics appraisal and the requirement that the vessel be subject to periodic in-service volumetric inspection for defects. Any flaws or indications found in such an examination are then assessed for growth and failure conditions by some method such as that using linear elastic fracture mechanics (l.e.f.m.) concepts. Inspection requirements and definition of acceptable sizes of defects are mandatory in the U.S.A., through the use for nuclear vessels of Sections III and XI of the American Society of Mechanical Engineers (A.S.M.E.) Boiler and Pressure Vessel Codes, which also indicate non-mandatory methods for the application of fracture mechanics. A U.K. Study Group (Marshall 1976) recently assessed p.w.r. vessel integrity. Accepting and using this background as a baseline safety argument, the Study Group highlighted several areas where uncertainties existed and further development was required. While this study concentrated upon the numerical values resulting from a specific reactor design, several of its conclusions are relevant to fracture mechanics applications in other reactor systems.

As is well known, the l.e.f.m. concepts require calculation of the stress intensity factor $K_{\mathrm{I}}$ at any defect using a relation of the form $K_{\mathrm{I}} = A\sigma\sqrt{a}$, where $A$ is a function dependent upon stress level and defect shape, $\sigma$ is the stress acting upon the defect, and $a$ is the critical dimension of the defect. Failure is considered to occur when $K_{\mathrm{I}}$ attains the critical value $K_{\mathrm{Ic}}$, the plane strain stress intensity factor, a material property often termed 'fracture toughness'. Other fracture mechanics approaches have parallel factors so that accurate definition of defect size, stress level and toughness are necessary in any assessment.

In applying such treatment to reactor plant, it is necessary to determine the relevant stress levels, fracture mechanics analyses being performed on selected regions such as those of highest stress levels (for example, those at changes of section thickness) and those areas subjected to neutron irradiation around the reactor core (belt line). The basic data on stress are obtainable from the stress analysis report for the vessel but more elaborate computations are essential in several situations. Possible areas of uncertainty relate to the value to be used for the function $A$ (necessary to calculate the applied stress intensity factor), which is not well defined for complex geometries, e.g. nozzle corners and in the treatment of residual stresses due to welding of main vessel seams or brought about by austenitic weld cladding of the inside of the vessel. The pressure transients occurring during reactor life can vary in range from 2 to 3100 lbf/in$^2$ (from *ca.* 14 to *ca.* 22000 kPa); some 35 different transients have been identified with lifetime occurrences of each ranging from 1 or 2 to more than $10^6$ at 2 lbf/in$^2$ (*ca.* 14 kPa)). These transients determine the extent of cyclic crack growth, the very large numbers of small pressure cycles showing significant calculated growth.

While the pressure transients influence crack growth and will dictate failure conditions under normal operating conditions, in many cases the highest stresses arise when cold water is injected into the vessel if normal coolant flow is lost owing to rupture of a coolant pipe (loss of coolant accident), or the rupture of a steam line between steam generator and turbine (steam line break accident) results in 'blow-down' of the secondary circuit and rapid cooldown and depressurization of the primary circuit. These events are regarded as 'fault' conditions having a very low probability of occurrence but must be taken into account in safety assessments, and, because of the large tensile thermal stresses at the inner wall of the vessel, they can produce a most onerous condition with respect to critical size of defect.

Turning now to the materials property aspect, A.S.M.E. (1977), in defining the fracture toughness $K_{Ic}$ of the constituent parts of the vessel, made use of Charpy V-notch impact tests and drop weight tests to determine a 'Reference temperature', $T_{r,\,n.d.t.}$ Tests are taken from plate or forging, weld metal and heat-affected zone produced by welding. This reference temperature is then related to a relation of reference toughness '$K_{Ir}$' against temperature relative to $T_{r,\,n.d.t.}$ to determine the variation of fracture toughness with absolute temperature (figure 1).

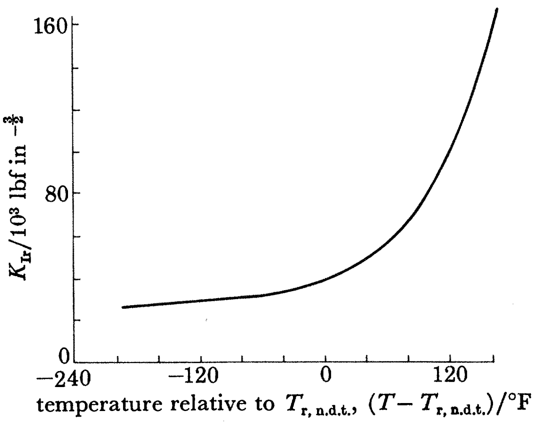


FIGURE 1. $K_{Ir}$ plotted against $(T-T_{r,\,n.d.t.})$. relation of appendix A (A.S.M.E. 1977): $(K_{Ir}-26.78) = 1.223\, e^{0.0145\,(T-T_{r,n.d.t.}-160)}$, where $K_{Ir}$ is reference stress intensity factor, $T$ is the temperature at which $K_{Ir}$ is permitted and $T_{r,\,n.d.t.}$ is reference nil ductility temperature. 1 lbf in$^{-\frac{3}{2}}$ ≈ 1099 N m$^{-\frac{3}{2}}$; 1 °F = $\frac{5}{9}$ K.

The reference toughness is stated to represent a lower bound of dynamic ($K_{Id}$) and crack arrest ($K_{Ia}$) toughness, this being selected to produce conservative or safe values in the absence of directly measured toughness values. Valid plane strain toughness measurements are practicable at temperatures up to about 50 °C, and common practice has been to assume consistency of toughness between the onset of these upper shelf conditions and operating temperatures of about 300 °C.

The final parameter in a fracture mechanics analysis is defect size. This may be introduced as a postulated non-existing size in a design stage calculation to give a demonstration of integrity; this is done in the non-mandatory appendix G of A.S.M.E. III, 'Nuclear power plant components', where it has to be shown that the structure will withstand a large imagined defect, typically under normal operating conditions, of depth equal to one quarter of the vessel wall thickness. Alternatively, and more appropriately for many cases, the treatment can be used to determine the critical defect sizes under the various conditions, including fault conditions. This can then be used to specify the necessary sensitivity of non-destructive inspection used for pre-service and in-service inspection and, by taking cyclic crack growth into account, also allows judgements to be made on the periodicity and extent of such inspections.

Typical values of critical defect depth at various locations for a particular example are reproduced in table 1. For normal operating conditions, the sizes are appreciable and would have a high probability of detection by in-service inspection. For major plant fault conditions, smaller critical sizes apply, these being strongly dependent upon the level of fracture toughness assumed, the computations used in defining temperature and pressure transients, and the stress intensity factor resulting from them. In such cases a crack arrest situation may sometimes be involved, it being argued that an acceptable crack arrest will occur when propagation has proceeded to an area of lower stress or higher temperature. The effect of the in-service environment must be taken into account, e.g. in defining crack growth rates (where surface-breaking cracks may suffer enhanced cyclic growth rates owing to corrosion fatigue effects) and changes in fracture toughness with time (ageing effects and particularly irradiation hardening providing a decrease in toughness at the belt line). Continuing reappraisals during service life are essential, taking into account actual – as distinct from design – transients, materials changes and the evidence gained from in-service inspections, including improvements in design to facilitate such inspections.

Table 1. Estimated critical crack depths in p.w.r. vessel (Marshall 1976)

| thickness/mm ... | 200 | 157 | 330 |
|---|---|---|---|
| transients | beltline | top head | nozzle corner |
| normal, upset, test | | | |
| cold hydro | 125 | 124 | 113 |
| steady state | 150 | 134 | 166 |
| loss of power | 142 | 126 | 149 |
| loss of coolant accident | 29 | — | — |
| steam line break accident | 38 | — | — |

*Appraisal of methods used*

This degree of detail in fracture mechanics analyses, which is required for licensing a p.w.r. vessel, has been developed over several years and is far in excess of typical specification requirements for a non-nuclear class I pressure vessel. Because the U.S.A. National Regulatory Commission (N.R.C.) stipulates that many of the requirements are mandatory, great emphasis is laid on compliance with A.S.M.E. Boiler and Pressure Vessel Codes and A.S.T.M. standard testing methods, and the background development has been extensive. However, the requirements do not necessarily represent the most sophisticated treatments possible nor, possibly because a wide consensus is necessary to obtain Code adoption, do they represent the most recently developed approaches, the principal objective being to obtain a conservative assessment.

The use of the approach has several implications for in-service requirements. For example, the stress analysis and predicted transients have a strong influence upon definition of safe conditions. Improved methods of stress analysis lead to greater sophistication and accuracies and reappraisal is often required during life of the vessel. Forecasts of vessel transients may prove incorrect, and this aspect may have to be reconsidered in the light of experience. To this end, monitoring of plant conditions is essential to permit accurate comparison with the conditions assumed in design assessments and hence to show when reappraisal may be necessary.

Similarly, in determining the function used to calculate the applied stress intensity factor, continuing calculation and experiment results in more accurate values. The values recommended by A.S.M.E. XI (Marston 1978) were selected from widely varying options, and for some areas of complex stress, typically nozzle corners, there are as yet no agreed values to be used for the function.

Derivation of material toughness, $K_{Ic}$, is indirect but based on a very extensive testing programme initiated by the U.S.A. Heavy Section Steel Technology (H.S.S.T.) Program (Canonico 1979). The programme concentrated on Mn–Mo steel plate of the type used almost exclusively for the vessels. Tests on forgings, weld metal and heat-affected zones were more limited but showed that toughness was generally superior to that of plate. While the correlation used with Charpy impact and drop weight test pieces may have wide applicability, evidence on other steels, or steels from other sources, is limited; further information is desirable and indeed some form of specific measurement for each application is preferable. The directly measured or derived toughness values may change during service owing to neutron irradiation or thermal ageing effects, so that monitoring or surveillance samples are essential to evaluate precise toughness during all stages of life.

The l.e.f.m. assessment assumes that such an approach must result in a conservative prediction of critical size of defect. In essence it assumes that crack initiation under plane strain conditions represents a minimum fracture energy criterion that with derived safety factors will result in under-prediction of the critical defect size. The requirements to maintain plane strain conditions prohibit, for all practical purposes, direct measurement of $K_{Ic}$ at temperature ranges from about 50 °C to operating temperatures. Toughness measurements of the $J$-contour integral or crack opening displacement (c.o.d., $\delta$) derived from elastic–plastic fracture mechanics (e.p.f.m.) calculations show some decrease in toughness with temperature. Typical $K_{Ic}$ values derived from such measurements show minimum initiation toughnesses of *ca.* 150 MN $m^{-\frac{3}{2}}$ (Ingham & Sumpter 1978) compared with l.e.f.m. values of *ca.* 200 MN $m^{-\frac{3}{2}}$ at the onset of upper-shelf behaviour. Analyses have shown (Harrop & Lidiard 1978) that such a reduction in toughness would not have a large effect upon the failure rate of vessels under normal operating conditions. Advances in e.p.f.m. suggest that higher toughnesses may be justified than those calculated at the first initiation of slow tearing. Much development is required in this area to permit quantification of safe acceptable amounts of slow crack growth in both test-piece and structure. When failure violates structural safety requirements, it is likely that initiation values, which appear to represent a material property, will be used in fracture mechanics analyses. The use of a limiting plastic collapse situation is, however, a valuable adjunct to l.e.f.m. or e.p.f.m. methods, and the two-criteria assessment method (Harrison & Milne, this symposium) can give useful guidance in sensitivity analyses.

Although uncertainties in stress, stress transients or toughness affect the accuracy of fracture mechanics assessments, by far the greatest uncertainty arises from the lack of information on defect detection and measurement, and lack of knowledge of possible defect distributions. Estimates, based on operator experience, of the probability of missing defects ultrasonically at pre-service inspection (Marshall *et al.* 1976) showed a rapidly increasing probability as defect depths fell below about 50 mm (see figure 2). Practical measurements by several operators using methods recommended for in-service inspection showed lower reliability of detection (O'Neill & Caussin 1979) and emphasized the need for improved and more reliable examination methods. With this background it is hardly surprising that probability analyses of failure rate are hampered by a virtual absence of knowledge of defect distributions in an inspected vessel. Practical application of in-service examination methods has led to changes in design of components to permit more reliable inspection and shows the need for improved access.

Overall, the general principles applied in fracture mechanics assessments of p.w.r. pressure vessels represent the ideal in that the definition of treatment of stresses, toughness and defect sizes represent the best available practicable methods at the time of formulation. Application of these principles during operation requires continual updating in terms of plant performance, stress analyses, material properties, improvements in non-destructive testing technology and the continually advancing science of fracture mechanics.

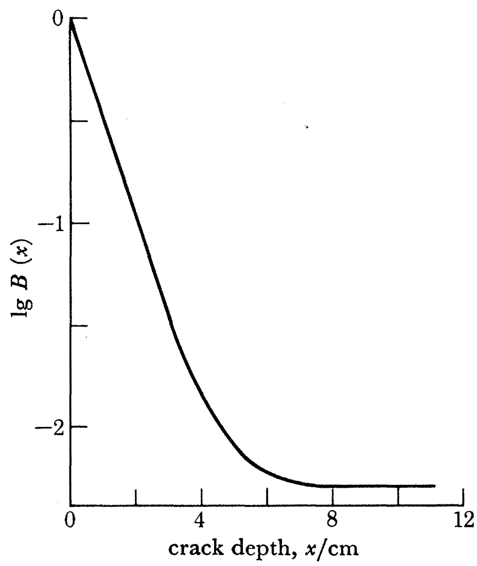


FIGURE 2. Probability of not detecting a crack at depth $x$ (Marshall 1976).

## APPLICATION OF FRACTURE MECHANICS TO OTHER NUCLEAR PLANT

The potentially elaborate fracture mechanics treatment that can be afforded to a new design of p.w.r. pressure vessel is generally not applicable to older plant nor indeed to the older pressure vessels. Such plant was generally constructed to the best standards available, often with supplementary requirements for nuclear construction, but rarely was precise information on fracture toughness obtained nor was stress analysis carried out in detail beyond that necessary to show compliance with Code requirements. Nevertheless, fracture mechanics methods have been applied in retrospect, even if this resulted in excessively conservative analyses, to assess tolerance to postulated defects and help define inspection sensitivities, and to assess defects found by in-service inspection. Application has been made to chemical plant, storage vessels, steam generator tube plates, steam drums and zirconium alloy pressure tubes. Examples discussed below highlight the problems encountered in application, the necessarily conservative approach adopted and the conclusions applicable to plant where rigorous fracture mechanics analyses are likely to be required to endorse safety.

Periodic in-service volumetric inspection is applied to nuclear plant where it is warranted by considerations of safety or reliability. Ultrasonic examination of a mild steel steam drum revealed the presence of a defect 13 mm long in weld metal of a set-through nozzle in the drum (figure 3). The defect was characterized, by using the rules of A.S.M.E. XI IWA-3300, as a sub-surface flaw that was non-interactive with the unfused land. Assuming that a value of 20 % of yield stress for residual stress in the weld was additive to the applied stresses, the linear elastic stress intensity factor was evaluated for the most severe loading conditions of the steam drum, including a periodically applied hydraulic test. The defect was considered to lie in either of two planes corresponding to extremes of stressing in one or more of the possible transients. The resulting maximum value of $K_I$ was *ca.* 23 MN m$^{-\frac{3}{2}}$ (table 2). Estimation of the critical size of defect presented a problem common to all plant designed and fabricated without fracture mechanics concepts being taken into account. Materials data over the range of temperature where operating stresses occur (0.1 MPa at 100 °C to 6.9 MPa at 300 °C) is non-existent for the actual materials used and sparse for any materials to the same nominal specifications. However, by comparison with known data on similar steels it can be shown that a toughness ($K_{Ic}$) value of at least 100 MN m$^{-\frac{3}{2}}$ will be attained over the appropriate temperature range, giving a substantial margin over the calculated maximum stress intensity factor of 23 MN m$^{-\frac{3}{2}}$.

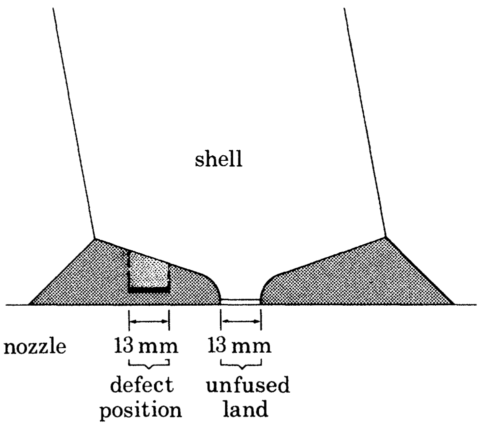


FIGURE 3. Position of defect in set through nozzle weld of steam drum.

TABLE 2. THE CALCULATED MAXIMUM STRESS INTENSITY FACTORS FOR THE DEFECT AND UNFUSED LAND UNDER VARIOUS LOADING CONDITIONS OF MILD STEEL STEAM DRUM

| | $K_I$/(MN m$^{-\frac{3}{2}}$) (excluding residual stress) | | | | $K_I$/(MN m$^{-\frac{3}{2}}$) (including residual stress = $\frac{1}{6}\sigma_y$) | | | |
|---|---|---|---|---|---|---|---|---|
| | defect | | unfused land | | defect | | unfused land | |
| load condition | plane 1 | plane 2 | plane 1 | plane 2 | plane 1 | plane 2 | plane 1 | plane 2 |
| normal running | 9.7 | 11.8 | 7.9 | (12.4) | 15.9 | 18.1 | 15.1 | (20.0) |
| overpressure to safety valve lift | 12.2 | 14.8 | 10.7 | (15.7) | 18.5 | 21.3 | 18.2 | (23.6) |
| spurious x-trip | 11.8 | 3.8 | −2.8 | (−2.6) | 18.3 | 10.0 | 4.3 | (4.4) |
| hydraulic test | 6.3 | 11.9 | 5.8 | (11.7) | 12.1 | 18.2 | 13.0 | (19.2) |

Parentheses indicate projected position of unfused land (see figure 3).

The detection of such a defect in service requires an assessment of whether it has been present and remained undetected at the start of service or has extended to its detected size by cyclic crack growth. Since cyclic crack growth rates are not sensitive to material variations, the crack growth rate based on data from other steels and weld metals was calculated to be less than $10^{-7}$ mm per cycle. On this basis it is virtually certain that measurable crack extension had not occurred during steam drum operation and that detection was due to more searching and sensitive methods of ultrasonic examination than had been applied previously. Final confirmation is obtained from accurate measurement applied at repeat periodic inspections.

In-service examination of a pressure vessel in low alloy steel to BS 1501-271 showed a defect at a nozzle wall interface extending the full circumference of the nozzle weld (figure 4). A similar linear elastic calculation to that used for the steam drum nozzle showed that, with the use of the most pessimistic assumptions of stressing defect size and position, the applied stress intensity factor was 40 MN $m^{-\frac{3}{2}}$ compared with the estimated minimum fracture toughness of the weld metal at 76 MN $m^{-\frac{3}{2}}$. Cyclic crack growth was insignificant. The defect was cut out, repaired and local post-weld stress relieving treatment applied.

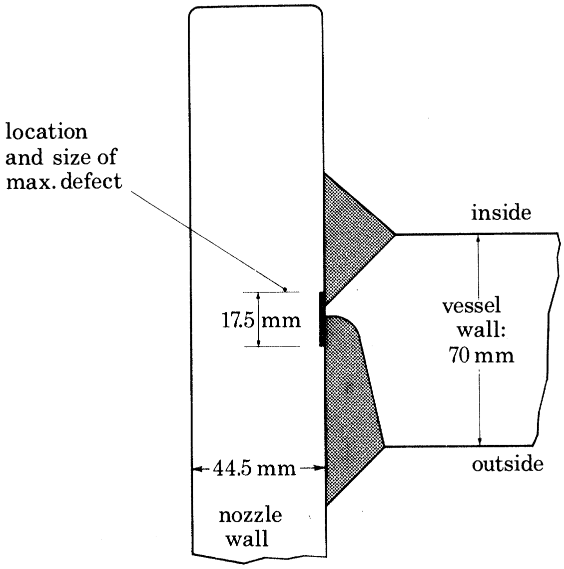


FIGURE 4. Position of defect in pressure vessel nozzle weld.

The Zircaloy-2 pressure tubes in the Winfrith Steam Generating Heavy Water Reactor form the primary containment for the coolant. As in the steel pressure vessels, it has been shown that failure is virtually incredible in the absence of defects. However, because of the size (125 mm diam. × 5 mm wall thickness), it has been possible to make direct determinations of critical sizes of defect by tests on defected full-size tubes. Tests could take directly into account the effects of zirconium hydride formation due to corrosion and the hardening effects of neutron irradiation. The high toughness of the material is reflected in the critical length of defect of over 100 mm at the operating stress and a defect depth of at least 80% of the wall thickness being necessary before snap-through occurs (Pickles *et al.* 1974). The controlling condition at failure is plastic collapse of the ligament beneath the defect or of the tube geometry, and the experimental measurements have shown that the normally accepted flow stress criterion provides an under-estimate of failure conditions. Crack growth measurements have shown behaviour in accordance with the Paris relation and have taken into account effects of corrosion fatigue. The data have been used to evaluate crack growth under pressure transients and vibrational stresses and to define frequencies of in-service ultrasonic examination of the pressure tubes.

## Conclusion

Fracture mechanics forms an important part of safety and reliability assessments applicable both in design and operation of nuclear plant. The degree of detail that can be applied depends upon the acceptance of fracture mechanics requirements at the design stage of the plant and a continuing feedback from fabrication, operation and in-service inspection of the plant to permit continuing accurate assessments.

The need for in-service volumetric examination, especially of selected weld areas, may require attention to overall access requirements in design involving, for example, detail requirements of adequate nozzle spacing, positioning of welds, etc. Equally, the design and stress analysis must take account of the possibility that some defects may remain in the structure and must show adequate tolerance to them.

The selection of an appropriate fracture mechanics approach is dictated by the current state of knowledge but one has to attempt to make some provision for changing science over the 20–30 year life of the plant. Conservative approaches are essential when the overriding requirement is safety and prevention of initiation of crack extension is likely to be the criterion adopted in the e.p.f.m. régime until structural behaviour can be quantified more accurately, probably by component tests.

The need to characterize fracture toughness over all ranges of operating temperature leads to specific requirements in both quality assurance and quality control. The direct measurement of toughness tends to be opposed both by steelmaker and fabricator. Quality control by Charpy impact and drop weight tests is accepted for p.w.r. vessels; these tests make use of empirical correlations on one type of steel to infer linear leastic fracture toughness. Improved quality control, backed by quality assurance, using small-scale e.p.f.m. test-pieces offers significant improvement in confidence of material properties. The alternative is a large increase in fracture toughness tests in research and development programmes to substantiate correlations of a wide range of material within the usually accepted quality control tests. For structures having a strongly safety-orientated function it is essential that archive material, covering plate, forgings and all types of welding used be produced to permit in-life reassessment of critical properties pertinent to the requirements of the developing science.

Continued reassessment demands updating of plant transients, material properties and assessment of defect significance found by inspection. This in turn calls for monitoring of plant behaviour, provision of material to assess the effects of corrosion, ageing and neutron irradiation and continuing reappraisal of inspection techniques, and, where appropriate, direct continuous measurement of plant strains and deformation. Improvements in ultrasonic examination technique and a better knowledge of inherent distribution of defects are necessary.

While these developments are necessary to full fracture mechanics assessments and would be a significant advance in providing data for use in failure probability analyses, there is often a demand to apply fracture mechanics treatments to plant that was constructed with little or no contribution at the design stage from fracture mechanics requirements. In such cases the need to establish relevant information can be balanced against the longer-term economic penalty of unnecessary repair or premature shutdown.

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## *Discussion*

C. I. L. Evans (*Rolls-Royce and Associates, Derby, U.K.*). Residual stresses have been mentioned by several speakers, but remarkably few have attempted to explain how to take them into account in a fracture mechanics analysis. Residual stresses of up to yield magnitude can and do exist in many engineering structures, and when such stresses are fed into the analysis an unacceptable answer is often the result.

It seems to me that residual stresses are of significance for structures operating in the l.e.f.m. régime, but, as a previous speaker has suggested, such structures are probably inherently unsafe anyway. For a properly designed structure, using correctly selected materials, significant plastic deformation and stable crack growth will precede unstable fracture. In the latter situation it should be safe to neglect the influence of short-range displacement-controlled stresses, such as residual stresses. I would welcome comments on this suggestion.

R. W. Nichols. I agree that it is important to establish the situation with regard to the extent to which instability conditions are affected by residual stresses – and indeed, other strain-controlled stresses such as thermal stresses and differential expansion stresses. Indeed, for some structures (such as those made from austenitic steel and those not given an effective stress-relief treatment), the level of such stresses can approach or exceed the level of the applied mechanical stresses. I also agree that under relatively brittle conditions, near the range of l.e.f.m. applicability, such stresses should be added into the stress assessment in full, while under plastic instability conditions such stresses can usually be completely ignored. The range of uncertainty is just the range of practical interest, however, that of the COD/R6 applicability. Dr Chell and others have made some proposals as to how to deal with this, and at R.N.L. there is currently a programme of tests, since it may not always be appropriate to make the pessimistic approach of adding such stresses in full, as is often recommended.