Fracture 1977, Volume 4, ICF4, Waterloo, Canada, June 19 - 24, 1977

FRACTURE PROBLEMS IN NUCLEAR REACTOR TECHNOLOGY[+]

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1. INTRODUCTION

The above title was to have been that for a plenary paper by Professor Corten, who unfortunately has had to withdraw at the last minute. The conference organisers felt that the topic was of such importance that a plenary contribution on fracture problems in nuclear technology was most desirable. I was therefore asked to give this off-the-cuff presentation, for the roughness of which I apologise. Time limitations will make it necessary to limit my treatment of the title to that of large-scale structural components which is, indeed, the focus of this plenary session : nuclear *fuel* behaviour is covered in Workshop Session VI.3 of the Conference. The following discussion thus refers to coolant boundary aspects - the *pressure vessels* and *piping* of thermal reactors and the *primary tanks* of Liquid Metal Fast Breeder Reactors (LMFBR). Since the given title refers to *Problems*, I will confine my paper to outlining areas where future work in the fracture field is likely to be most rewarding.

2. THERMAL REACTOR PRESSURE VESSELS

Since the early discussion of this topic at ICF1 in Sendai, there has been major development of the application of Linear Elastic Fracture Mechanics (LEFM) to the large, thick-walled steel pressure vessels of Light Water Reactor (LWR) systems, to the extent that assessment techniques based on LEFM are codified in the non-mandatory appendices to the ASME Boiler & Pressure Vessel Code, Section III Appendix G and Section XI Appendix A. LEFM also played a prominent role in the acceptance of the novel concept of allowing flaws to remain in pressure vessels if found during service, and if they were smaller than sizes calculated as permissible on LEFM principles. These are major steps forward : such codification of procedures in what is in effect a legal document, having required much first rate technical work. In order to indicate what are the most important problems still remaining I will sketch in the procedure.

The first step is to define what conditions the vessel and circuit is expected to withstand. This is perhaps one of the most difficult steps of all. Automatic control during normal operation leads to large numbers of small variations in coolant conditions on which we need more information to calculate

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[+] The text of this paper represents an edited transcript of the lecture Dr. Nichols, President of ICF 1977-1981, gave on short notice. We are particularly grateful to Dr. Nichols for consenting to step in and fill what otherwise would have been an unfortunate gap in this session and indeed the Conference as a whole.

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fatigue behaviour. But more important is to establish what reactor fault and engineering conditions must be examined, and what are the resulting conditions of temperature and pressure. This work can involve extensive calculations of hydrodynamics and heat flow dynamics for such situations as a major coolant pipe failure or breaks in steam lines, pump bodies and heat exchanger tubes. Having made reasonable assessments of each of these, the next step is that of converting them into stress intensity values at a defect, which may be assumed to occur at any point in the system. The problem here is twofold - the *first* being that of *design geometry*, and indeed there have been major strides in the development of computer calculation to cover the various difficult geometries around nozzles, flanges and supports. The *second* point is that the actual geometry can be different from that of the design, and there is need for more work on the effect on local stresses of errors in alignment, of local weld profiles and of non-regular geometries.

The next step is to feed in the appropriate fracture toughness value for the local material and here we strike major problems. As George Irwin said in his plenary paper, almost all the interest, except perhaps for some accident calculations for breaks in steam-line calculations, is at temperatures when the material used displays upper shelf toughness values, whereas most of the K_I curves relate to sub-transitional temperatures. Moreover, the upper shelf toughness may decrease with increasing temperature, so that it is *not* sufficient to assume that measurements at lower temperatures give lower values. Here we need development of techniques, more measurements, and in particular, decision on the instability criterion. There is a large difference in values between the results for the point of *first growth of a crack*, possibly in a stable manner, and the point of maximum load, and use of the former is believed to provide a considerable margin of safety. The difference in instability conditions for different geometries makes it likely that the computation problems alone will make it necessary for the safety assessment of reactors to be based on *first initiation* for a long time to come. Having developed a method, we still need to know more about variations due to fabrication, welding, strain aging and environmental effects, and how to measure and control production.

Recently in the U.K. I have been involved in carrying out such an assessment. With all these limitations, the best estimates we can make show that the critical defect size, even in stress concentration areas, is > 50 mm under operating, test and upset conditions. Only under certain reactor fault conditions is the critical size ~ 25 mm, and in such cases there is a strong thermal gradient through the wall thickness, resulting in a gradient in fracture toughness. Thus, one can well argue that even if an unstable crack initiates it should be arrested. To prove that such arrest will, in fact, occur needs a greater understanding of the conditions controlling crack arrest than we have now. The recent Oak Ridge work on this aspect should be of great interest. Another area where further work is required is that of the effect of environment and mode of stressing on the rates of crack growth.

At present we can conclude that it is desirable to show that there are no defects in the component bigger than 25 mm deep. In principle this is well above the sensitivity of ultrasonic testing techniques, but there are occasions in practice when such defects may be rejected with only rather poor reliability. In part this is due to *physical* difficulties of ultrasonic examination (UE) - dependence on coupling, surface effect, defect orientation, attenuation or obstruction effects and local geometry, and in part due to *human* aspects inherent in using manual operators. Indeed, a recent review of various trials with UE suggests that manual techniques, unless very closely specified and practised by experienced personnel, may have only about 50% chance of finding such a defect. A major problem is thus both to improve the reliability of UE (e.g. by the use of mechanical recording multi-probe techniques) and to know more accurately this reliability. The reason for this last aspect is that there is considerable interest in assessing the risk of failure quantitatively using the technique of probabilistic analysis of the various fracture mechanics parameters. It would appear that the two parameters in which there is most uncertainty, relate to the number of defects above a given size likely to remain in the structure, and to the fact that the currently low failure rate depends more on getting a fabrication route which shows intrinsically a low rate of defect production, rather than relying on detecting and repairing all such defects.

Another approach to the same problem is to reduce the number of welds and to make them easier to fabricate and inspect. In this respect recent developments of pressure vessel design in Europe and the U.S.A. involve heavy forgings with integral flanges, nozzles and supports, which, together with fewer welds in the pressure vessel rings and heads, results in the vessel having only 20% of the welds of earlier designs. Moreover, in these designs, such welds can be positioned where they can be more readily inspected.

A similar advantage is associated with the thermal reactor design which uses pressure tubes rather than pressure vessels. In these a simple inspectable geometry is combined with the absence of welding. Mention of this reactor reminds me of another aspect of fracture research, that of determining the likely results of fracture - e.g. whether the component will fragment. One of the papers in Part VI [1] describes work to demonstrate that such pressure tubes will not fragment. On the other hand, one could argue that a better understanding of the events after fracture initiation is needed if one is to design protection against the possibility of pressure vessel failure as is currently suggested in Germany.

Time does not permit me to say much about fracture problems in the pipework, except that there is need for considerably better understanding of the detailed parameters controlling stress corrosion cracking in austenitic stainless steel welds, and how to inspect for such cracks, particularly in transition welds between austenitic and low alloy steels. In this respect Acoustic Emission methods are proving very useful.

3. FAST BREEDER REACTORS

In conclusion I will mention some of the fracture problems associated with the nuclear reactor which many regard as providing the only real hope of maintaining our existing standard of living into the next century, that is the LMFBR. The problem is very different from that in the steel pressure vessel of the light water reactors, as the pressure loads are small. The problems should thus be less and of a different nature, which will depend on design details. I will give two examples based on current U.K. work in this area. First there is the need to ensure that the primary vessel wall will not completely fracture, so that part of the vessel could drop from its supports. The second aspect is the need to demonstrate that the core support cannot crack, as this may allow the fuel positioning to change adversely. Both of these problems relate to fracture mechanics assessment of austenitic stainless steel, for which LEFM is not really applicable. Various alternatives are being studied, including COD, J and the 2-criterion approach described at this conference by Milne [2]. The lower mechanical stresses in these components are in some situations supplemented by high thermal stress and high residual welding stresses, such that even with these relatively ductile stainless steels, care is needed in design, or small defect sizes could lead to some degree of crack extension from a defect. However, such crack extension would in the main be due to the strain-limited thermal stresses and residual stress, which together make up almost the whole loading. An important area needing further analysis is whether such loading can cause significant crack extension. A further series of fracture problems arises from the sodium cooling itself. Firstly there is the effect of the sodium in any crack on all of the aspects discussed in Section 2 - crack detectability, fracture toughness, creep ductility and fatigue life - considerable work is in hand on these aspects. Then the ability of high heat transfer of the sodium brings fluctuating surface temperatures caused by flowing pockets of coolant which have different temperatures. This "thermal striping" problem puts great importance on the design assessment of thermal fatigue and the need to avoid undue conservatism in our estimates of permissible stress/cycles under these conditions. Finally, these conditions lead to creep/fatigue interactions where the sort of approaches outlined by Ashby [3] need more application.

However, to conclude, it is perhaps appropriate to emphasise that in most of these problems the best protection is to design for a situation where one can get warning of potential trouble by a small leak in sufficient time to take preventive action before a major failure occurs - the so-called *leak-before-break* [4] or *drip-before-flood* concept. Perhaps the most important area for future fracture work is in the proving of the criteria which define when leak-before-break occurs - how does the fatigue crack grow, what is the effect of mixed mode loading, does the crack change shape as it enlarges, what is the rate of bulging in giving leak before break? Perhaps at the next Conference in this series we may find some of the answers to these important questions.

4. REFERENCES

1. PICKLES, B.W., JOHNSON, E.R., and COCKS, H., "Fracture 1977 - Advances in Research on Fracture and Strength of Materials", ed. D.M.R. Taplin, Vol. 3B, Pergamon Press, New York, 1977, page 713 (Conference Edition, University of Waterloo Press).

2. MILNE, I., "Fracture 1977 - Advances in Research on Fracture and Strength of Materials", ed. D.M.R. Taplin, Vol. 3A, Pergamon Press, New York, 1977, page 419 (Conference Edition, University of Waterloo Press).

3. ASHBY, M.F., "Fracture 1977 - Advances in Research on Fracture and Strength of Materials", ed. D.M.R. Taplin, Vol. 1, Pergamon Press, New York, 1977, page 1 (Conference Edition, University of Waterloo Press).

4. COTTRELL, A.H., "Fracture 1977 - Advances in Research on Fracture and Strength of Materials", ed. D.M.R. Taplin, Vol. 4, Pergamon Press, New York, 1977, page 85 (Conference Edition, University of Waterloo Press).