THE PREVENTION OF FRACTURE INITIATION IN REACTOR STRUCTURAL MATERIALS

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The integrity of pressure retaining circuits in nuclear reactor systems is dependent on their tolerance to defects. When the size of a defect and its stress field reach a critical value, fast unstable fracture will occur. The relationship between defect size and stress field is brought together by the science of fracture mechanics. For materials failing under brittle conditions linear elastic fracture mechanics has been developed and applied, especially in U.S.A. to the fracture of 200-300 mm thick steel pressure vessels for PWR and BWR systems.

For materials which fail under more ductile conditions (non plane strain) general yield fracture mechanics, utilising a critical value of crack opening displacement (C.O.D.), is more applicable. This C.O.D. approach has been developed in terms of testing technique and its applicability to structures. Data are presented which demonstrate the test method as an extension of that used in linear elastic fracture mechanics test methods and, from tests on wide plates and pressure vessels, confirm the validity of the C.O.D. concept. Its direct use in reactor technology is exemplified in considering failure conditions in zirconium alloy pressure tubes in the Steam Generating Heavy Water Reactor (S.G.H.W.R.). C.O.D. test pieces are used for surveillance of embrittlement due to neutron damage and hydrogen pick-up and the C.O.D. values from such specimens have shown good agreement with the measured failure conditions of experimentally irradiated pressure tubes. It is concluded that general yield fracture mechanics offer a viable concept of quantifying failure conditions in the more ductile materials.

Whilst fracture mechanics permits a good prediction of failure conditions of materials, its application is dependent upon a knowledge of stress fields and actual defect sizes in structures. Defects may be found and quanified by non destructive testing before service. During reactor operation growth to the critical size may occur by pressure cycling, thermal cycling, stress corrosion etc.. Such growth should be quantified by periodic inspection of the structure during service. The use of surveillance test pieces permits the changes in toughness due to service conditions to be evaluated throughout reactor life; knowledge, by direct measurement, of changing defect sizes in the structure permits the safe remaining life to be calculated.

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DISCUSSION

Q R. L. CLOUD, U. S. A.

I would like to congratulate Dr. Nichols on a lucid and comprehensive presentation. His final point that: tough and sound materials are the best protection against fracture is certainly correct.

In connection with the recommendations made, this audience will be interested to know that the PVRC has formulated a fracture prevention criterion based on fracture mechanics. Sooner or later this criterion or a similar one will be adopted.

I disagree with Dr. Nichols that a failure is a failure. Certainly a catastrophic failure has different consequences than a leak. This is an important consideration in designing with austenic material. Design criteria must be formulated with a view toward consequences.

Second, existing transition temperature fracture prevention methods are qualitative and rather untidy. They are not unsafe. An unblemished record with respect to brittle failure of well over 100 commercial water cooled reactors is factual testimony to the safeness of the rules. They are safe because of controls on all fracture parameters, material, temperature and applied stress and also good quality control.

A R. W. NICHOLS, U. K.

Thank you for your kind remarks and for the information on the PVRC formulation; this seems to promise an important step forward. With regard to the question of whether a leak is a failure, I accept fully that there is a big difference in potential consequences which must be taken into account. Nevertheless I would stress that even for a leak in a reactor pressure vessel, the economic consequences of shut-down for repair and the effect on public confidence can be sufficiently great for the utility to wish to avoid it. From the point of view of performance a leak is a failure. Turning to your last point, I accept your comment, although the total number of vessel operating years is at present small, and certainly is not sufficient to justify changing or decreasing present estimates of probability of failure (1 in 10^5 vessel years). My main point however is that with continued extrapolation of material, thickness, stress and size comparison with present service is not meaningful and it is important to have a valid basis for fracture control if one is to avoid, and show that one is avoiding, the risk of failure.

Q R. W. DERBY, U. S. A.

1. Part of my business is to make cracks. I have worked closely with ultrasonic specialists and I have reservations about our ability to detect very tight cracks. Ultrasonics works fine when the structure is loaded, but not so well when it is unloaded and the crack is full of oil or water.
2. I think we should ask ourselves what we really mean by a leak in a PWR. Will it be a thin opening from which comes a jet or could it be that a large flap, say the size of a bed, will be pushed out ?

A R. W. NICHOLS, U. K.

1. In our experience it is rare to have a crack so regular or closed that it cannot be found by ultrasonics in the unstressed condition, but cracks can be overlooked if they are in a compressive residual stress field. This situation is less dangerous as such cracks will not grow as long as the stress field is compressive. Nevertheless, this is a further argument for additional testing techniques such as acoustic emission.

2. There is no general answer to your question. An irregular or composite crack could be of the critical size even where this is of the order of twice the plate thickness without any detectable leakage, a further argument against the "leak-before" break" approach. The subsequent behaviour will depend on the structure, end-effects, the pressurizing medium and the material toughness. Again one's best defence is material so tough that the critical crack is several times the plate thickness.