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DISCUSSION

E. C. Miller[2]

The authors describe the technical criteria used to establish the adequacy of steels for nuclear reactor pressure vessels based on the UKAEA philosophy for design against catastrophic failure. They provide a particularly worthwhile, critical, objective evaluation of pertinent information selected from the mass of available material related to the failure of engineering structures. The paper should serve as an extremely valuable summary of the subject for reactor designers and materials engineers, who should, in turn, apply the information to their own problems with an objectivity comparable to that which the authors have applied to the problems of the British gas-cooled reactor program.

A number of significant observations are made or reconfirmed in the paper. One is recognition of the very considerable length (sometimes of the order of feet) of through-thickness defect necessary to initiate catastrophic failure of vessels operating at conventionally established design pressures. Another is the extent of damage which results when this large critical defect size is exceeded. Still another is the increase in this critical propagation-initiating crack length which can be achieved by using materials with greater notch toughness and by selecting geometries which minimize stress concentration factors.

The authors properly caution their readers that leakage of coolant, which can be a serious failure itself in some situations, can occur well before the critical crack length is reached. The history of the development of tests for brittle fracture and crack arrest, and the critical evaluation of the test results are of particular value; they provide a basis for the responsible application of judgment to the correlation of experimental test data with probable vessel behavior. The authors sound proper notes of caution in pointing out the relatively large number of cases where crack arrest does not occur until temperatures are reached where the Charpy fracture appearance is fully fibrous, and in suggesting that the crack arrest temperature for 3 to 4 -in. thick plate will approximate NDT +90 deg F.

The authors provide a basis for evaluating the adequacy of weld metal in relation to pressure vessel safety considerations. Similarly, they have developed sound guides for considering creep deformation, stress rupture, stress concentration, fatigue under design stress loading, and high strain fatigue. In considering the possibility of extension of defect sizes to critical crack lengths by these various mechanisms, they conclude that the probability of failure in the anticipated life of a reactor vessel is small. The writers have stated their case well and the principal questions which come to mind relate, not directly to the subject of the paper, but to the possible extrapolation of the information to other reactor types and conditions.

1 The authors do not discuss the subjects of residual stresses or thermal stress relief, presumably because specific requirements are included in BS.1500. However, a brief exposition of the authors' views on the influence of residual welding and fabrication stresses on crack extension and propagation and the effectiveness of the stress relief practices of BS.1500 in minimizing stresses, should be of interest.

2 Under the heading "High Strain Fatigue," the authors mention "initial pressurization." However, it is not clear if they are referring to initial service pressurization at working pressures or to a higher initial pneumatic test at some fraction above the working or design pressure. In any event, I should like to learn the authors' evaluation of the initial pressure test as a means of redistributing stresses and thereby reducing susceptibility to brittle failure of a vessel actually operating in the brittle temperature range.

3 The experiments described by the authors were presumably performed on material which had relatively high impact resistance (e.g. 80 to 100 ft-lb V-notch Charpy) at temperatures above FTE or CAT, that is, in the ductile range. However, consideration has been given in this country to pressure vessels of high strength quenched-and-tempered steels, some of which have relatively low ductile tear strength or impact resistance—in some cases as low as perhaps 30 ft-lb V-notch Charpy. Some quite ductile nonferrous materials exhibit similarly low impact values through the entire temperature range. Also, conventional pressure vessel steels subjected to long time irradiation by high energy neutrons show reduced impact values in the ductile range (in addition to increased NDT temperatures). I should like to learn the authors' views on possible similarities (or differences) of behavior of these three different types of materials, the critical defect lengths required for ductile failures in such low-energy ductile materials, and the relative probability of slow extension of cracks in these materials.

W. R. Smith, Sr.,[3] and F. A. Brandt[3]

The authors are to be complimented on a paper presenting a wide range of solutions to the practical metallurgical problems associated with the design of pressure vessels. It is refreshing to read a paper which makes positive statements on subjects that can be directly applied to equipment production.

We would like to ask the authors questions similar to some asked of Messrs. Pellini and Puzak, who are also presenting a paper on this same general subject at this conference.

First: No comment is made in the paper on the role of rolling direction in its effect on crack propagation once the critical crack size has been reached. Pellini and Puzak show that low-energy tearing of high-strength steels is associated with low upper-shelf energy in the Charpy-V test curve. Lower upper-shelf energies are also observed in transverse Charpy-V tests as compared to longitudinal tests. Can one assume that lower-energy tearing can also be associated with crack propagation parallel versus across the rolling direction at temperatures above the crack-arrest point

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once the critical crack size has been exceeded? Will rolling direction affect the critical crack size?

Second: Fig. 1 of your paper illustrates that a crack at the end of a 24 in.-long slit will propagate at the same stress at the FTE temperature and at the NDT temperature. As shown by the dotted lines in the same figure, one would expect from the Pellini-Puzak analysis that the stress to propagate the crack should be considerably higher at the FTE temperature. Do you have an explanation for this apparent difference?

Finally: You indicate that conventional quality-control tests (i.e., the Charpy-V impact test) cannot be used to predict crack-arrest values to an accuracy sufficient for safety requirements. What are the fundamental characteristics of the isothermal crack test which provide it with the ability to measure the true crack arrest values accurately?

Authors' Closure

The authors would like to record their appreciation to the contributors to the discussion for their generous comments. In attempting to review the whole field of reactor pressure vessel design and operation considerable detail had of necessity to be omitted. This opportunity to reply to the discussion will, perhaps, rectify some of these omissions.

BS.1500 requires stress relief to be applied to all Class I vessels, the recommended values being 1 hr per in. of thickness at 600-650 C with an alternative of longer holding times at lower temperatures. Stress relaxation tests on reactor quality steels have shown that, accepting a criterion of maximum residual stress in this laboratory test of about 2 tons per sq in., BS.1500 gives effective stress relief at temperatures above 550 C [26]. Below this temperature the holding time recommended is inadequate to allow relaxation to this stress level. In practice, however, the large mass of the gas cooled reactor vessels have necessitated site stress relief with very long heating and cooling times of the order of 25 hr or more above 600 C [27]. Thus, providing the temperature gradient in the vessel is kept to low values, stress relief of these large vessels exceeds the requirements of BS.1500 by a considerable margin. While reducing the residual stresses to satisfactory limits, this prolonged heat-treatment can result in deterioration of tensile, creep, and notch toughness properties. This has necessitated extensive investigations of these changes in properties [14].

Thus, as far as the reactor vessel is concerned, residual stresses can virtually be disregarded. In the general case however, we would, to a first approximation, regard them as additive to the effects of applied pressure. Evidence of this effect was obtained in the tests of the 5-ft-dia vessels [2]. Over zealous application of a flame to the ends of a slit induced tensile residual stresses and failure occurred at a $pd/2t$ value of 4 tons per sq in. Extrapolation of other test values suggested a failure condition of about 8 tons per sq in. and this was obtained in a repeat test when care was taken to avoid residual stress formation.

In discussing high strain fatigue "initial pressurization" referred to a general case; in the case of most steel pressure vessels a proof test pressurization and the first service pressurization require separate consideration. Usual practice is to proof test at, or not far above, ambient temperature to 150 percent of the working pressure. Subsequent service pressurizations, if at the same temperature and with similar stress system, would give reduced amounts of yielding at stress concentrations. However, when the first service pressurization is at a high temperature, the change in mechanical properties, particularly reduced yield strength, and possible effects of thermal stresses may result in similar or even additional yielding to that encountered in the ambient temperature proof test. Thus the initial service pressurization could be the controlling factor of the strain cycle to be imposed during operation.

There has been considerable discussion in the Panel Session on the virtues of an initial warm pressure test relative to operation in the brittle range. In summary it may be said that such a test confers a degree of safety; we think advantage of this test can only be taken if service conditions are similar to the test conditions and especially there should be no risk of impact loading or of defects lengthening beyond their original yielded stability limits. We consider that there is insufficient experience of this approach to recommend operation of a reactor pressure vessel in the brittle range.

Referring to Mr. Miller's query on material quality we would emphasize that the test data shown in Fig. 1, refer to a 0.36 percent C steel having Charpy V-notch energy values at the FTE of only 20–50 ft lb; in the fully ductile condition above FTP this rises only to 40–60 ft lb. Subsequent tests on vessels over the same temperature range, but containing an Al grain refined reactor quality steel, showed that stresses of the order of the Y.Pt. were necessary to initiate 12 in., slit lengths, compared with values of $^1/_2$–$^2/_3$ Y.Pt. for the 0.36 percent C steel. A correlation between the Charpy energy value and the failure stress has been proposed [28] for the range of steels so far tested but we would not hazard a guess as to whether or not it is applicable to high strength steels or to nonferrous alloys.

The effect of reduced Charpy energy after irradiation on critical crack length might be predictable from this relationship. At the life doses (—1.10^{18} n/cm > 1 MeV) suffered by existing vessels the reduction in Charpy energy is comparatively small and, on this basis, the stress for failure of a given crack length would still exceed, by a considerable margin, that necessary in the 0.36 percent C steel. For this type of failure the accompanying increase of yield strength due to irradiation should prove to be beneficial.

Replying to the first question of Messrs. Smith and Brandt there is only limited evidence to show the effect of rolling direction. With one exception the crack direction was at right angles to the rolling direction, that is the same direction as the crack in the longitudinal Charpy V-notch specimens. In this exception the crack direction was parallel to the rolling direction and, using the Charpy correlation referred to above, the failure pressure could be predicted from the relevant Charpy V-notch energy value in the transverse direction. This suggests that, at constant yield and tensile strength, the Charpy energy value allows a moderately accurate prediction of critical crack conditions. Further tests are in progress to investigate the relative effects of fracture toughness and tensile strength.

The small temperature dependence of the critical crack length again agrees with the low slope of the Charpy V-notch energy curve of the material [2]. Similar temperature dependence in vessels of different steels having 10 in. and 20 in. slit lengths was found by Pellini and Puzak [4]. It has not yet been possible to investigate fully the temperature dependence of other steels in the (Charpy) transition range. In the tests no attempt was made to measure stresses at the tips of the defects although the plastic zone, found in every test, did increase in size with applied pressure.

Adoption of the isothermal crack arrest criterion as a means of minimizing the risk of *brittle* failure is based on the assumption that measures to given freedom from *brittle* crack initiation cannot be applied with confidence. Thus, if initiation is accepted, the criterion adopted must consider a brittle crack propagating into a structure, that is a steel plate under conditions of constant temperature and an applied stress. We consider that the closest approach to these conditions is given by the isothermal crack arrest test in which an artifically initiated brittle crack is allowed to pass into a stressed plate.

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