TOWARDS AN ELASTIC-PLASTIC FRACTURE MECHANICS PREDICTIVE CAPABILITY FOR REACTOR PIPING

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SUMMARY

Intergranular stress corrosion cracks have been discovered in the recirculation bypass piping and core spray lines of several boiling water reactor (BWR) plants. These cracks initiate in heat-affected zones of girth welds in Type 304 stainless steel and grow radially and circumferentially by combined stress corrosion and fatigue. The discovery of these cracks has caused considerable concern. The central problem was (as is) the difficulty of making accurate predictions of the failure loads to be expected in the presence of flaws. Linear elastic fracture mechanics is not applicable because of the high ductility and toughness of reactor piping: catastrophic rupture in these materials is preceded by considerable amounts of stable crack growth accompanied by large plastic deformations. Thus, more refined techniques than those that simply treat the initiation of crack growth in materials behaving in a predominately linear elastic fashion are required for the analysis of reactor piping.

This paper is based upon research initiated by a need to develop a failure criterion and a way to delineate leak-before-break conditions for reactor piping. An effective engineering solution for the type of cracks that have been discovered in BWR plants was first developed based upon a simple net section flow stress criterion. Subsequent work utilizing an elastic-plastic fracture mechanics point of view has indicated how a more precise approach to the problem might be developed. A survey of progress being made towards an elastic-plastic fracture methodology for ductile high toughness materials together with some preliminary applications specifically to reactor piping are also described in this paper.

In work aimed specifically at developing a fracture criterion for BWR piping, an integrated program of theoretical analysis and experiment was conducted. The program had three main tasks: flat-plate experiments, finite-element computations, and full-scale pipe experiments. By using the experiments and finite-element computations in combination, it was found that both the onset of growth and the stable crack-growth regime may be governed by a critical value of the crack-tip stretch criterion of about 2.5 mm. However, a simpler alternative procedure was made possible by the finding that the onset of crack growth and fracture for a wide range of crack sizes in Type 304 stainless steel could be correlated with temperature-dependent net-section flow-stress values. At 24 C, these are 403 MPa and 438 MPa, respectively. At 205 C, the appropriate values are 276 MPa and 348 MPa. As shown in the paper, these values can be used to obtain a simple, but accurate way of estimating the margin of safety in reactor piping containing circumferential cracks.

Current work aimed at the development of an elastic-plastic fracture methodology for reactor grade steels is examining a wide range of crack-tip fracture criteria. Of these, the most prominent are the crack-opening displacement, the J integral, and a generalized energy-release parameter. Values of these parameters are conventionally computed by forcing a computer model to match the applied load-crack lengths observed in center-cracked flat-plate specimens pulled to failure. Critical values of the crack-growth criterion can thereby be inferred from the calculations. These critical values can then be used in a finite-element model for a cracked pipe or other structure to calculate the failure load that terminates the stable crack-growth period. Guided by current results, the paper offers some conclusions on computational procedures for reactor materials in general and outlines some further steps that must be taken to treat highly ductile piping components.