OVERVIEW OF IRRADIATION EFFECTS ON FRACTURE TOUGHNESS AND CRACK-ARREST TOUGHNESS OF RPV STEELS*

R. K. Nanstad, S. K. Iskander, D. E. McCabe, M. A. Sokolov, and T. M. Rosseel

Metals and Ceramics Division
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831

SUMMARY

The safety of commercial light-water reactors (LWRs) is highly dependent on the structural integrity of the reactor pressure vessel (RPV). The degrading effects of neutron irradiation on carbon and low-alloy pressure vessel steels have been recognized and investigated since the early 1950s. In those steels at LWR operating temperatures (-288EC), radiation damage is produced when neutrons of sufficient energy displace atoms from their lattice sites. The defects formed in the steel as a result of those displacements typically cause hardening and a decrease in toughness. Tensile behavior exhibits an increase in yield strength, a decrease in the ultimate to yield strength ratio, and a loss of ductility as measured by specimen elongation. The decrease in toughness is most commonly represented by an increase in the ductile-brittle transition temperature and a decrease of the upper-shelf energy as measured by the Charpy V-notch (CVN) impact test. The synergistic effects of neutron fluence, flux, and spectrum, the irradiation temperature, and the chemical composition and microstructure of the steel must be understood to allow for reductions in uncertainties associated with the development of predictive models of embrittlement. The CVN toughness, however, is a qualitative measure which must be correlated with the fracture toughness and crack-arrest toughness properties, K_{Ic} and $K_{Ia,}$ necessary for structural integrity evaluations.

During the 1960s, it was well recognized that the effects of irradiation could degrade the materials, but definitive effects on fracture properties, especially in thick sections, were not available. Then, the field of fracture mechanics was in the early stages and even the amount of data on other material properties under LWR conditions was deficient. When the Heavy-Section Steel Technology (HSST) Program was initiated in 1967, the U.S. Atomic Energy Commission had, in fact, already sponsored two irradiation effects projects, and the HSST Program assumed managerial responsibility for them and for the formulation of plans for extensions of those projects. The results from those early programs were important in that they showed irradiation-induced degradation of fracture toughness, a strong temperature dependence of postirradiation fracture toughness, a need for larger specimens, and that the K_{Ic} temperature shift was about the same as the CVN 41-J shift. At about the same time, in late 1968, Potapovs and Hawthorne had

---

*Research sponsored by the Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, under Interagency Agreement DOE 1886-N695-3W with the U.S. Department of Energy under Contract No. DE-AC05-96OR22464 with Lockheed Martin Energy Research Corp.

reported that some residual elements, particularly copper, increased irradiation sensitivity. Subsequently, Title 10, Part 50 of the *Code of Federal Regulations* (10CFR50) evolved to include requirements for fracture toughness of RPVs. Those requirements included surveillance testing with CVN specimens and required fracture toughness specimens if the surveillance materials were predicted to exhibit marginal properties. Furthermore, 10CFR50 requires prediction of radiation effects using *Regulatory Guide 1.99* (Rev. 2). Additionally, screening criteria are specified for toughness transition temperatures which, if attained by the surveillance tests or by prediction, require plant-specific analyses to demonstrate adequate protection against pressurized thermal shock (PTS). As part of those requirements, 10CFR50 refers to the ASME *Boiler and Pressure Vessel Code,* Sects. III and XI, for fracture toughness and ASTM E 185 for surveillance testing and analysis as well as application of the test results. Moreover, *Regulatory Guide 1.154* incorporates estimates of the variability in fracture toughness and crack-arrest toughness for the critical RPV material in PTS analyses. Thus, it is important to recognize that the developments of fracture mechanics and knowledge of irradiation effects in RPV steels have occurred concurrently; moreover, the rate of developments in fracture mechanics have been significantly compelled by radiation effects research on RPV steels.

In 1972, the HSST Program began a series of irradiation experiments in response to the need for information regarding effects of neutron irradiation on the mechanical properties, particularly fracture toughness, of RPV steels. [In 1989, the HSST Program irradiation effects task was organized into a separate HSSI Program.] The eight completed projects include irradiation effects on (1) dynamic fracture toughness; (2) and (3) ductile tearing resistance; (4) state-of-the-art welds; (5) and (6) temperature shift and shape of K_{Ic} and K_{Ia} curves; (7) stainless steel cladding; (8) commercial low upper-shelf welds; and (9) thermal annealing. Two ongoing projects include effects of irradiation on the shape of the fracture toughness master curve for highly embrittled steel, and the effects of irradiation, post-irradiation thermal treatment, and reirradiation on the propensity for temper embrittlement in heat-affected zones. Concurrently, a number of other research programs on radiation effects in RPV steels were also in progress within the United States and in other countries. As the developments in fracture mechanics have led from the linear-elastic to the elastic-plastic regimes, the specimen size requirements for measuring fracture toughness has significantly decreased. At ORNL, the HSSI Program has irradiated and tested a large number of fracture toughness specimens up to and including 100-mm in thickness (4T). Such experiments have provided results leading to understanding of specimen size effects and, in fact, have contributed significantly to the development of ASTM standard test methods which allow the use of relatively small specimens (e.g., 0.5T and precracked CVN) to establish the material fracture toughness. The results have also provided important data regarding variability of fracture toughness in RPV steels which allow for statistically-based analysis. Such results have been obtained both for cleavage initiation in the ductile-brittle transition region and for ductile tearing resistance. Similar experiments have provided key results on the effects of irradiation on crack-arrest toughness and have demonstrated a decrease in the temperature difference between the K_{Ic} and K_{Ia} curves with irradiation embrittlement. Statistical analysis of data from around the world have indicated that the assumption of equivalent irradiation-induced CVN 41-J and fracture toughness transition temperature shifts may not be appropriate for all RPV steels. The experimental programs have provided key results regarding the fracture behavior of RPV steels under conditions of irradiation, thermal annealing, and reirradiation, to include effects of copper and nickel content, relationships between Charpy impact toughness and fracture toughness/crack-arrest toughness, specimen size effects, and statistical variability. Relative to PTS analysis, the results are directly applicable as the calculations of failure probability are directly dependent on the initiation and arrest toughnesses of the materials. The existing procedures for determining reference temperatures and associated uncertainties bear reevaluation with regard to the results obtained. Remaining issues regarding fracture toughness of RPV steels include limits of applicability of small specimen measurements and the associated uncertainties, effects of high levels of embrittlement on both fracture toughness and crack-arrest toughness, potential effects of so-called “late blooming phases,” the relationship between CVN toughness and fracture toughness for steels following post-irradiation heat treatment and reirradiation, and effects of dynamic loading and intergranular fracture on the shape of the fracture toughness master curve.