Scaling Methods for RIA Data

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Most of the test data for reactivity-initiated accidents (RIAs) with high-burnup PWR fuel rods have been obtained in the Cabri test reactor in France and the Nuclear Safety Research Reactor (NSRR) in Japan. Both test reactors have provided data on the fuel enthalpy required to produce cladding failure, which is important in some safety analyses. However, neither of these facilities produces PWR conditions, so it is desirable to scale these data to PWR conditions to obtain results relevant to commercial reactors.

There are several ways to use test reactor data for RIA analysis for commercial reactors. The traditional way is to use the data to validate a transient fuel rod code and then perform the commercial reactor analysis with that code. The difficulty with this indirect use of test reactor data is that it assumes that an appropriate failure model is available in the code and all code modeling assumptions and materials properties data are adequate for RIA analysis. Modeling assumptions (e.g., symmetric fuel pellet loading of the cladding, homogeneous and isotropic cladding mechanical properties) are not very accurate, and the mechanical properties data base for irradiated cladding is quite limited at this time. But the biggest difficulty is with the failure model; a detailed understanding of RIA failures is not yet available. In fact, the failure modes observed to date range from brittle to mixed to ductile. Also, the presence of non-homogeneous hydride precipitates and blisters may have a significant impact on the failure mode.

To minimize these uncertainties, a more direct way to use test reactor data for RIA analysis has been chosen. This method uses code stress and strain predictions at the time of cladding failure in the test reactor to determine critical values associated with the fuel rod segment used in the test. In order to apply these results to predictions for the behavior of the test rod segments in a PWR environment, it is necessary to estimate how these critical values would change with cladding temperature and strain rate. An algorithm for this method is described here for scaling RIA test reactor data to the RIA history relevant to a PWR. Such an approach can be refined as more mechanical properties and test reactor data become available.

For failures that occur in the elastic region, calculated hoop stress is considered to be the most important parameter. Brittle failure occurs at a critical stress intensity factor (i.e., fracture toughness), which is proportional to the product of the nominal applied stress and the square-root of the flaw size. For scaling purposes, the flaw sizes and distribution of flaws are assumed to be identical for the test reactor and PWR cases. Using FRAPTRAN, the hoop stress is calculated as a function of time for the actual test reactor pulse. The calculated hoop stress at the time of failure is taken as the critical failure stress. The calculation is then run again, but this time pulse shape, coolant temperature, coolant pressure, and rod internal pressure are changed to those that would be expected in a PWR. The previously determined value of critical failure stress is then located in the new calculation of hoop stress as a function of time, and the corresponding time is taken as the time of expected failure during the hypothetical PWR pulse. If the cladding temperature is not the same in the two calculations at the time of failure, then an adjustment is made for the temperature dependence of the critical stress intensity (i.e., fracture toughness). A few iterations are required to converge on consistent stress and temperature values. Once the time of expected failure is found in the second calculation, then the corresponding fuel enthalpy can be determined.

Preliminary calculations have been performed for Cabri's REP-Na10 test, which resulted in failure without any uniform permanent plastic strain based on measured residual strain in unfailed tests in Cabri. This test had a 31-ms pulse with a total deposited energy of 107 cal/g and was initiated at 553 K coolant temperature. The corresponding PWR case had a pulse width of 10 ms, approximately the same deposited energy, and the same initial coolant temperature. If we assume that critical hoop stress (or fracture toughness) is reduced about 25% for a 100 K temperature reduction, then the fuel enthalpy at failure is reduced about 20 cal/g from the 68 cal/g (in our calculation) enthalpy increase in the test. Roughly half of this reduction is due to the pulse width alone and half is due to the assumed temperature dependence of fracture toughness.

For failures that occur with some plastic hoop strain, ductility is considered to be the most important parameter. Strength is no longer the important parameter because the loading is "displacement-controlled" and cladding deformation progresses beyond the plastic yield strain (yield strength) and beyond uniform elongation (ultimate tensile strength) in many cases. Using FRAPTRAN, the plastic hoop strain is calculated as a function of time for the actual test reactor pulse and for a corresponding PWR pulse. The method of comparison is the same as above except that a failure strain is determined instead of a failure stress. If the cladding temperature is not the same in the two calculations at the time of failure, then an adjustment is made for the temperature dependence of failure strain (total elongation). Once the time of expected failure is found in the second calculation, the corresponding fuel enthalpy can be determined as above.

Preliminary calculations have also been performed for NSRR's HBO-1 test, which resulted in failure with about 0.7% plastic strain based on measured residual strain in unfailed tests in NSRR's HBO series. This test had a 4.4-ms pulse with a total deposited energy of 93 cal/g and was initiated at room temperature. The corresponding PWR case had a pulse width of 10 ms and an initial coolant temperature of 550 K, thus ensuring a much higher calculated cladding temperature than for the actual test. If we assume that failure strain (total elongation) increases about 0.4% strain for each 100 K temperature increase, a PWR pulse with the same deposited energy as the actual test pulse was found to be incapable of producing the larger failure strain. A pulse with twice the original deposited energy was found to produce adequate strain to reach this failure strain, and the fuel enthalpy at failure occurred about 40 cal/g higher than the 62 cal/g (in our calculation) enthalpy increase in the test. If a much larger temperature dependence for failure strain (total elongation) is assumed, the ductility of this moderately corroded HBO rod would increase so much that cladding failure by pellet-cladding mechanical interaction (PCMI) might not occur at all.

Details of these scaling calculations will be presented along with similar calculations for several other tests with cladding failure in Cabri and NSRR.