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Applicability of modified burst test data to reactivity initiated accident

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ABSTRACT

A comprehensive irradiated cladding mechanical property dataset was generated by a recently developed modified burst test (MBT) under reactivity initiated accident (RIA) loading conditions [1,2]. The test data contains a wide range of test conditions that could bridge the gap between fast transient test reactor data (short pulse and/or low temperature) and prototypical commercial reactor conditions. This paper documents an evaluation performed to demonstrate the applicability of the MBT data to fuel cladding performance under RIA conditions. The current effort includes a comparison of calculated fuel cladding failure/burst strain for tests conducted at the Japan Atomic Energy Agency's (JAEA) Nuclear Safety Research Reactor (NSRR) to the MBT dataset, and an evaluation of potential mechanisms on how some NSRR tests survived beyond the cladding loading capacity. A simple shell model, coupled with temperature output from the Falcon fuel performance code, was used to calculate the fuel pellet thermal expansion of NSRR tests at the point of failure. The calculated fuel pellet thermal expansion correlates well directly with the MBT data at similar loading conditions. A 3-dimensional (3D) finite element analysis (FEA) model was used to evaluate fuel movement potential during a RIA. The evaluation indicates fuel relocation into the pellet chamfer and later into the dish is possible once a temperature threshold is reached before cladding failure and thus could significantly increase the fuel rod energy absorption capacity in a RIA event.

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1. Introduction

The failure of the first CABRI RIA test [3] by pellet cladding mechanical interaction (PCMI) at low energy deposition generated intense interest in the nuclear industry. Although the initial test was later attributed to a localized hydride anomaly [3], several laboratories in Russia, Kazakhstan, and Japan also started their own test programs. A number of tests were performed at the Kazakhstani Impulse Graphite Reactor (IGR), Russian Large Impulse Graphite Reactor (BIGR) and Materials Science Research Reactor (MIR) using fuel clad with the E110 alloy [4]. Due to the low hydrogen pickup of the E110 alloy from normal operations the cladding was essentially ductile and failures were by high temperature mechanisms. The Japanese program at the Nuclear Safety Research Reactor however tested multiple fuel cladding types with a range of hydrogen concentrations [5–7]. Many tests ended in cladding failures over a wide range of energy depositions and hydrogen concentrations. The energy deposition of tests that ended in failure have been widely used as a starting point to establish pellet cladding mechanical interaction (PCMI) limits [8]. However, the NSRR test data is believed to be conservative since many of the tests were conducted at room temperature and pulse widths much shorter than limiting RIA events in a commercial power plant. Literature data suggests the cladding ductility improves with both temperature and longer pulse width [1,2]. Ductility improvement suggested by the literature data is supported by CABRI REPNa3 [3] test where UO_2 fueled test samples survived to higher energy deposition.

Fuel pellet thermal expansion is not expected to be pulse width dependent since it is a fundamental material property, and therefore it would be possible to translate the NSRR test data to commercial reactor conditions if the cladding property is known at both conditions. The actual fuel pellet dimensional change is weakly dependent on the pulse width since cracking and crack closure may have a slight pulse width dependence. A number of mechanical tests have been developed to characterize cladding behavior under transient conditions [9–16], but most of these techniques have associated test artifacts such that the data is not directly comparable to test reactor failure strains or testing was of insufficient scope to derive necessary trends for translation.

Recently, a new modified burst test was utilized in an extensive

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irradiated cladding characterization test program [1,2]. The modified burst test simulates pellet expansion by pressurizing and deforming a high strength driver tube. A gauge section machined into the inner wall of the driver tube allows for test sample deformation to be localized and thus enables continuous measurements of the cladding diameter change during a test. In this paper, the measured cladding failure strain is compared to the calculated test reactor failure strain.

2. Evaluation methodology

The failure strain of test rodlets from test reactor RIA simulation tests is not directly measured. This presents significant difficulties in post-test evaluation as the cladding strain and failure strain depend on many variables such as equivalent pre-transient fuel cladding gap, transient pulse width, cladding type, cladding hydrogen concentration, pre-transient conditioning temperature, etc. To reduce the uncertainty, an effort was undertaken to fully characterize the cladding behavior from test reactor to commercial reactor conditions using the modified burst test apparatus. In order to use the cladding characterization data to translate from test reactor to commercial reactor conditions, it must first be demonstrated that the failure strains measured from the MBT technique are comparable to the calculated test reactor simulation tests. Of the reported RIA simulation tests, most of the tests that ended in rodlet failure have been conducted at the JAEA NSRR reactor. The approach taken to demonstrate that the MBT reasonably simulates the cladding behavior under RIA conditions is to show that the measured burst strain is comparable to the calculated JAEA NSRR tests failure strains. This evaluation is conducted under conditions outlined in the following sections.

2.1. In-reactor simulation test sample selection

A number of RIA simulation tests have been conducted in test reactors. The IGR/BIGR/MIR programs tested fuel clad with the E110 alloy and failures were by high temperature mechanisms since the cladding was highly ductile due to low hydrogen pickup during operation. A few of the CABRI tests did fail by PCMI mechanisms, however most of them were attributed to local hydride anomalies. Only a single failed CABRI test could not be attributed to hydride blisters but it was mixed oxide fuel and failed at 502 J/g fuel enthalpy increase.

A number of RIA simulation tests conducted in the NSRR test reactor failed via the PCMI mechanism and thus could be used to benchmark the modified burst test data. Since the failure strain was not measured a proper evaluation requires the use of the parent fuel rod power history in order to ascertain the initial fuel condition. Unfortunately the information is not publically available for all the tests conducted in the JAEA NSRR programs. A detailed literature search yielded limited power history data on some of the tests [17–23]. Key attributes of the tests with last cycle power information is tabulated in Table 1.

2.2. Pre-transient fuel condition

A key input parameter to a RIA transient analysis is the equivalent gap between the fuel and the cladding. The gap influences an RIA event by absorbing part of the energy deposition before the fuel pellet expansion could stress the fuel cladding. For high burnup fuel, an observable gap typically does not exist since the fuel would be bonded to the cladding. Fuel materials used in test reactor RIA tests typically come from fuel discharged from commercial reactors. During power generation, the inside of the fuel pellet was hotter than the pellet periphery. On powering down, the pellet interior experiences a much larger temperature decrease and therefore thermally contracts more than the pellet exterior. When the temperature gradient is sufficiently high, crack opening is visible in metallographic examinations. An example of interior cracking is shown in Fig. 1. Prior to the initiation of a zero power RIA transient, the pellet is in a power down state and therefore the thermal shrinkage could be considered as an equivalent gap. The amount of shrinkage is a function of the pre-transient temperature gradient or power level. Not all of the thermal shrinkage may manifest in visible crack openings since the outer portion of the fuel is in compression and therefore some of the potential thermal shrinkage may be held as tensile strain. A hand calculation of the fuel creep potential showed after 12 months of operation, up to 0.2% creep strain is possible at 723 K with a stress of 1 MPa. Since the fuel tested in the various test reactors operated for an entire cycle at near constant power, the calculation clearly shows the fuel had sufficient time to reach equilibrium, and the thermal shrinkage is a function of the last cycle temperature profile and not influenced by earlier cycles. Therefore, test reactor tests with known last cycle power histories are included in the evaluation, even if the prior cycle power histories are not known.

2.3. Transient fuel and cladding temperature profiles

The fuel pellet expansion during a RIA transient is temperature driven. Thermal expansion is a basic material property of the uranium dioxide matrix and should be independent of the heat up rate. In order to calculate the expected fuel pellet expansion at the time of cladding failure, the temperature profile of the fuel pellet is needed. A fuel temperature calculation was performed with the Falcon Version 1.2 fuel performance code [24] using pulse width and energy deposition reported in literature. Examples of pulse profile and resultant temperature are shown in Figs. 2 and 3, respectively. The Falcon fuel performance code was used in a recent RIA benchmark exercise [25]. All the codes participated in the benchmark showed similar temperature profile for cases analyzed.

Unlike most power transients, the pellet periphery is heated rapidly to temperatures higher than the pellet interior. Due to the short duration of the NSRR pulse width, the fuel heat up is nearly adiabatic with very little heat conduction into the fuel cladding until 5 ms into the transient. The outer cladding surface does not appreciably heat up until 10 ms into the transient.

2.4. Fuel and cladding strength during transient

As shown in Section 2.3 the fuel pellet does not heat up uniformly. The higher temperature reached by the outer layers of the fuel causes that portion of the fuel to thermally swell more than the pellet interior. This complicates calculation of the effective fuel pellet thermal expansion. Temperatures reached in the outer portion of a pellet in a RIA could approach that of the uranium dioxide melting point and therefore its yield strength is significantly reduced. Fuel yield strength used in the current evaluation is based on reference [26] (see Fig. 4). The literature data has a maximum strain rate of 10/min or 0.17/s, which is slightly lower relative to the expected NSRR test sample strain rate of approximately 2/s, and the measurements only extends to 2300 K. Multiple loading rates reported in the reference indicate the fuel strength dependence on the loading rate is small and thus a conservative polynomial was fitted to the 0.17/s loading rate test data and extrapolation was used to extend the range to the melting point of the fuel. Fuel melting temperature for high burnup fuel is expected to be between 3100 K and 3400 K. For mechanical strength considerations, the exact melting point temperature is not important since strength already decreased to a fraction of the fuel room

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