LOCA DUCTILITY TESTS

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Background

Safety analyses for loss-of-coolant-accidents (LOCA) address several phenomena related to the behavior of fuel rod cladding: (a) ballooning deformation, (b) conditions for bursting, (c) oxidation kinetics, and (d) embrittlement. The first three are described by correlations, and cladding embrittlement is addressed by criteria in 10 CFR 50.46. These embrittlement criteria currently consist of a 17% limit on cladding oxidation and a 2200°F (1204°C) limit on cladding temperature.

The original motivation for the LOCA testing at Argonne National Laboratory (ANL) was to look for burnup effects on the embrittlement criteria, with burnup effects on ballooning, bursting, and oxidation as secondary interests. Interest was intensified in 1998 and 1999 when NRC first issued an Information Notice and then established the position that the 17% oxidation limit should encompass accident and pre-accident oxidation thus approximately accounting for the significant corrosion that accumulates with burnup [1,2].

Later, when Framatome's M5 cladding was introduced in the U.S., there was a desire to confirm that this new alloy, and the earlier Westinghouse ZIRLO alloy, both behaved adequately under LOCA conditions. While it was known that their ballooning deformation might be altered because of changes in the phase diagram for these niobium-bearing alloys in comparison with the tin-bearing Zircaloy alloys, data showed that oxidation and embrittlement were about the same as for the Zircaloys [3,4]. Data on another niobium-bearing cladding alloy, however, showed very different behavior [5,6,7,8]. It therefore became important to examine alloy effects more carefully and to understand the factors that could cause different LOCA behavior in some zirconium-based cladding alloys.

More recently, proposals have been made to replace the Zircaloy-based 17% and 2200°C limits with a performance based requirement in 10 CFR 50.46 to avoid the need for regulatory exemptions when new alloys are introduced and to accommodate any burnup effects. These current numerical limits were derived from ductility tests, so the proposal included the substitution of some suitable ductility test [9,10]. In addition to defining a suitable ductility test, additional research would be needed to confirm the similarity of oxidation kinetics for all zirconium-based alloys in order to substantiate other assumptions needed relative to peak cladding temperature [10].

After considering several possibilities, it has been decided to continue investigating the ring-compression test as the potential performance-based ductility test for 10 CFR 50.46, provided that it can be confirmed to be adequate. Ring-compression tests are less expensive to perform than the alternatives, and because such tests were used to develop the original embrittlement criteria, their continued use should contribute to regulatory stability. Two basic questions of adequacy will be addressed in the current research program. One is about our ability to interpret the results of ring-compression tests unambiguously, and the other is about the efficacy of a test on a small ring specimen to represent the behavior of a fuel rod in a ballooned and ruptured region. These will be discussed in the following paragraphs.

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Ring-Compression Tests

The schematic arrangement for a ring-compression test, as performed by Hobson and others, is shown in Fig. 1 [see 11]. Segments of tubes were oxidized on the inside and the outside

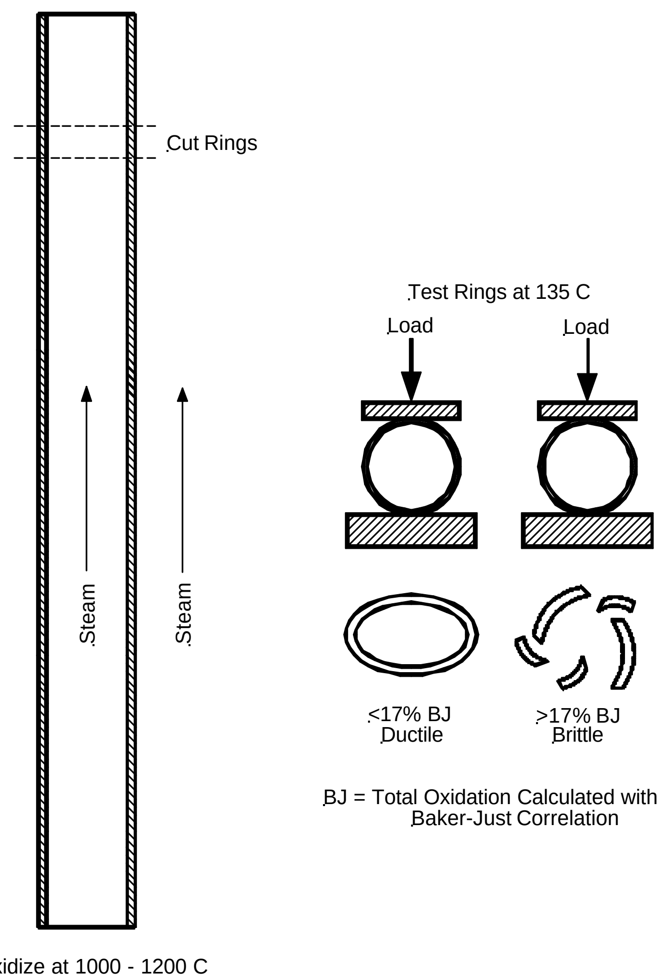

Fig. 1. Diagram of Hobson-type ring-compression tests that were used to obtain current LOCA embrittlement criteria

at various high temperatures in the range of 920-1320°C. After cooling, they were mechanically tested in compression over a range of relatively low temperatures and evaluated at 135°C. This temperature was selected as the lowest water temperature that would be present in a reactor after a LOCA. Based on Hobson's data, it was found that specimens would exhibit ductile behavior if the calculated oxidation (Baker-Just correlation) was less than 17% equivalent cladding reacted (ECR) as long as the oxidation temperature was not much above 1200°C. Hobson did not measure actual oxidation in the specimens, and we believe the critical ECR (boundary between ductile and brittle behavior) is really around 13% rather than 17% because of the over prediction of the Baker-Just correlation. We will measure the amount of oxidation in all of our tests and will therefore work with true values.

The principal stresses in the ring specimen are tensile stresses that result from bending, and these stresses are shown qualitatively in Fig. 2 by double ended arrows. This stress pattern

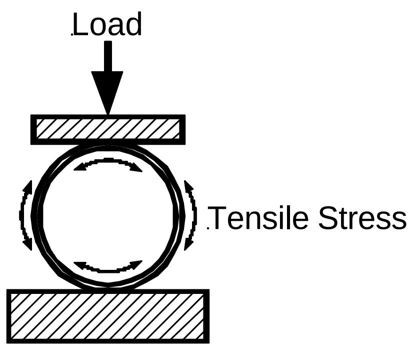

Fig. 2. Large OD and ID tensile stresses in ring between flat plates

usually results in four cracks through the cladding wall: two starting from the outside at the 3 and six o'clock locations, and two starting from the inside at the 6 and 12 o'clock locations. None of these cracks completely unloads the test apparatus, so instead of getting a load that drops to zero when a crack occurs, one gets a saw-tooth load-vs-deflection curve such as seen in Fig. 3. This figure is from recent work at the Russian Research Center, Kurchatov Institute. Figure 3 shows how Kurchatov analyzed the data to eliminate deformation in the load train and get a measure of plastic deformation in the specimen.

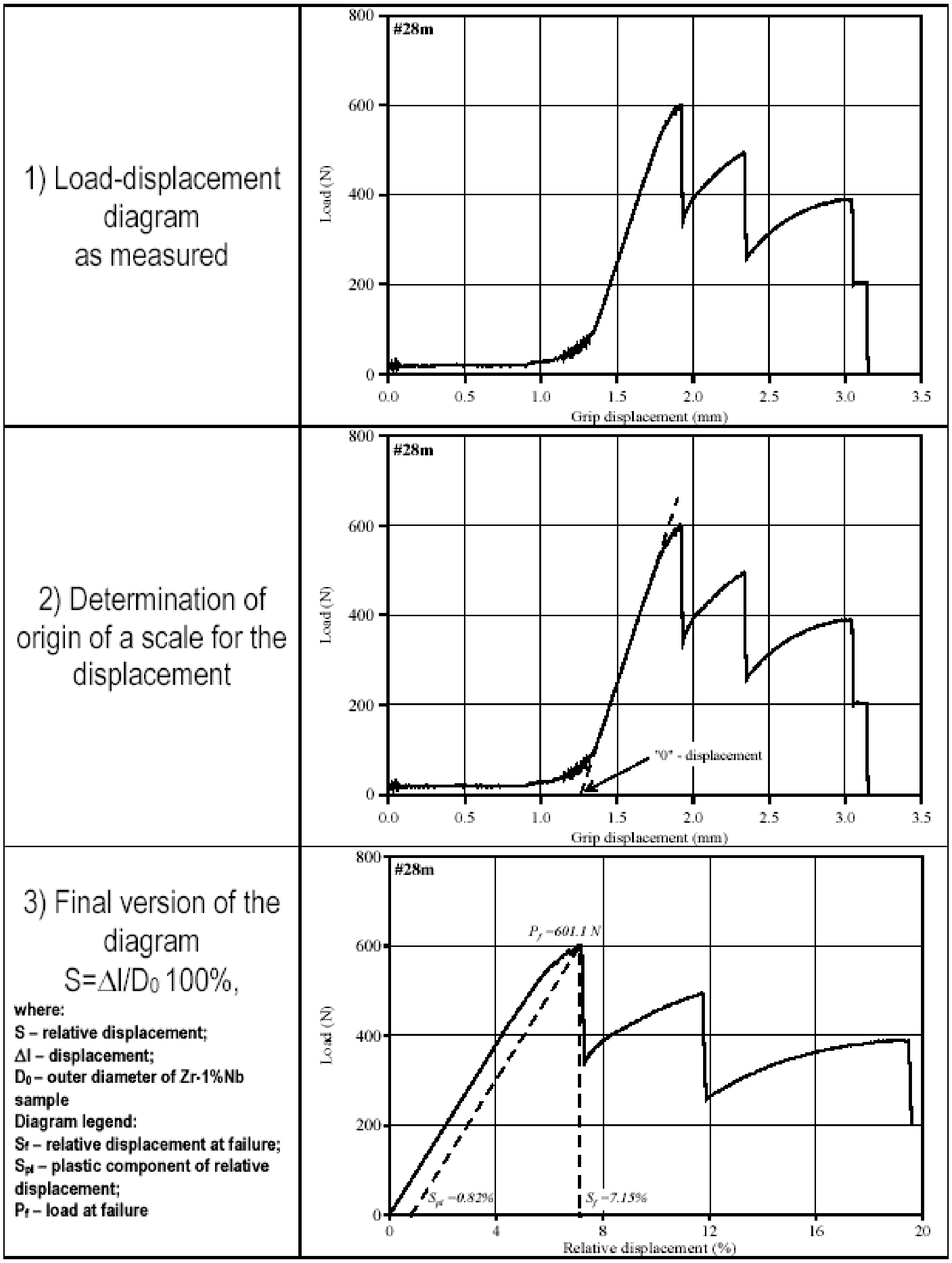

Fig. 3. Load-vs-displacement curve for ring-compression tests showing Kurchatov method of analyzing results

For a combination of reasons, it seems desirable to oxidize the specimens from the outside only. One advantage of this is that it will make the ring specimen more ductile on the inside diameter and, therefore, less susceptible to fracture at the 6 and 12 o'clock locations as just discussed. If, in addition, the top and bottom loading plates have curved surfaces, the bending stress at the top and bottom will be reduced thus further diminishing the potential for cracking at the 6 and 12 o'clock locations such that cracking should always occur at the 3 and 9 o'clock locations. This situation is sketched in Fig. 4 and should result in just two saw teeth in the

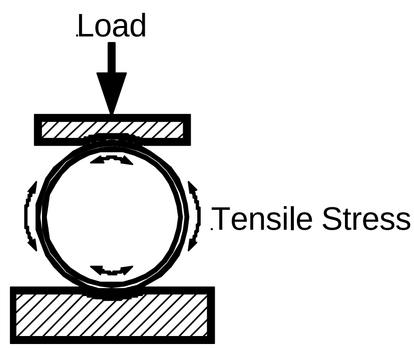

Fig. 4. Smaller ID tensile stresses in ring between curved plates

load-vs-deflection curves. This arrangement and the Kurchatov analysis procedure have been selected for the ring-compression tests. A transducer may be placed inside the rings to directly measure deformation if that is found to be practical. Some microscopy of fracture surfaces will also be performed to confirm the brittle or ductile failure mode. Tests will be conducted primarily at 135°C with some at 23°C to bound the range of interest and to facilitate comparison with earlier data bases.

Three-Point Bend Tests

Although more costly, a three-point bend test is probably better in several respects than a ring-compression test. Such a bend test is sketched in Fig. 5 along with a double arrow to indicate

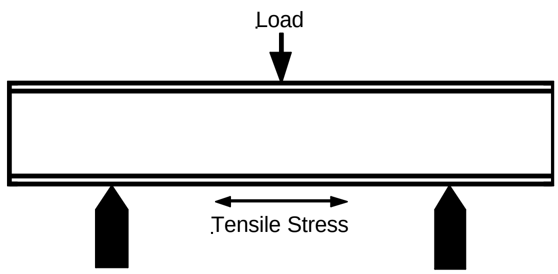

Fig. 5. Three-point bend test with tensile stress on lower OD surface

the location of maximum stress. The first advantage of this test is that the tensile loads are applied in the axial direction rather than in the circumferential direction. This is probably more representative of stresses that might arise from horizontal accelerations (earth quakes), plant vibrations, and spacer grid interactions. Furthermore, the load-vs-deflection curve for this test is simple and easy to interpret. As soon as a crack propagates through the tube, the load falls to zero without any ambiguity as seen in Fig. 6 from Framatome's recent work [3].

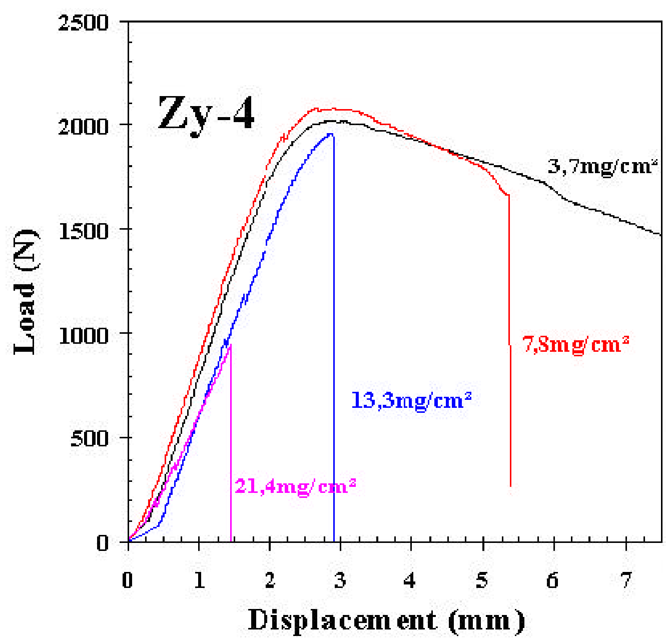

Fig. 6. Load-vs-displacement curve for four Framatome three-point bend tests

If the ring-compression test and the three-point bend test both show the same critical ECR for the same material, then we can use the less expensive ring-compression test. Framatome has performed ring-compression tests and three-point bend tests on M5 tubing. If Framatome is able to make those data openly available, Anatech (for EPRI) will make the assessment to see if the two tests produce the same result. Otherwise, some three-point bend tests will be performed at ANL to generate data for this assessment.

Four-Point Bend Tests

The four-point bend test that we plan to use is shown schematically in Fig. 7. This test, with

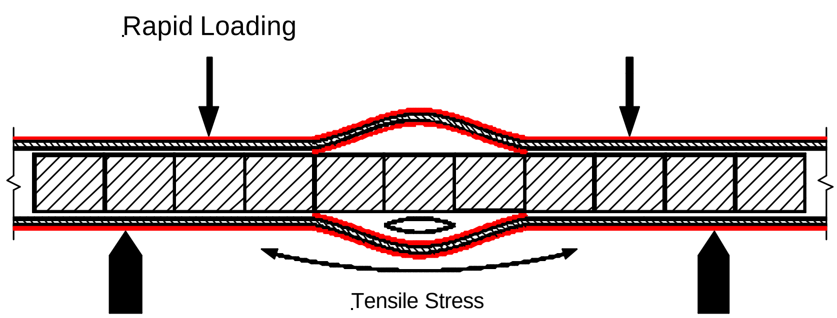

Fig. 7. Four-point bend test on ballooned and ruptured segment of rod containing fuel; tensile stress on lower OD surface

fuel pellets inside, is most prototypical for investigating the behavior of the ballooned region of a fuel rod. Double-sided oxidation will take place as appropriate, with steam entering through the burst opening. Any enhanced hydride absorption due to inside oxidation will be present. Loading points are away from the deformed region, and the specimen will break naturally at its weakest location. While this is clearly the most expensive test, it only needs to be used in a confirmatory way. If results from the ring-compression tests can be applied in the ballooned region, and if that adequately predicts ductile or brittle behavior, then the ring-compression tests will have been confirmed. In a way, Chung & Kassner's 0.3 Joule impact tests of 1980 provided this confirmation for the 17% and 2200°F values for unirradiated Zircaloy [11].

Test Matrix

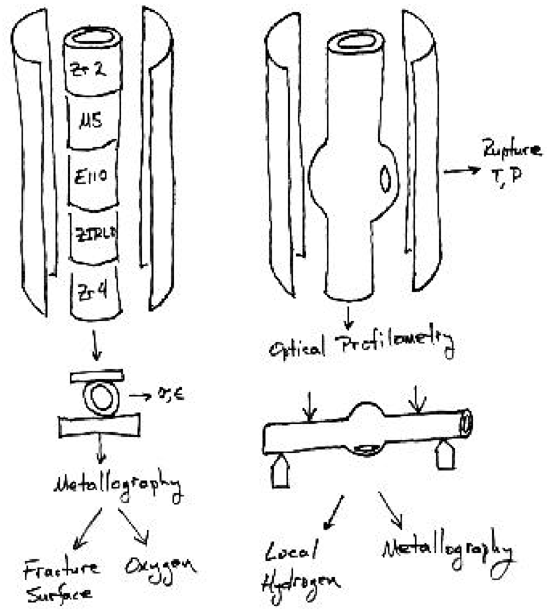

Fig. 8. Schematic diagram of testing sequence

Figure 8 shows a schematic diagram of the testing sequence. The ring-compression tests and the four-point bend tests will be integrated into the overall LOCA test program. Unirradiated tubing, as received, will be tested first. Irradiated cladding, as it becomes available, and hydrogen-charged tubing will be tested later to investigate burnup effects. Two or more alloys will be oxidized together in the same furnace to reduce the number of furnace runs needed to produce ring specimens (and three-point bend specimens, if necessary). Oxidation kinetics can also be obtained from these furnace runs, and examination of ring fragments after compression will give fracture morphology and oxygen content. Specimens for the four-point bend tests will consist of those specimens that survive thermal shock in the integral tests. After optical profilometry, those specimens will be tested in the four-point bend apparatus and will likely break. Metallography and hydrogen measurements can be made on fragments after the bend tests.

The number of integral tests will be small. Approximately three tests per alloy type will be performed for irradiated material along with a somewhat larger number of tests on unirradiated tubing. The number of these tests will govern the number of four-point bend tests that are performed. We will not try to refine this estimate at this time.

The number of ring-compression tests will be large, however, and attention is needed to control the test matrix to a manageable size. First we noticed that Kurchatov has performed tests under a variety of conditions including heating rate, cooling rate, test temperature, and inside-vs-outside oxidation. Differences were small. Figure 9, for example, shows various

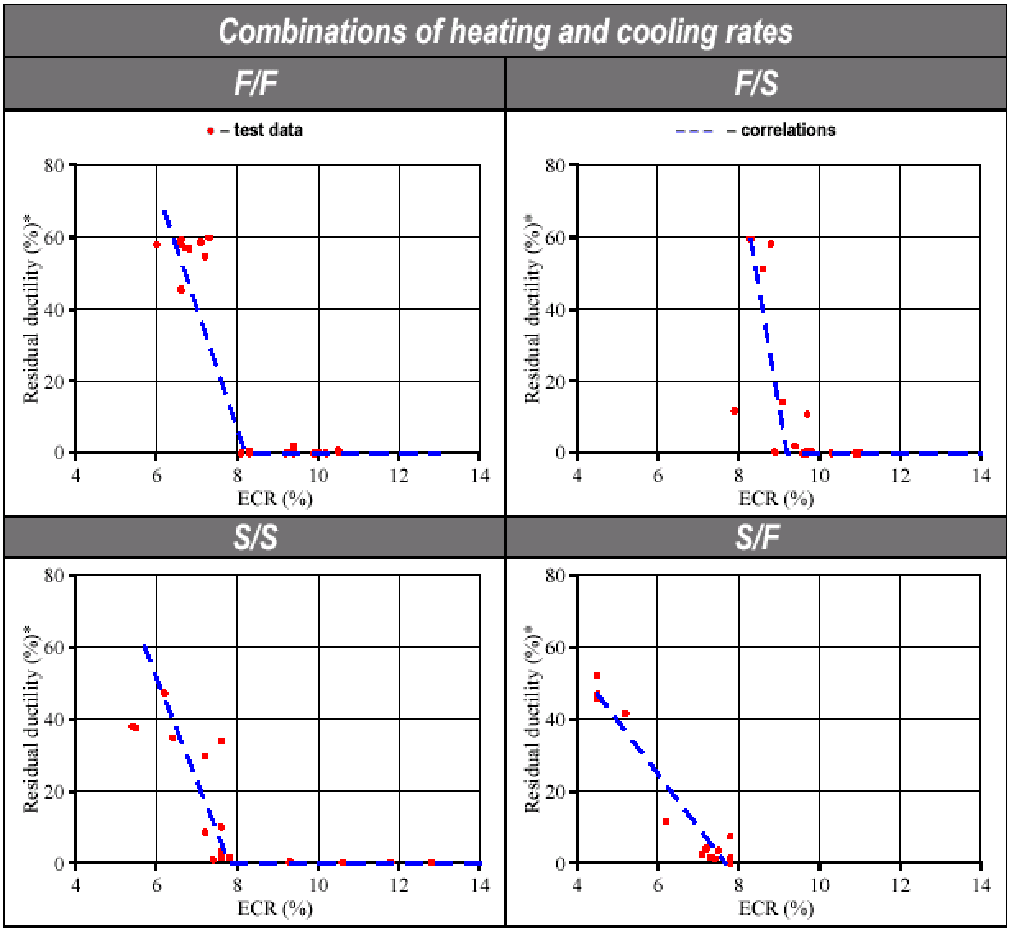

Fig. 9. Residual ductility versus oxidation for four Kurchatov combinations of heating rates

combinations of heating and cooling rates, which had very little effect on the critical ECR of around 8% for E110 cladding. These plots also show that multiple ECR values need to be tested to determine a critical ECR value.

Five nominal ECR values will be tested for each of the five materials (Zircaloy-2, Zircaloy-4, ZIRLO, M5, and E110) with the oxidation produced at three different temperatures spanning the range of interest (approx. 1000-1265°C). The first tests will be done with specimens oxidized at 1200°C to 5% ECR as this will provide one point with significant residual ductility for all alloys and permit the measurement techniques to be worked out. The next tests will be done with specimens oxidized at 1200°C to 10% ECR. One alloy (E110) should be brittle at this level, but the rest should still be ductile. This test will let us evaluate the ability of the test to discriminate between alloy types. The third tests will be done with specimens oxidized at 1200°C to 20% ECR to ensure that all specimens are brittle. The fourth and fifth tests will be done with intermediate ECR values to home in on the critical ECR values as well as possible. Decisions will be made later about oxidation temperatures above and below 1200°C that need to be tested. In light of the above, it is clear that some scheme of oxidizing multiple specimens in a furnace run is needed to prevent the number of furnace runs from becoming impractically large. This capability exists at ANL with the use of alumina spacers and zirconia washers between tubing pieces in the furnace.

References

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