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Session Title: LOCA Embrittlement Criteria
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Question: Confirm that ANL [Argonne National Laboratory] uses the Cathcart-Pawel oxidation relation and JAEA [Japan Atomic Energy Agency] uses the Baker-Just relation to calculate ECR [Equivalent Cladding Reacted].

Answer [ANL]: That is correct. ANL uses the Cathcart-Pawel oxidation relation and JAEA uses the Baker-Just relation to calculate ECR.

Question: Other than being nice to have more data, what specific deficiencies do you see in NRC's rulemaking strategy that require more data prior to changing the 17% limit to a performance-based limit that will apply to all zirconium alloys, including M5?

Answer [Electric Power Research Institute (EPRI)]: That depends to a great extent on what NRC will propose for the revised criteria and how it will propose addressing issues such as those raised by IRSN (at this meeting) or by the ongoing experimental program at Halden. Without a clearer understanding of the potential impact of phenomena such as the uptake of oxygen from the ID surface of the cladding, the brittle behavior of the ballooned region, extent of fuel relocation into the ballooned region, dispersal through the burst opening, etc. the regulatory tendency is likely to be to address these phenomena in an unnecessarily conservative manner, assuming that they are all 100% relevant.

Question: Initially, the USAEC [U.S. Atomic Energy Commission] chose ductility rather than strength because LOCA [loss-of-coolant accident] loads were essentially unknowable. What is the basis for the maximum load assumed in Japan?

Answer [JAEA]: The maximum load has been investigated experimentally in JAEA and Japanese industries. The maximum load of 540 N (50 kgf), used in the JAEA's thermal shock test, is the highest value measured in these experiments. Most data are ~200 N or lower, but we adopt the 540 N as a conservative, bounding condition.

Question: The [Halden] 650.4 rod was about 90 GWd/MtU. Would IRSN support the testing of a more reasonable burnup (60 – 70 GWd/MtU) to remove excessive pellet degradation from the considerations?

Answer [Institut de Radioprotection et de Sûreté Nucléaire (IRSN)]: The Halden test matrix should of course be complemented by tests performed at burnups around 60-70 GWd/MtU. Testing at higher burnups will nevertheless remain useful for our understanding of burnup effect on relocation and dispersion, and should not be excluded from our investigation field.

Results from other experimental programmes (ANL, FLASH…) have shown a high fragmentation of fuel in the burst region for burnup around 50 GWd/MtU, thus HALDEN IFA 650-4 results shall not be disregarded.

Question: Experimental data show hydrogen in [the] burst region to be the main problem/uncertainty. In 50.46 proposed rulemaking, has NRR considered (a) limiting PCT < T_{burst} <u>and</u> (b) reducing transition break size to ~SBLOCA? BE methods should show PCT < T_{burst} and the need to understand H_2 effects would go away.

Answer [NRC]: NRC has no plans to change the peak cladding temperature (PCT) limit of 1204°C (2200°F) in 10 CFR Part 50.46(b). Since cladding rupture occurs at substantially lower temperatures (e.g., 800°C - 900°C), the change proposed in this question would be very limiting. For current operating reactors, it is doubtful that even best-estimate methods could ensure that PCT < T_{burst} for the large break loss-of-coolant accident. For smaller break sizes (i.e., below transition break size), such behavior is possible. However, NRC has no plans to reduce transition break size to account for cladding behavior.

Question: We all understand that the mechanism of embrittlement is related to the beta layer. Do you see any problem with NRC's using an empirical correlation that is related to calculated oxidation?

Answer [IRSN]: Defining a safety criterion based on a calculated oxidation rate is consistent with the original approach of the 1973 criterion, but will require (a priori) a calculation methodology that is conservative with regard to all the transients and physical mechanisms that could affect the clad ductility.

Since embrittlement is directly related to the beta layer and its content of O and H but is not directly related to the cladding oxidation rate, the approach of USNRC presents two types of risk:

- the first is to forget or fail to consider some possible combinations of physical phenomena when fixing the maximum acceptable oxidation rate and thus create a non-conservative criterion,
- the second is that a too simple criterion formulation might lead, in some situations, to an excessive conservatism.

Question: You suggested using impact tests and using evaluation of strength as a criterion. This was specifically turned down in the "Statement of Considerations" in the 1973 Rulemaking as very impractical. How would you deal with thermal stress during quench and vibrations?

Answer [EPRI]: We suggested that strength as measured by impact resistance or by survivability of quench under an axial load (such as done in Japanese experiments) could be used as an alternative to ductility. In addition to giving us some margin, a strength-based approach is likely to give us a means for addressing the brittle ballooned region. The thermal stresses that occur during quench are specifically addressed by the quench survivability tests.

Question: With respect to the issue of "chips and fines" released during RIA tests, what is the NRC's position on fuel dispersal from a burst region during a LOCA test conducted by [Halden and cited by] IRSN?

Answer [NRC]: The concept of "chips and fines" was used in the Research Information Letter 0401 as a possible explanation for data scatter in the onset of cladding plastic strain measurements in RIA tests. It does not refer to fuel relocation and dispersal observed in the Halden LOCA tests cited by IRSN. NRC is reviewing the relocation and dispersal issue in the context of 10 CFR 50 Appendix K (LOCA models) rather than 10 CFR 50.46(b) (cladding embrittlement).

Question: With respect to CABRI RIA testing, what is the hydrogen concentration in the various tests? Were SEM analyses done for the various test samples? Has this information be[en] generally released to the industry?

Answer [IRSN]: The cladding hydrogen concentration of fuel rods depends mainly on the clad and of the burnup. A large spectrum of local and average hydrogen concentrations has been covered by fuel rods tested in CABRI: up to 1370ppm and locally up to 2000ppm. Hydrogen concentrations have been systematically measured and results have been made available for all the CABRI programme partners.

Question: What was the maximum fuel burnup tested?

Answers:

[ANL] Rod average burnups are listed on Slide 13 in the ANL presentation. With regard to high-burnup cladding alloys tested to date, the highest are: about 70 GWd/MTU rod averaged and about 76 GWD/MTU local burnup.

[EPRI] The Halden test (IFA 650.4) that resulted in fuel dispersal used a fuel specimen with a butnup of 91.5 GWd/MTU.

[IRSN] Fine fuel fragmentation has been observed in the HALDEN test 650-4 for 91.5 GWd/MtU, but also in tests FLASH-5, ANL ICL-2 and Halden test 650-5 respectively for 50, 56 and 83 GWd/MtU.

[JAEA] ~76 GWd/t at JAEA.

Question: Is there a performance-based hypothetical burnup limit for Zr-2 and Zr-4 fuels?

Answer [NRC]: No. As long as hydrogen absorption is controlled to a low level, no burnup limit is foreseen for any cladding alloy. On the other hand, the recent Halden test (IFA-650.4) suggests that there might be a burnup limit associated with the fuel as opposed to the cladding. In that test, conducted at a burnup of about 92 GWd/t, a very large "rim" structure developed in the pellet. This resulted in a substantial volume of particulate fuel, which flowed out of the burst opening under gravity. Only small "rims" are seen at the current operating limit of 62 GWd/t, so there is probably a need for a technically-based limit at some burnup around or above the current operating limit.

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