EFFECTS OF PELLET EXPANSION AND CLADDING HYDRIDES ON PCMI FAILURE OF HIGH BURNUP LWR FUEL DURING REACTIVITY TRANSIENTS

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SUMMARY

To provide a data base for the regulatory guide of light water reactors, behavior of reactor fuels during off-normal and postulated accident conditions such as reactivity-initiated accident (RIA) is being studied in the Nuclear Safety Research Reactor (NSRR) program of the Japan Atomic Energy Research Institute (JAERI). A series of experiments with high burnup fuel rods is being performed by using pulse irradiation capability of the NSRR. This paper presents recent results obtained from the NSRR power burst experiments with irradiated PWR fuels with ZIRLO™ and MDA (Mitsubishi Developed Alloy, Zr-0.8Sn-0.2Fe-0.1Cr-0.5Nb) claddings, and discusses effects of pellet expansion as PCMI (Pellet-Cladding Mechanical Interaction) loading and cladding embrittlement primarily due to hydrogen absorption. Studies on post-failure events and DNB occurrence are also described.

Tests OI-10 and -11

High burnup PWR fuels irradiated in Ohi Unit 4 reactor were subjected to the Tests OI-10 and -11. A fuel of the Test OI-10 has an MDA cladding and that of the Test OI-11 has a ZIRLO™ cladding. A test fuel rod of the OI-10 was sampled from the 2nd span from the top, and has a burnup of 60 MWd/kgU (averaged in the test segment) and cladding oxide thickness of ~30 µm. The test fuel rod was subjected to the pulse-irradiation in the NSRR on July 11, 2003 with conditions of 0.44 kJ/g (104 cal/g) for a peak fuel enthalpy and 5.6 ms for a pulse-width. The fuel remained intact in the OI-10. A fuel rod of the subsequently performed OI-11 was sampled also from the 2nd span, and has a burnup of 58 MWd/kgU and cladding oxide thickness of ~30 µm. The test fuel rod was subjected to the pulse-irradiation on July 28, 2003 with conditions of 0.66 kJ/g (157 cal/g) for a peak fuel enthalpy and 4.4 ms for a pulse-width. The peak fuel enthalpy of 0.66 kJ/g is the highest in the NSRR experiments with LWR fuels irradiated in commercial reactors. The Test OI-11 resulted in fuel failure, pellets fragmentation and mechanical energy generation. Although data were still preliminary, transient records showed that a fuel enthalpy at a time of failure was higher than those observed in previously tested fuels with Zircaloy-4 cladding and exceeded 0.50 kJ/g (120 cal/g). The results from two tests, no failure in the OI-10 and the higher failure energy in the OI-11, reflects the better performance of these new cladding materials in terms of corrosion, the thinner oxides and accordingly lower hydrogen content generated during irradiation in the PWR. The two experiments were performed as a collaboration program between Japan Atomic Energy Research Institute and Mitsubishi Heavy Industries, Ltd. by using fuel rods transferred from Kansai Electric Power Company, Inc.

Pellet expansion

Transient cladding deformation of high burnup fuel was measured by strain gauges in NSRR tests. The tests revealed that brittle cladding fracture occurred at a small cladding strain of ~0.4% during an early phase of the transients. The transient measurement was made in two BWR fuel tests, FK-10 and -12, and in a PWR fuel test, TK-10. Hoop strain at a time of cladding failure was 0.33% and 0.37% during the transients of the BWR fuel tests. Post test examination of the BWR cladding in earlier BWR fuel tests indicated residual hoop strains below 0.1% at an enthalpy level of about 0.25 to 0.29 kJ/g (60 to 70 cal/g). The maximum elastic strain level was estimated to be about 0.5% from the residual strain using cladding properties of MATPRO package. The elastic strain level is consistent with the measured peak strains. A PWR fuel test indicated consistent peak strain of 0.37% at a fuel enthalpy of 0.29 kJ/g. Although cladding deformation due to thermal expansion of the pellets could vary depending on the pellet-cladding gap condition and constraint by the cladding, the deformation would be ~0.5% at fuel enthalpy of 0.29 kJ/g according to the MATPRO. These results suggested that the cladding deformation was caused primarily due to thermal expansion of pellets and fission-gas-induced pellet expansion was negligible in the early phase of transients.

Hydrides effect

Influence of hydriding of Zircaloy claddings on their failure behavior under RIA conditions was examined through pulse-irradiation tests of fresh fuel rods with artificially pre-hydrided cladding and their out-of-pile mechanical testing. Brittle cladding failure similar to those observed in tests with high burnup PWR and BWR fuels occurred in fresh PWR fuel rod tests with the hydrided cladding. Failure enthalpies and hydrogen content, however, were higher in the fresh fuel tests than those in the high burnup fuel tests. The result suggested that strong influence of the hydrides on the failure behavior but also irradiation induced embrittlement of the cladding. Ring tensile tests under uni-axial stress condition and tube burst tests under bi-axial stress conditions were conducted with the fresh pre-hydrided PWR and BWR cladding. In the mechanical tests, failure limits in hoop strain decreased significantly with increasing hydrogen content. Sensitivity to the hydrogen content was larger under bi-axial stress conditions in tube burst tests with axial constraint and in pulse-irradiation tests. The sensitivity also varied depending on the cladding materials. Recrystalized Zircaloy-2 cladding of BWR fuel rods generally shows larger failure strains than those of stress-relieved Zircaloy-4 cladding of PWR fuel rods. Stronger influence of hydrides, however, was observed in the BWR cladding than in the PWR cladding. These results indicated that the cladding failure limits under RIAs should be examined under bi-axial stress conditions which simulate cladding deformation due to PCMI.

Post-failure events

The mechanical energy generation in PCMI failure is being investigated with a separate-effect test series with powder fuels. A comparison between the powder fuel experiments and high burnup fuel tests concluded that thermal interaction of dispersed fuel fragments with coolant water should be the dominant factor of the mechanical energy generation. The finer fuel particles generated more mechanical energy at the same energy deposition level.