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Current Issues on Hydride Effects of Zr-base Cladding Tube on the Ductility in RIA-simulating Tests

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1. Introduction

During operation in nuclear reactor the cladding tube forms a hydride rim that resides above a substrate that is relatively free of hydrides. A prediction of the ductility of such cladding tubes must take into account: the density of the hydrides as a layer/rim and the rim thickness, the ability of the hydrides to deform, their circumferential orientation within the layer, and the presence of a relatively unhydrided substrate.

Recent experiments based on unirradiated cladding tubes containing hydrides in the form of a rim indicate a significant loss of ductility with (a) increasing hydrogen content [*1*] and/or (b) increasing hydride rim thicknesses [*2*]. These results suggest that a ductile-to-brittle transition occurs with increasing hydride rim thickness. Since the hydride rim initiates a crack early in the deformation process, fracture mechanics has been recently used to predict failure on the basis of crack propagation. While this type of analysis can be applied to brittle cladding with thick hydride rims, failure of cladding with small- thickness hydride rims exhibits significant ductility; importantly, this cladding does not appear to obey fracture mechanics, as the fracture stress approaches the tensile strength of the cladding.

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) has been studied in the Nuclear Safety Research Reactor (NSRR) program in Japan. A series of experiments with high burnup fuel rods were 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^{TM} 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.

2. 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.

3. 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.

4. Conclusions

From the review on the effects of hydride on the ductility behaviors of Zry-based cladding, the following main conclusions were drawn.

First, Results suggest that strong influence of the hydrides but also irradiation induced embrittlement. In the mechanical tests, failure limits in hoop strain decreased significantly at increased hydrogen concentration.

Second, cladding ductility is very sensitive to hydride rim thickness at both room temperature and 620K. This sensitivity is manifested in a loss of ductility with increasing hydride rim thicknesses.

REFERENCES

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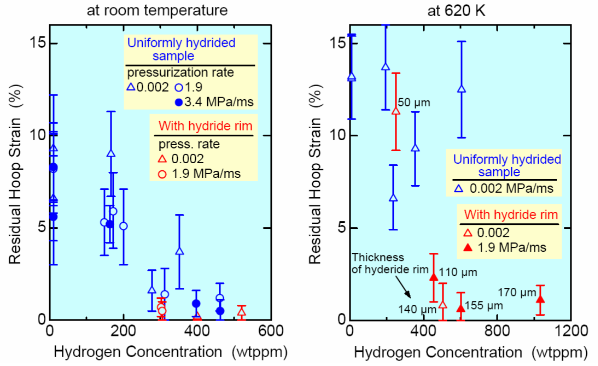

Fig. 1. Hoop strain with H concentration (Burst test)

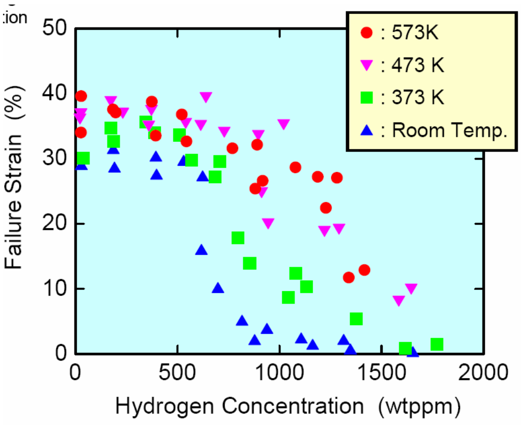

Fig. 2. Failure strain with H concentration (Ring tensile test)

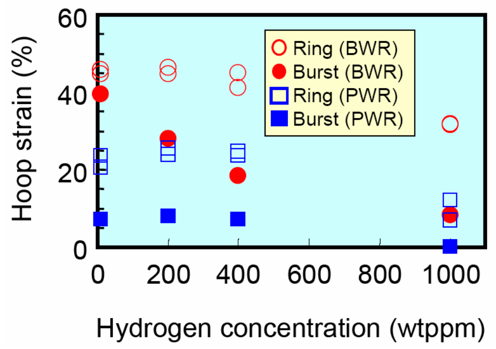

Fig. 3. Hoop strain with H concentration for artificially-hydrided cladding (Ring tensile test, Burst test)

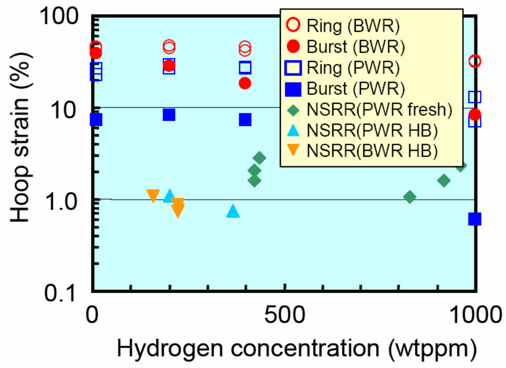

Fig. 4. Hoop strain with H concentration for artificially-hydrided cladding (Ring tensile test, Burst test, NSRR test)