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Evaluation Study on the Advanced Creep and Hydride Reorientation Model for Spent Nuclear Fuel during Dry Storage

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1. Introduction

The regulation for storage, as given in 10 CFR 72, requires that the spent fuel must be readily retrievable from the storage systems. Thus, the spent fuel cladding must be protected against degradation that cause gross failure of the fuel and must be ensured its confinement and containment during storage. Creep and hydride reorientation are known to the dominant degradation mechanisms for cladding under loading and normal conditions for dry storage. The relatively high temperature, differential pressure between the inside and outside of the fuel rod, and hoop stress will lead to permanent deformation of the cladding during dry storage period. Although extensive efforts over the last several decades have been devoted toward proving the technical basis for the dry storage of spent fuel assemblies, these efforts have done mainly for the fuel assemblies with average burnup less than 45 GWd/MTU [1-3]. In accordance with US NRC ISG-11 Rev.3 [4], high burnup fuel with average burnup exceeding 45 GWd/MTU may have comparatively thin cladding walls from in-reactor formation of oxide and hydride, therefore, the maximum thickness of cladding oxide and hydride layer should be specified for evaluating the structural integrity of the cladding during dry storage. Furthermore, a percentage of zirconium hydrides will be dissolved at elevated temperature and will be precipitated perpendicular to the hoop stress under decreasing temperature, radially oriented hydrides may cause gross rupture of the cladding. Recently, Boufioux et al. [5] published an advanced creep model, so-called EDF-CEA Model-3, with explicit dependence on stress, temperature and fast fluence, however, the model does not account for the effect of hydrogen. EPRI has also reported a newly developed a hydride reorientation model for irradiated Zirconium alloy cladding materials [6], but it has not been implemented by coupled analysis method with fuel rod performance code. This paper presents modified creep modeling incorporating the effect of hydrogen on cladding creep rate using data from Bouffioux et al. [7] as well as the evaluation results of the creep and hydride reorientation analysis for the high burnup spent fuel during 40 year dry storage by FALCON code [8].

2. Analysis Cases and Creep Modeling

2.1 Analysis Cases

The spent fuel rod's conditions affecting the creep and hydride reorientation calculations are consist of: (a) internal pressure driven by initial filling He gas and fission gas released, gap size between the pellet and cladding, oxide thickness and hydrogen concentration from in-reactor operation; (b) source term and decay heat from cooling time after reactor discharge. The temperature and pressure histories were calculated by FALCON code and the fuel rod dimensions and materials are taken from 16x16 PLUS-7 rod design. The thermal input to the FALCON code consists of the decay power from fuel, the cladding outer wall heat transfer coefficient and the ambient temperature during the dry storage. The decay heat was taken from the ORIGEN [9] code results and the ambient temperature was assumed to be 40℃. The heat transfer coefficient was determined by FALCON code by iterating the value to match the calculated peak cladding temperature to the desired value and the determined heat transfer value was kept constant with time. The analysis cases were made for 5, 7.5 and 10-year cooled spent fuel rod with 60 GWd/MTU burnup respectively. Fig. 1 shows decay power histories of 5, 7.5 and 10-year cooled spent fuel rod for 40 years.

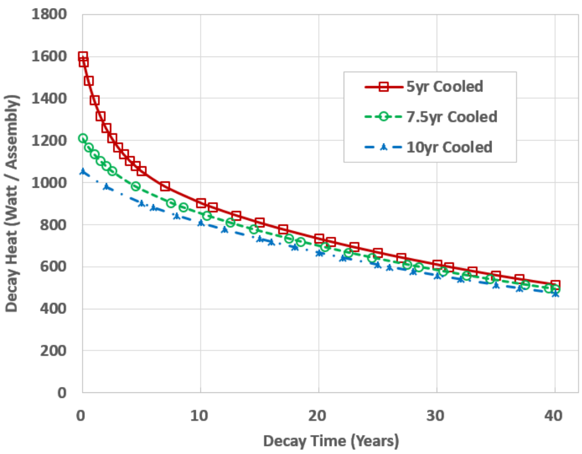


Fig. 1. Decay Power from ORIGEN Calculation

2.2 Creep Model of Hydrogen Effect

In general, a typical creep model for Zircaloy cladding comprised of a single independent variable terms, i.e., stress(σ), temperature(T), neutron flux(ϕ), time(t), and hydrogen(H) as given in equation (1) where $\dot{\varepsilon}$ is creep rate. The effect of hydrogen was derived by data from Bouffioux et al. [6, 9] and expressed in equation (2) where H is the total hydrogen concentration in ppm.

$\dot{\varepsilon} = f(\sigma, T, \phi, t, H)$ (1)

F(H) = 0.883exp(−0.00153H), 100≤H≤700ppm (2)

2.3 Hydride Reorientation Model

The earlier version of the hydride reorientation model developed in EPRI [10] was found that the model under-predicted the radial hydrides concentrations for irradiated fuel cladding especially in the lower stress regimes [6], which motivated to develop a new hydride reorientation model expressed in equation (3)

$$F_\sigma = \frac{F}{F+(1-F)\exp(\frac{V_k^0 \sigma_\theta \bar{\delta}}{kT})} \quad (3)$$

where, F_σ is radial hydride reorientation fraction, F is stress-free radial hydride fraction, V_k^0 is critical volume of hydride nucleus, σ_θ is hoop stress and $\bar{\delta}$ is net misfit strain.

3. Analysis Results

Fig. 2 shows peak cladding temperature of 5, 7.5 and 10-year cooled spent fuel rod for 40 years cooled spent fuel rod with 60 GWd/MTU burnup respectively. Similar to the previous result of the decay power illustrated in Fig. 1, the peak cladding temperature decreased during the storage time. The initial peak cladding temperatures of 5, 7.5 and 10-year cooled spent fuel were 380, 348 and 335 °C respectively, however, there is no significant difference in the peak cladding temperature between the 5, 7.5 and 10-year cooled spent fuel after 40 year storage time. The rod internal pressure and peak cladding hoop stress data depicted in Fig. 3 (a) and (b) respectively. The 5-year cooled spent fuel rod results in larger decreases in rod internal pressure and peak cladding hoop stress caused by larger decrease in peak cladding temperature during the storage time than for those of both 7.5 and 10 year cooled spent fuel rod. As can be seen in Fig. 4, a 5% creep strain was reached at about 30 years storage time for the 5-year cooled spent fuel rod while less than 1% creep strain was reached for both 7.5 and 10 year cooled spent fuel rod.

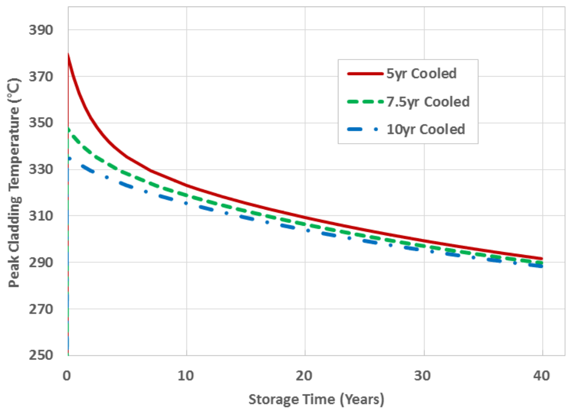
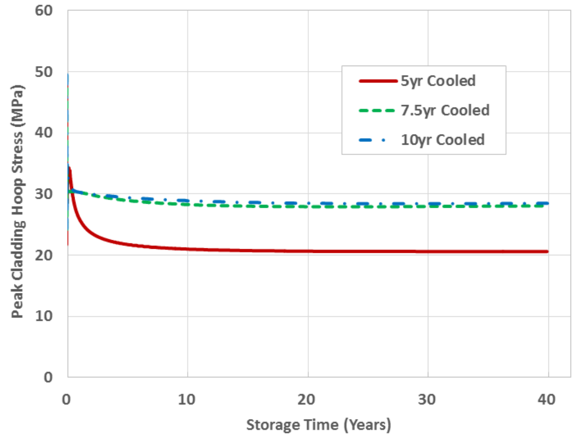
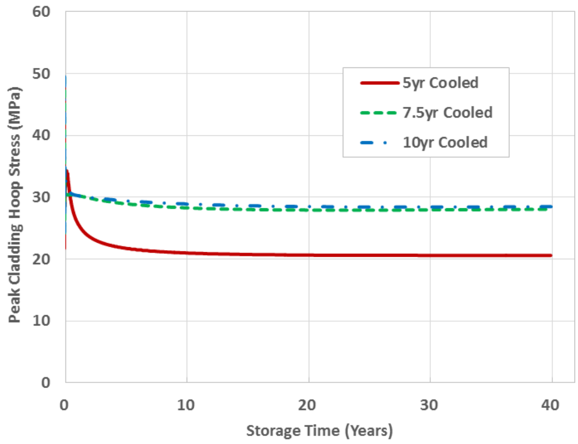


Fig. 2. FALCON Calculation Results of Peak Cladding Temperature



(a)



(b)

Fig. 3. FALCON Calculation Results; (a) Rod Internal Pressure and (b) Cladding Hoop Stress as a function of storage time

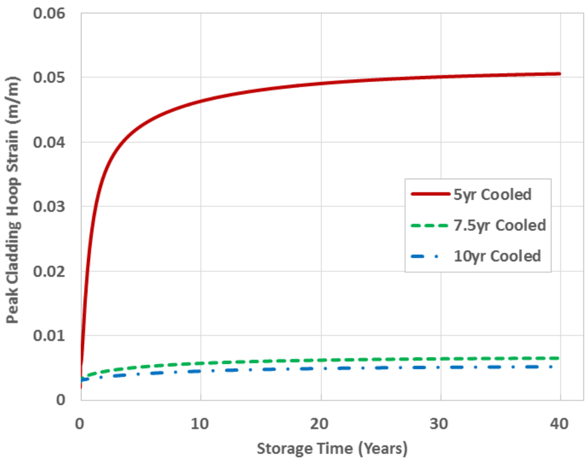


Fig. 4. FALCON Calculation Results; Peak Cladding Hoop Strain as a function of storage time

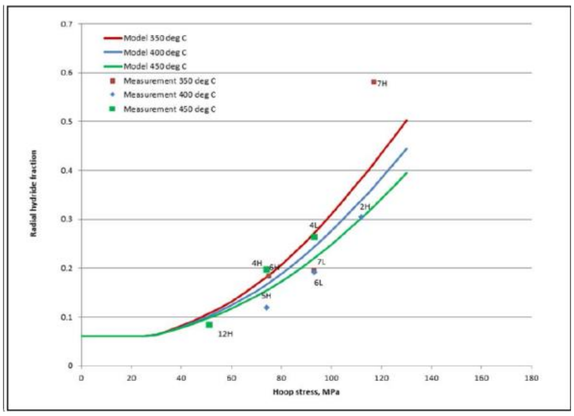


Fig. 5. Radial Hydride Fraction as a Function of Hoop Stress for Fuel Cladding [6]

4. Conclusions

The creep and hydride reorientation study using the advanced model with fuel performance code for the spent fuel in dry storage was investigated in this paper, which demonstrates that spent fuel in dry storage can be reliably analyzed in terms of the true physical conditions of the cladding. This paper focuses on evaluating the cladding temperature, rod internal pressure, hoop stress and strain and radial hydride fraction of the spent fuels having assembly-average burnup of 60 GWd/MTU during the dry storage. The analysis demonstrates that occurrence of creep rupture during dry storage for 40 years has little possibility and the advanced hydride reorientation model shows good agreement with several benchmarking measurement data.

ACKNOWLEDGMENTS

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