Creep Behavior Evaluation for Spent Nuclear Fuel in Dry Storage

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ABSTRACT*: Creep has been identified as one of the concerning behaviors among the potential degradation mechanisms, which include stress corrosion cracking, oxidation, hydride reorientation and delayed hydride cracking, postulated for spent fuel in dry storage. According to previous studies, the spent fuel creep rupture during dry storage is not likely to occur as long as hoop stresses in the cladding remain smaller than the yield or certain strength throughout the storage period. The Zirlo material cladding creep for spent nuclear fuel in dry storage was analyzed using a reliable methodology and implementation of a model in a state-of-the-art fuel behavior code, FALCON, in this paper. The FALCON fuel performance code was used for the modeling and analysis of creep phenomenon in dry storage according to the applicable post-irradiation thermal creep model and supporting data. The research presented in this paper focuses on evaluating the cladding temperature, rod internal pressure, hoop stress and strain 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 when compliance with the acceptance criterion is achieved.*

KEYWORDS*: Creep, Spent Fuel, Falcon, Modeling*

I. 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 is the dominant degradation mechanism for cladding under normal conditions of 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. This paper presents modified creep modeling incorporating the effect of hydrogen on cladding creep rate using data from Bouffioux et al. [6] as well as the evaluation results of the creep analysis for the high burnup spent fuel during 40 year dry storage by FALCON code [7].

II. ANALYSIS CASES AND CREEP MODELING

II.A. Analysis Cases

The spent fuel rod's conditions affecting the creep calculation 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 [8] 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.

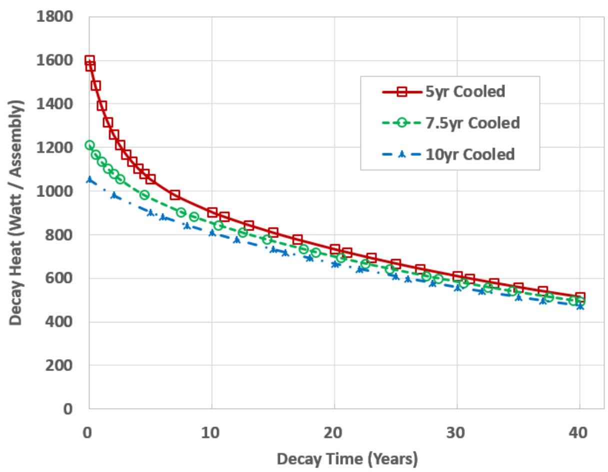


Fig. 1. Decay Power from ORIGEN Calculation

II.B. 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.

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

$$F(H)= 0.883\exp(-0.00153H),\ 100 \le H \le 700 \text{ ppm} \quad (2)$$

II.C. Cumulative Damage Index Model for Creep-Rupture Failure Criteria

The cumulative damage index (CDI) is developed specifically for the cladding failure mechanism and represents cladding vulnerability to failure as a history-dependent phenomenon [10]. The CDI concept assumes that the materials experiences cumulative damage due to sustained stress; the higher the stress, the shorter the time to cladding failure. This implies that an applied stress of σ_0 at certain temperature of T_0 lasting for a fraction of time Δt will cause the fractional damage ΔD as:

$$\Delta D(\sigma_0, T_0) = \Delta t / t_f(\sigma_0, T_0) \quad (3)$$

where t_f is the time to failure when σ_0 is applied. The relationship for the time to failure used in the CDI model has been developed from pressurized Zircaloy tube.

III. 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. Table I shows the results of CDI of 5, 7.5 and 10-year cooled spent fuel rod. The analysis results indicate that all cases satisfy the acceptance criterion. The Damage Index is less than 3.2% for all cases, implying a failure probability of less than 0.5% for these cases.

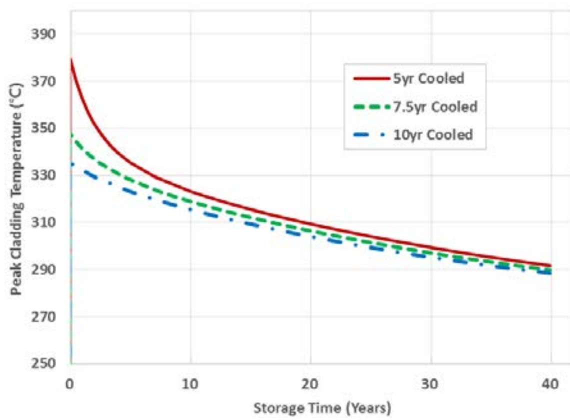
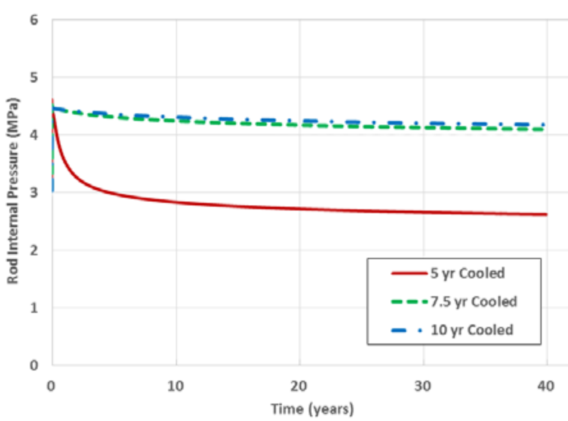
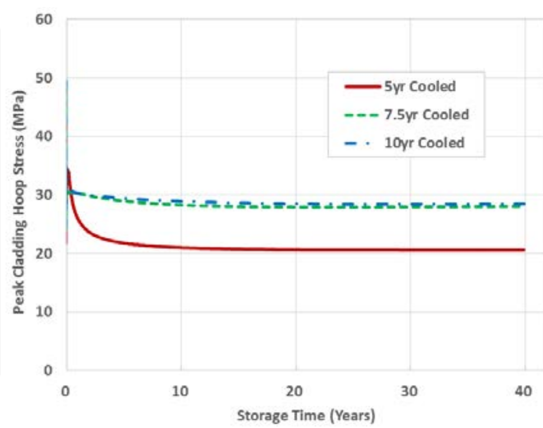


Fig. 2. FALCON Calculation Results of Peak Cladding Temperature



(a)



(b)

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

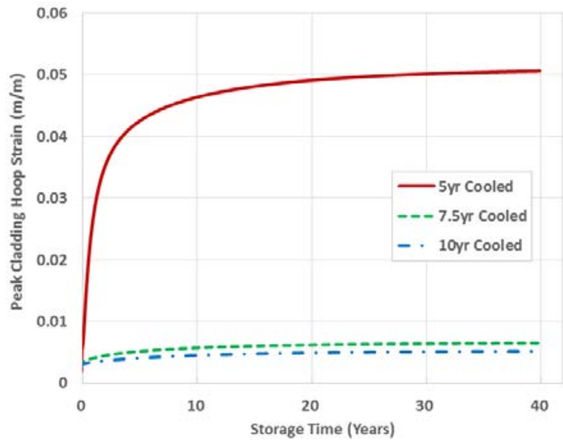


Fig. 4. FALCON Calculation Results; Peak Cladding Hoop Strain as a function of storage time

TABLE I. Maximum Cumulative Index

Case	CDI (%)
5 year cooled	3.0
7.5 year cooled	3.1
10 year cooled	3.2

IV. CONCLUSIONS

The creep modeling and analysis 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 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 when compliance with the CDI acceptance criterion is achieved.

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REFERENCES

1. R. E. Einziger, S. D. Atkin, D. E. Stellbrecht, and V. Pasupathi. 1982. “High Temperature Postirradiation Materials Performance of Spent Pressurized Water Reactor Fuel Rods Under Dry Storage Conditions.” Nuclear Technology, v. 57, p. 65.
2. Y. R. Rashid, D. J. Sunderland, and R. O. Montgomery. 2000. “Creep as the Limiting Mechanism for Spent Fuel Dry Storage - Progress Report.” EPRI TR-1001207.
3. A. Machiels. 2002. “Regulatory Applications Lessons Learned -- Industry Perspective.” NEI Dry Storage Information Forum. Naples, FL. May 15-16, 2002.

4. SFST-ISG-11, Revision 3, “Cladding Considerations for the Transportation and Storage of Spent Fuel”, 2003.

5. Bouffioux, Pol, “Interim Dry Storage of PWR’s Spent Fuel – Development of a Creep Law to Assess the Fuel Cladding Integrity”, ICEM01 Conf., Bruges, Belgium, Sept. 30-Oct. 4, 2001.
6. Bouffioux, P. and Legras, L., “Effect of Hydriding on the Residual Cold Work Recovery and Creep of Zircaloy 4 Cladding Tubes”, LWR Meeting, Park City, Utah, April 10-13, 2000.
7. Fuel Reliability Program Falcon Fuel Performance Code: Version 1.3.1, 2016.
8. I.C. Gauld, et al., ORIGEN-ARP: Automatic Rapid Processing for Spent Fuel Depletion, Decay, and Source Term Analysis, NUREG/CR-0200, ORNL/NUREG/CSD-2/V1/R7 (2004).
9. Bouffioux, P. and Rupa, N., “Impact of Hydrogen on Plasticity and Creep of Unirradiated Zircaloy-4 Cladding Tubes”, ASTM STP 1354, pp 399-422.
10. A. Machiels, “Creep Modeling and Analysis Methodology for Spent Fuel in Dry Storage”, EPRI TR-1003135, 2001