Effects of Thermal Conductivity Degradation of UO_2 Fuel on Safety Margins

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1. Introduction

Thermal conductivity of UO_2 fuel is reduced by irradiation damage, the buildup of fission products and the formation of cracks. However, we noticed that some fuel performance codes used for licensing application did not include the conductivity degradation effects with increasing fuel burnup properly. U.S. NRC also announced an improper use of conductivity model in the fuel performance codes approved by NRC before 1999(Information Notice 2009-23[1]). This means that due to the improper use of conductivity models the safety margins to specificed allowable fuel design limits (SAFDLs) may be less conservative than previously understood. In this study, we have assessed conductivity degradation effects to power to melt and rod ejection accident (REA).

2. Analysis Details

Thermal behavior of fuel rod with burnup increase was analyzed by use of FRPACON-3.4 and it also utilized to establish burnup-dependent initial conditions to the REA analysis. REA was analyzed by use of FRAPTRAN-1.4 fuel codes. The UO_2 thermal conductivity model in the FRAPCON-3.4 and FRAPTRAN-1.4 is the same and it is a modified Nuclear Fuel Industries (NFI) model [2]. The model is depicted in Fig.1.

The fuel design considered in this analysis is 17x17 PWR fuel with ZIRLO^{TM} cladding. To establish a reasonable power pulse for high burnup fuel under REA, Gaussian power pulse shapes were, see Fig. 2. The full width at half maximum (FWHM) of applied Gaussian power pulse was 12.5, 25 and 50 ms. The pulse amplitude was also changed to determine the power which induces pellet incipient melting at the given fuel burnup. The core condition assumed under REA is hot zero power (HZP). The axial power shape of fuel rod is prescribed such that the power peak is observed slightly above the core centerline with a peaking factor of 1.19. It is also assumed that thermal-hydraulic boundary conditions such as heat transfer coefficients from cladding to coolant, pressure and temperature of bulk coolant were not changed under REAs.

3. Results

3.1 Power to Melt

Fig. 3 shows effects of thermal conductivity degradation on the required linear local power to melt of UO_2 pellet as a function of burnup. As conductivity degradation was properly factorized in FRAPCON-3.4 by use of the modified NFI model, the reduction in power to melt with burnup increase becomes more significant than the un-factorized ones. As fuel nodal burnup increased up to 68 GWd/MTU, the required power is 17.6 kW/ft. This implies due to the improper use of the conductivity, power to melt at 60 GWd/MTU(rod average) is about 27 percent over-estimated. Power to melt is used to the rod failure criteria in design basis accidents. As the result this reduced safety margin suggests that radiological consequence be reanalyzed, if needed.

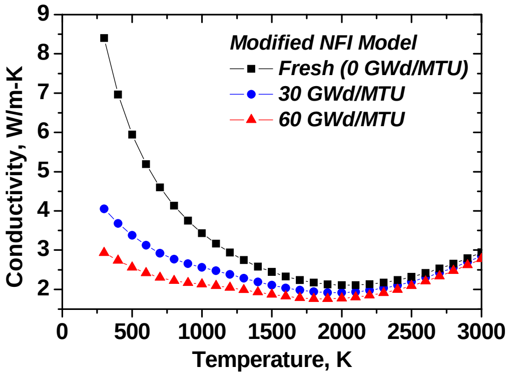

Fig.1 Changes of UO_2 fuel thermal conductivity with burnup and temperature

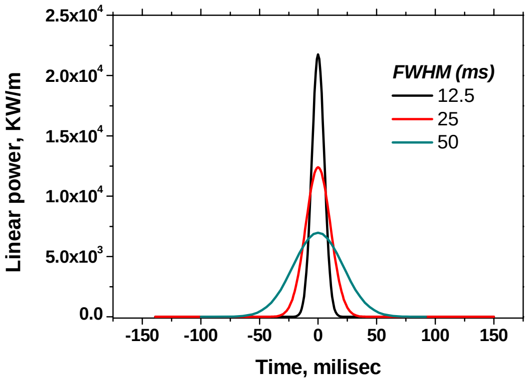

Fig.2 Applied Gaussian power pulse shapes under REA

3.2 Temperature Evolution under REA

Fig. 4 is the temperature profiles under REA at 68 GWd/MTU fuel burnup. Due to high burnup of the fuel, the temperature profiles were strongly peaked to the pellet surface, and incipient fuel melting was observed

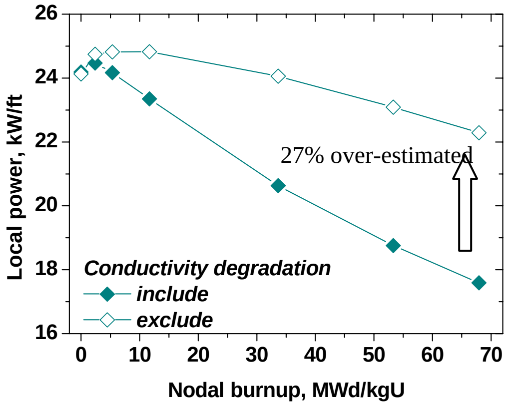

Fig. 3 Best-estimate power to melt as a function of fuel burnup and thermal conductivity

about 20 ms later after maximum power reached. The radial position of incipient fuel melting occurred moves toward pellet surface with increasing burnup because of the peaked radial power and the burnup induced depression of melting temperature at the pellet periphery. Thermal conductivity degradation effects are also illustrated in Fig. 4. If the conductivity degradation is not considered the temperature peaking is slightly reduced, but fuel temperature inside the periphery is increased a little bit.

3.3 Fuel Enthalpy to Incipient Melting under REA

Thresholds radial average fuel enthalpy for incipient fuel melting is illustrated in Fig. 5. In a fresh fuel the enthalpy rise to melt is 227 and 233 cal/g when the FWHM is 50 and 12.5 ms, respectively. In general, the radial average enthalpy to melt decreases with burnup increase. As described in 3.2, this is due to the radial power peaking and the depression of fuel melting temperature with burnup. When 12.5 ms FWHM is applied, the calculated enthalpy threshold decreases gradually with burnup, from 233 cal/g at zero burnup to 129 cal/g at 68 GWd/MTU. When 50 ms FWHM is applied, it decreases more gradually with burnup than the shorter FWHM cases, from 227 cal/g at zero burnup to 163 cal/g at 68 GWd/MTU. Thermal conductivity degradation effects on threshold fuel enthalpy are also shown in Fig. 5. The results indicated that the reduction in threshold enthalpy with burnup increase was relieved as conductivity degradation effect was not factorized. As the results, the increased enthalpy threshold at 68 GWd/MTU is about 4.2 and 8.2 percent as FWHM is 50 ms and 12.5 ms, respectively. This implies that the reduced safety margin represented as enthalpy thresholds is approximately up to 8 percent.

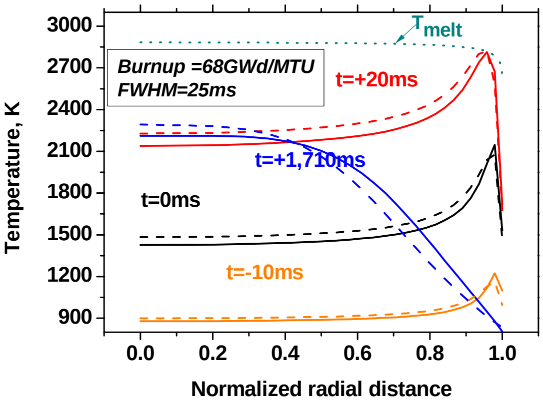

Fig. 4 Best-estimate evolution of fuel temperature profiles across pellet radius, t=0 defines the time at which maximum power is attained. Dashed lines are analysis results without considering the conductivity degradation of the UO_2 fuel.

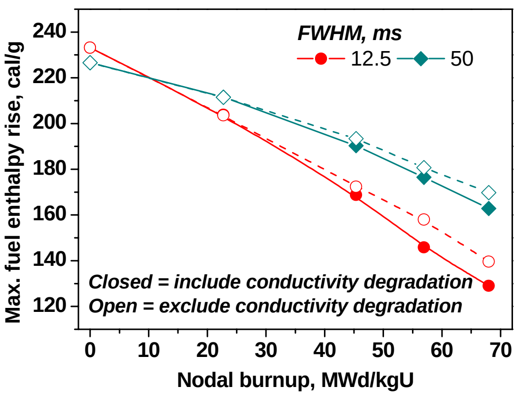

Fig. 5 Best-estimate required fuel enthalpy for incipient fuel melting. Open symbol with dashed lines is the thresholds enthalpy to melt when conductivity degradation is not included.

4. Summary

Related to the effects of thermal conductivity degradation of UO_2 fuel on safety margins, following results can be drawn.

- Due to the improper factorization of the thermal conductivity degradation into the fuel code, the over-estimated power to melt was approximately 27 % at 60 GWd/MTU (rod average).
- If fuel conductivity degradation was considered under REA analysis properly, the safety margin represented as enthalpy thresholds to incipient melting was reduced approximately up to 8 percent at 60GWd/MTU (rod average) with FWHM of 12.5ms.

REFERENCES

[1] NRC Information Notice 2009-23, *Nuclear Fuel Thermal Conductivity Degradation*, October 8 (2009)
[2] D.D. Lanning et. al., *FRAPCON-3 Updates, Including Mixed-Oxide Fuel Properties*, NUREG.CR-6534, Vol.4, (2005)