Transactions of the Korean Nuclear Society Autumn Meeting
Pyeongchang, Korea, October 30-31, 2014

The Effect of High Burnup on Fuel Modeling in APR1400 SBLOCA Analyses

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1. Introduction

Because of major advantage in reactor operation, the current trend in the nuclear industry is to increase fuel discharge burnup. To address the performance of the advanced cladding alloys under LOCA, especially at high burnup, the USNRC established a testing program at Argonne National Laboratory. The results of recent investigations have been interpreted and new embrittlement criteria will be established for assurance of adequate safety margin for high burnup operation.

This study is intended to evaluate the compliance with the revised performance-based safety criteria. Physical phenomena for thermo-mechanical behavior of irradiated high burnup fuels were identified and modelled. And, the influence of high burnup on the peak cladding temperature (PCT) and equivalent cladding reacted (ECR) was investigated with current SBLOCA methodologies.

2. Analysis Details

For SBLOCA analysis of APR1400 plants, a limiting break of 92.9 cm^2 (0.1 ft^2) in a DVI line is selected.

2.1 Analysis Code Structure

In current LOCA analyses, sBLOCA Evaluation Model (sEM) [1] is used for the thermal-hydraulic calculations, as shown in Figure 1. The sEM has been developed for the purpose of the conservative evaluation of SBLOCA in PWRs. In the sEM, the modified version of RELAP5/MOD3.3ef reflecting the requirements of the conservative evaluation model prescribed in KINS/GT-N007-1 [2] was used for the calculation of the system thermal hydraulics and the fuel rod heat conduction. Overall configuration of the sEM including inputs and outputs is shown in Figure 1.

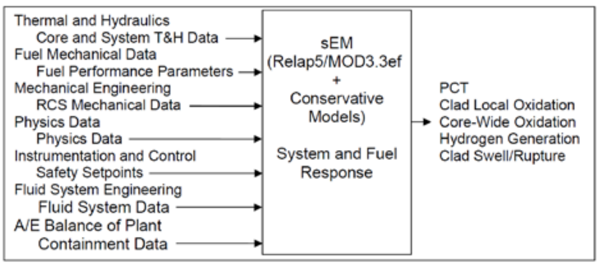

Figure 1. Overall Configuration of the sEM Code Including Inputs and Outputs

2.2 Modeling of High Burnup Fuel

In traditional methods, no implicit sensitivity studies on the burnup effects are performed. The most limiting burnup in terms of initial stored energy occurred at beginning of life (BOC). The corresponding fuel conditions at the maximum stored energy are used as input data to the fuel rod model in the LOCA codes.

For regulatory purposes, at rod exposure above 40 GWd/MTU (hot rod average), extrapolation from a low-burnup data base is needed to be reassessed more carefully. The fuel thermal conductivity degradation (TCD) and higher initial oxidation and rod internal pressure (RIP) take place at higher burnup. Higher burnup may be more limiting.

To take account for high burnup effects, SBLOCA analysis was performed for the whole range of burnups up to 60 GWd/MTU. The burnup-dependent data was provided from the FRAPCON-3 code [3]. This has been developed to calculate the steady-state high burnup response of a single fuel rod.

A peak linear heat generation rate (PLHGR) of 15.5 kW/ft was used. The fuel thermal analysis shows the initial fuel rod stored energy increases with the increasing fuel burnup due to the TCD and increase of porosity fraction for a constant linear power density. The maximum stored energy occurs at end of life (EOL) for a constant peaking factor (F_q), or at intermediate burnup if crediting the reduction of F_q at higher burnup.

2.3 Revised Safety Criteria

The USNRC established new embrittlement criteria for assurance of adequate margin for high burnup operation as follows:

- 1204℃ PCT regulatory limit remains adequate, and
- 17% ECR regulatory limit does not always ensure post quench ductility (PQD).

3. Results

3.1 Limiting Case Selection

The effect of the major parameters in a user input is investigated to select liming case in terms of PCT and peak local oxidation (PLO). The results from the sensitivity study are presented in detail in Table 1. The most limiting case was determined based on the combination of conservative values for all parameters analyzed.

Table 1. PCT and PLO Results from Sensitivity Study

Parameter	Min/ Max	Value	PCT (K)	PLO (%)	Quenching (sec)	ΔT (K)
SIP Flow Multiplier	Min	-0.5	878.8	1.1672	1064	241.8
SIT Water Volume	Min	50.7	879.3	1.1672	1070	0.5
SIT K	Max	25.0	878.8	1.1672	1070	-
SIT Water T	Min	322.0	882.7	1.1673	1084	3.9
SIT Pressure	Min	$4x10^6$	878.8	1.1672	1064	20.0
IRWST T	Max	322.0	878.8	1.1672	1064	36.2
RCP Volume	Max	3.8	878.8	1.1672	1064	1.0
RCP K	Max	0.6	879.7	1.1672	1062	1.2
Pressurizer Pres.	Max	157.9	952.9	1.1692	1068	74.1
Pressurizer Level	Min	5.9	940.0	1.1679	1042	42.5
Decay Heat	Max	1.2	878.8	1.1672	1064	241.8

3.2 Burnup Effect

For the most liming case selected, SBLOCA analyses cover the whole range of burnup up to EOL. A plot of PCT versus burnup is presented in Figure 2.

Due to the fuel TCD, a reduction of F_q at high burnup needs to be credited to assess the burnup effects. The maximum stored energy occurs at intermediate burnup, i.e., 34.1 GWd/MTU. For higher burnup fuel rods operating at lower local power density, the temperature transient is benign relative to the more limiting intermediate burnup fuel rods.

The BOC burnup results in the highest cladding temperature, 883.3 K, of the small break analyzed. This PCT is predicted to be only 2.7 K higher than 34.1 GWd/MTU case.

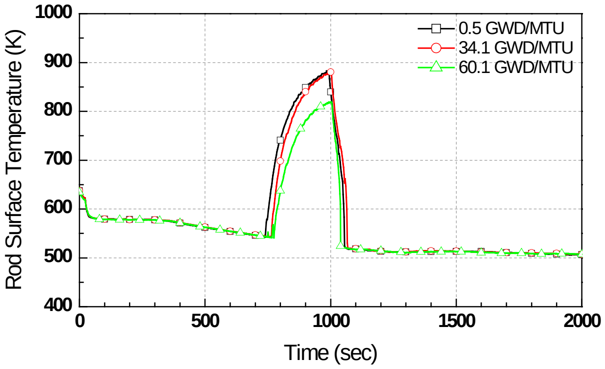

Figure 2. Hot Spot Cladding Surface Temperature As a Function of Burnup

Table 2 summarizes the important results of the APR1400 sEM analyses.

Table 2. PCT and ECR Summary for 92.9 cm^2 DVI Line Break

Burnup Condition (GWd/MTU)	PCT (K)	ECR (%)
0.5	883.3	0.0209
34.1	880.6	0.0207
60.1	819.4	0.0082

3.3 Revised Criteria

Evaluation of LOCA behavior is performed based on embrittlement criterion, represented by new ECR limit and the PCT limit, 1204 ℃. This assessment found that due to realistic fuel rod power history, measured cladding performance under SBLOCA conditions, and current analytical conservatisms, sufficient safety margin is expected to exist for APR1400 operating reactors.

4. Summary

To address effects of high burnup, SBLOCA assessment was performed. Because of the trade-off of initial rod power reduction and fuel conductivity degradation, safety margin is expected to exist. Current APR1400 SBLOCA analyses demonstrate compliance to the revised embrittlement criteria. Although the initial fuel rod stored energy increases with the increasing fuel burnup, the most limiting burnup in terms of PCT and ECR was predicted to occur at BOC.

REFERENCES

[1] "sEM Application to APR1400 Nuclear Power Plants," KNF-TR-SGA-11001 Rev. 0, KNF, July 2011.

[2] "Technical Guidelines for Conservative Evaluation of the Performance of Emergency Core Cooling System of PWR Nuclear Power Plants," KINS/GT-N007-1, KINS, 2004.

[3] K.J. Geelhood, et. al., "FRAPCON-3.4: A Computer Code for the Calculation of Steady-State, Thermal-Mechanical Behavior of Oxide Fuel Rods for High Burnup," NUREG/CR-7022, Vol. 1, PNNL-19418, Pacific Northwest National Laboratory, 2010.