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Preliminary Evaluation of APR1400 SB LOCA Analyses Against Breakaway Oxidation

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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 US NRC established a testing program at Argonne National Laboratory. The results of recent investigations [1] 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. Especially, breakaway oxidation is evaluated with current SB LOCA methodologies.

2. Analysis Details

For SB analysis of APR1400 plants, a limiting break of 0.4 ft^2 in a DVI line is selected.

2.1 Analysis Code Structure

The analysis was performed using the CE SB LOCA evaluation model [2], as shown in Figure 1. In the CE model, hot rod temperatures and oxidation percentages are calculated using the STRIKIN-II [3] and PARCH [4] computer programs.

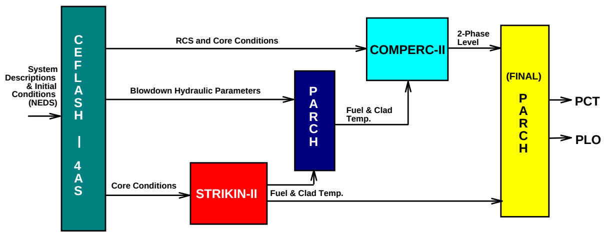

Fig. 1. Code Flow Chart for SB LOCA Analysis

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 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 conductivity degradation and higher initial oxidation and RIP take place at higher burnup. Higher burnup may be more limiting.

To take account for high burnup effects, SB LOCA analysis was performed for the whole range of burnups up to 60 GWd/MTU. A PLHGR of 15.0 kW/ft was used. The burnup-dependent data was provided from the FRAPCON-3 code [5]. This has been developed to calculate the steady-state high burnup response of a single fuel rod.

2.3 Revised Performance-based Safety Criteria

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

- 2200 °F PCT regulatory limit remains adequate,
- 17% ECR regulatory limit does not always ensure PQD, and
- New regulatory limit is required for breakaway oxide layer

For oxidation considerations, small break LOCAs are most important since oxidation is more severe for events involving extended time at high temperatures. All plants use 10 CFR 50.46, Appendix K models for SB LOCA. Appendix K requires the use of a conservative decay heat source and Baker-Just oxidation model.

Breakaway effects do not introduce any direct addition to uncertainties in oxidation rate data because this phenomenon does not occur over the range of temperatures of interest for LOCA analyses (>1832 °F, 1000 °C). Below this temperature, oxidation rates are generally so slow that the 17% ECR limit would not be expected to be approached.

Therefore, SB LOCA results are governed mainly by general hydrogen-induced embrittlement from breakaway oxidation. This term is employed to describe an apparent increase in oxidation rate which is not predicted by thermal arguments alone.

3. Results

Table 1 summarizes the important results of the STRIKIN-II/PARCH analyses.

Table 1. PCT Summary for 0.4ft^2 DVI Line Break

Burnup Case	PCT (°F)	Burnup Case	PCT (°F)
Case 1(0 GWd/MTU)	1140.4	Case 4* (0 GWd/MTU)	1155.5
Case 2(30 GWd/MTU)	1133.8	Case 5** (0 GWd/MTU)	1181.5
Case 3(60 GWd/MTU)	1019.9		

* Case 4 = Case 1 + initial conditions from FATES [6]
** Case 5 = Case 4 + higher rod power(5% increase)

3.1 Burnup Effect

SB LOCA analyses cover the whole range of BU up to EOL. A plot of PCT versus burnup is presented in Figure 2.

Due to the fuel thermal conductivity degradation, a reduction of F_q at high burnup need to be credited to assess the burnup effects. The max stored energy occurs still at BOC burnup(Case 1). For high burnup fuel rods operating at low 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, 1140 °F, of the small break analyzed. This reflood PCT is predicted to be 7 °F higher than 30 GWd/MTU case(Case 2).

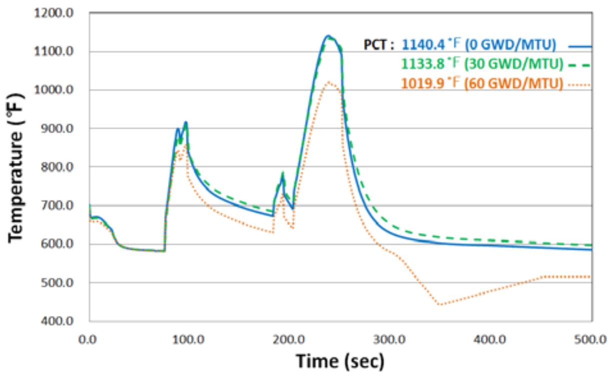

Figure. 2. Hot Spot Cladding Surface Temperature As a Function of Burnup

3.2 Initial Condition Effect

Codes such as FRAPCON-3 calculate the change with time(burnup) of fission gas inventory, fuel densification and swelling, cladding permanent strain, fuel radial power and burnup profiles, and other time/burnup dependent parameters. Variables written by FRAPCON-3 are used by STRIKIN-II for burnup initialization.

For Case 4, burnup-dependent parameters were initialized from the FATES steady-state single rod fuel performance code. As shown in Figure 3, the state of the fuel rod at the time of a transient is not changed based on FATES predictions. This reflood PCT is predicted to be about 15 °F higher than BOC case(Case 1).

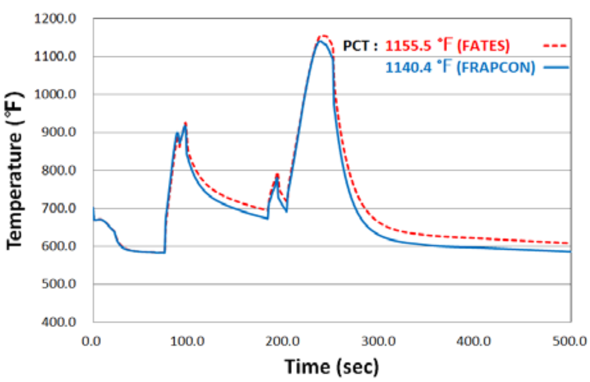

Figure 3. Hot Spot Cladding Surface Temperature Based on FRAPCON-3 and FATES Data

3.3 Power Effect

To consider power effect, 5% power decrease is applied to hot rod for Case 5. As shown in Table 1, hot rod power change does not significantly affect the reflood PCT. This reflood PCT is predicted to be about 26 °F higher than Case 4. The max stored energy is expected to occur at intermediate burnup if the reduction of F_q is not credited at higher burnup.

3.4 Revised Criteria

Evaluation of LOCA behavior is performed based on embrittlement criterion, represented by new ECR limit and the PCT limit, 2200 °F. For breakaway oxidation criterion, based on ANL and industry testing, the cladding peak temperature does not stay at 1472 °F (800 °C) for more than about 5000 seconds for typical small break LOCA transients.

This assessment found that due to realistic fuel rod power history, measured cladding performance under LOCA conditions, and current analytical conservatisms, sufficient safety margin is expected to exist for APR1400 operating reactors.

4. Summary

To address effects of high burnup, SB LOCA 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 SB LOCA Analyses demonstrate compliance to the revised embrittlement criteria.

REFERENCES

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[5] 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.

[6] “C-E Fuel Evaluation Model Topical Report,” CENPD-139, Rev. 01 (Non-Proprietary), July 1974.