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LBLOCA Analysis Methodology for New Acceptance Criteria

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1. Introduction

The U.S. Nuclear Regulatory Commission (NRC) is finalizing a rulemaking designated as 10 CFR 50.46c to revise the Emergency Core Cooling System (ECCS) acceptance criteria to include the effects of higher burnup on fuel/cladding performance. In this new rule, the NRC proposes a fuel performance based equivalent cladding reacted (ECR) criterion as a function of cladding hydrogen content before the accident (pre-transient) to include the effects of burnup on cladding performance. The pre-transient cladding hydrogen content is basically a function of the fuel burnup and cladding materials. As illustrated in Figure 1, a characteristic of the proposed rulemaking imposes more restrictive and fuel burnup-dependent cladding embrittlement criteria.

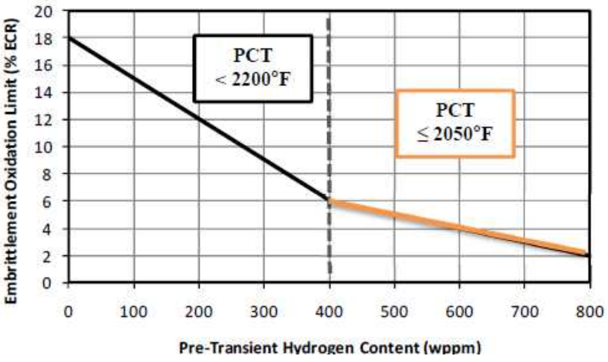

Figure 1. Acceptable analytical limits for ECR & PCT versus hydrogen [1].

Since tens of thousands of fuel rods with different burnup and power are present in the reactor core at a specific point in time, if the accident analysis is to be carried out very realistically, all fuel rods shall be modelled assuming their respective burnup levels. Moreover, the calculation should be made assuming several cycle times at least since it cannot be known which time-in-cycle will have the highest Peak Clad Temperature (PCT) or ECR.

However, doing that kind of accident analysis is not practical if the performance and calculation environment of the current accident analysis computer codes are considered. Thus, the Loss-Of-Coolant-Accident (LOCA) analysis using the SPACE code to date has modelled all the fuel rods using three representative fuel rods, the hot rod, the hot assembly average rod, and the core average rod. In this case, the core average rod has been assumed to have a rod burnup at which the fuel stored energy becomes maximum, while the hot rod and the hot assembly rod have a range where the most limiting burnup should be found through the whole analysis procedure.

It is not impossible to apply the current LOCA analysis method as such to the verification of new acceptance criteria. In other words, it is possible to conduct calculations assuming various burnups of the hot rod and the hot assembly average rod and compare PCTs and ECRs obtained from them with the acceptance criteria of Figure 1. To do this, however, an extremely large number of calculations are required because a large number of hot rod burnup cases should be considered as the acceptance criteria change in a continuous manner depending on the rod burnup. (To apply the current SPACE Large Break LOCA (LBLOCA) Realistic Evaluation Model (REM) as it is, several sets of 124 calculations should be conducted even with a fixed hot rod burnup. It means that several hundred calculations are needed to get only one set of PCT and ECR value at a rod burnup.) Besides, the current analysis methods simply model the various burnup levels of fuel rods, excluding the highest power assembly, as a single value, which can produce overly conservative PCT or ECR.

In order to improve these shortcomings of the current LBLOCA analysis method, a new modeling method for core and fuel rods has been proposed and applied demonstratively to an analysis for Shinkori Units 3 and 4 in this study.

2. Proposed LBLOCA analysis methodology

2.1 Core modelling

In the current SPACE LBLOCA REM, the core is divided into two hydraulic channels, the hot channel containing the highest power assembly and the average channel containing the remaining fuel rods. In this REM, rod heat-up calculations are made for only three rods; the hot rod representing a conceptual rod having the highest power, the hot assembly average rod representing a conceptual rod having the average power of rods in the highest power assembly except the hot rod, and the core average rod representing a conceptual rod having the average power of all the rods except those in the highest power assembly.

In the newly proposed analysis method, as shown in Figure 2, fuel rods in the core are grouped according to the number of batch loadings, into fresh rods, once-burnt rods, and twice-burnt rods. And then the fuel rods in the highest power assembly of each group are modeled using three hot rods and three hot assembly average rods each of which are located in one of separate three hot channels. In other words, the new method simulates the core with three hot channels and one average channel containing nine representative fuel rods. By applying these modelling, three PCTs and ECRs can be obtained from a calculation as three hot rods exist in the core.

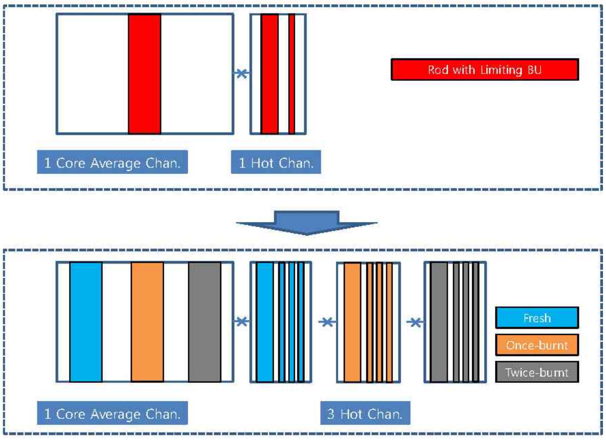

Figure 2. Change of core modelling.

As mentioned earlier, the new ECCS acceptance criteria should be verified for continuously changing rod burnup. So it would be more convenient if more number of hot rods are modeled so that a more number of PCTs and ECRs are produced from one calculation. However, increasing the number of hot rods may make considerable complications in code input preparation because whenever one additional hot rod is introduced, the power of that rod should be subtracted from the power of hot assembly average rod. It is not easy either to define the rod power of second or third hot rod because hot rod itself is not a real fuel rod but a conceptual rod having the bounding radial peaking factor, in the SPACE LBLOCA REM.

To address these inconveniences, a pseudo rod component was added to the SPACE code. This component is essentially the same as the fuel rod component, but it does not deliver heat flux to the fluid and it shares the convective heat transfer boundary condition of a pre-designated fuel rod component. That is, the pseudo rod component can be used to model the fuel rods that share the wall heat transfer conditions with a certain hot rod but have different rod burnup or rod power.

In the demonstrative analysis for Sinkori Units 3 and 4 described in Chapter 3, two pseudo rods were added for each of the three hot rods. In other words, a total of nine PCTs and ECRs were obtained in a calculation from three hot rods and six pseudo rods.

2.2 Inside surface oxidation and CRUD

RG-1.224 requires to consider the oxygen ingress on the cladding inside surface due to the fuel-cladding bond layer in the calculation for verifying the new ECCS criteria, especially for fuel rods with burnup levels exceeding 30 GWd/MTU. In the current methodologies, inside surface oxidation was considered only after the fuel rod burst. Therefore, the SPACE code was modified so that inside surface oxidation was calculated from the beginning of the accident under conditions of 30 GWd/MTU or higher. Note that no metal-water reaction heat is assumed in the case of inside surface oxidation prior to the fuel rod rupture.

NRC's draft final 10 CFR 50.46c also requires consideration of the thermal effects of CRUD. Therefore, a separate layer of CRUD was added to the fuel rod component of SPACE code and the thermal properties of CRUD were calculated in every time step using the properties of metallic materials composing the CRUD and the properties of fluid occupying the porous volume of CRUD. It was assumed that the metallic part of CRUD was composed of 15% NiO, 75% $NiFe_2O_4$, and 10% Fe_3O_4. It was also assumed that CRUD had a porosity between 0.4 and 0.8 and a thickness up to 30 micrometers.

The thermal conductivity of the CRUD was calculated using the Maxwell equation as follows:

$$k_{CRUD} = k_F \frac{\left\{1-\left(1-a\frac{k_S}{k_F}\right)(1-\varepsilon)\right\}}{1+(a-1)(1-\varepsilon)} \qquad (1)$$

$$\mathrm{a} = \frac{3k_F}{2k_F + 3k_S} \qquad (2)$$

where k_S, k_F are the conductivity of metal components and fluid, respectively and ε is the CRUD porosity.

2.3 Burnup and power of fuel rods

As described above, three core average rods, three hot assembly average rods, and nine hot rods (including six pseudo rods), each of which belong to the fresh fuel group, the once-burnt fuel group, and the twice-burnt fuel group, respectively, should be defined in the newly proposed method. In other words, the burnup and power of each of these fifteen fuel rods should be determined to define the initial conditions such as the gap size of each fuel rod, rod internal pressure, gas mole fraction, and etc.

The power of a particular fuel rod is a function of the rod burnup, which depends on the time-in-cycle. In other words, the initial conditions of the fuel rod depend on the cycle-by-cycle loading pattern so that LOCA analyses should be performed every cycle to reflect the real rod conditions.

However, it is not practical to do LOCA analyses every cycle in terms of time and cost. So the nuclear design data for a number of past and future cycles were analyzed to derive the correlation between time-in-cycle and the burnup of fuel rods in each group. For example, if the rod burnup of hot rods belonging to the fresh fuel group is expressed as a function of cycle burnup, the relationship shown in Figure 3 can be obtained. In this figure, the solid line is the linear fitting curve of the actual data.

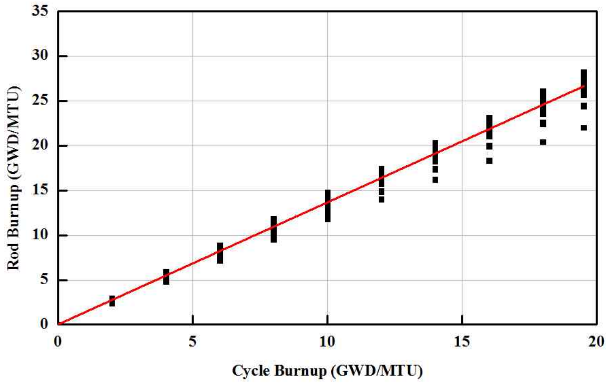

Figure 3. Hot rod burnup as a fuction of cycle burnup

Analyzing the same nuclear design data can also give a relationship between rod power and rod burnup. For example, the power of the highest-power fuel rods in the twice-burnt fuel assemblies can be correlated with the rod burnup level of those rods as shown in Figure 4. In this figure, the solid line is the bounding curve encompassing actual data and the rod power was normalized against the highest rod power in the entire core.

In summary, if a time-in-cycle or cycle-burnup is specified, the relationship as in Figure 3 can be used to determine the rod burnup of a particular fuel rod, and the power of that rod can be defined using the relationship as in Figure 4.

By the way, as Figure 3 shows, the rod burnup of a certain fuel rod has a range of variation. Such variation of rod burnup may not be very important when defining the core average rods or the hot assembly average rods, but it cannot be neglected when defining the conditions of the hot rods from which PCTs and ECRs are derived. Therefore, 2 pseudo rods were added to the hot rod of each group and the rod burnup of the pseudo rods is set to the maximum value and the minimum value that the rod burnup of the hot rod can have at a specific cycle time.

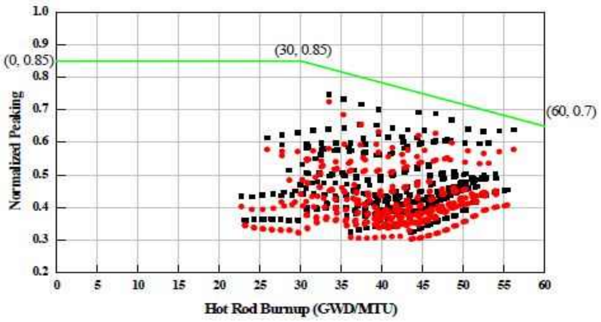

Figure 4. Hot rod power distribution for twice-burnt fuel

2.4 Safety metrics

Since both PCT and ECR limits are rod burnup-dependent, it is convenient to define new safety metrics that would synthesize PCT and ECR with fuel rod dependent cladding pre-transient hydrogen content. The safety metrics are defined as the ratio of the calculated PCT over PCT limits for each fuel rod, as well as the ratios of the calculated ECR over ECR limits, for each fuel rod and are expressed as follows[3]:

$$PCTR = \frac{PCT^{Calculated}}{PCT^{Limit}} \tag{3}$$

$$ECRR = \frac{ECR^{Calculated}}{ECR^{Limit}} \tag{4}$$

Then $PCTR_{max}$ and $ECRR_{max}$ are defined as the maximum value of *PCTR* and *ECRR*, respectively and the acceptance criteria for the safety metrics can be expressed as follows:

$$PCTR_{max} < 1.0 \tag{5}$$

$$ECRR_{max} < 1.0 \tag{6}$$

3. Demonstrative analysis

To demonstrate the applicability of the proposed methodology, a whole scope LBLOCA analysis for Shinkori Units 3 and 4 having 241 PLUS7 fuel assemblies of ZIRLO^{TM} cladding was performed. The analysis is composed of the break spectrum analysis to find the limiting break type and size at a time-in-cycle and the SRS calculations assuming limiting break type and size to quantify all kinds of uncertainties included in the analysis results.

3.1 Break spectrum analysis

The break spectrum analysis was performed for a range of break size and two types of break, i.e., guillotine breaks and split breaks. The analysis was performed for 5 time-in-cycle (0, 5, 10, 15, 20 GWd/MTU) assuming best-estimate or nominal values of uncertainty parameters and the chopped cosine power shape just following the current SPACE LBLOCA methodology.

The results of this break spectrum analysis are presented in Table 2 where the break size is expressed as a fraction double-ended pump discharge leg break area.

Table 2. The result of break spectrum analysis

Cycle burnup (GWd/MTU)	Blowdown PCT		Reflood PCT		CP-ECR	
	PCT(K)	Break	PCT(K)	Break	ECR	Break
0	1100	0.82 Split	1069	0.92 Guillotine	0.253	0.92 Guillotine
5	1104	0.87 Split	1050	0.95 Guillotine	0.223	0.87 Guillotine
10	1116	0.90 Split	1071	0.90 Guillotine	0.268	0.90 Guillotine
15	1142	0.89 Split	1062	0.91 Guillotine	0.405	0.91 Guillotine
20	1170	0.81 Split	1079	0.83 Guillotine	0.731	0.86 Guillotine

3.2 SRS calculations

The SRS calculations to take into account all kinds of uncertainties in a LBLOCA analysis were carried out for each of two or three limiting break type and size, presented in Table 2. For example, three sets of 124 calculations were made assuming the 0.82 split break, the 0.83 guillotine break, and the 0.92 guillotine break for zero time-in-cycle. Thus, in this demonstrative analysis, eleven sets of 124 calculations were conducted and 9×124 values of PCT and ECR were obtained since three hot rods and six pseudo rods were modeled in each calculation. Thus we have nine 3'rd highest PCTs and highest CP-ECRs in a set of 124 calculations. Recalling that eleven sets of 124 calculations were made, the number of 3'rd PCTs and CP-ECRs from the whole analysis becomes 99, respectively.

For each of 99 PCTs and CP-ECRs, *PCTR* and *ECRR* can be estimated and all 99 *PCTR*s and *ECRR*s are presented in Figure 5 and 6, respectively. In Figure 5, the highest *PCTR* is 0.865 and it means the acceptance criterion on PCT was satisfied. The same conclusion can be made on CP-ECR as the highest *ECRR* was 0.382.

Note that however, the *ECRR* values in Figure 6 were estimated using the ECR^{limit} based on a realistic rod power history. If a more conservative rod power history is used to cover some possible variations of loading patterns, ECR^{limit} would be very low near the maximum rod burnup and then *ECRR* may go over 1.0.

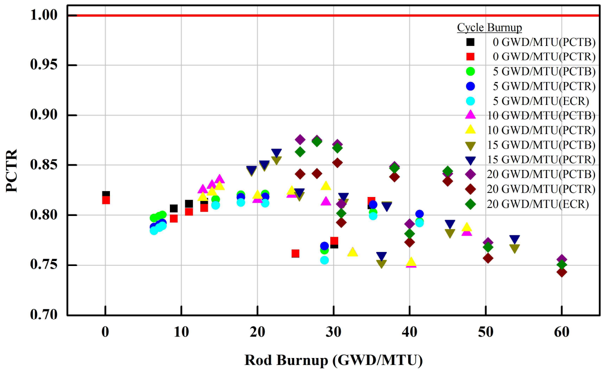

Figure 5. *PCTR* distribution of the limiting case

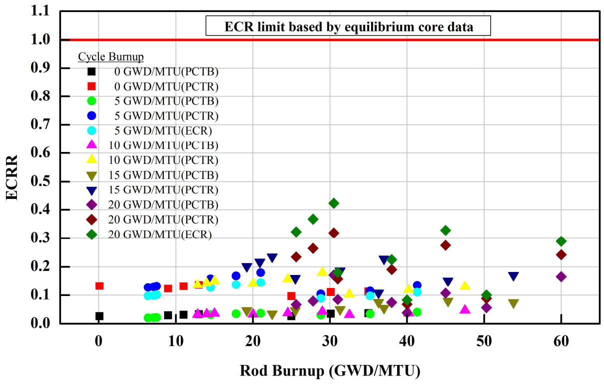

Figure 6. *ECRR* distribution (equilibrium core data)

4. Conclusions

A new LBLOCA analysis methodology has been proposed to evaluate the ECCS performance under the draft final 10 CFR 50.46c. Starting from the current SPACE LBLOCA REM, the core modeling was modified to have two more hot channels and the fuel rods were modeled after grouped in three based on how many times they have been loaded. A demonstrative analysis using the proposed methodology revealed that Shinkori-3/4 LBLOCA results satisfy the acceptance criteria in the draft final 10 CFR 50.46c.

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