Monte-Carlo CIPS and CILC Assessment to OPR1000 with HIPER16^{TM}

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1. Introduction

CIPS means the Crud Induced Power Shift, which is caused by subcooled nucleate boiling, corrosion products, boron, etc. CIPS is the phenomenon of the axial power distribution bias downward due to the accelerated deposition of boron compounds and crud at the upper part of the cladding. To assess the CIPS, the amount of the boron deposition in core is calculated using Monte-Carlo simulation. The Monte-Carlo simulation can estimate uncertainties of BOA code input variables, such as Nickel Alloy/Stainless Steel corrosion rate, crud mapping multiplier, etc. This simulation gives more reasonable results about the CIPS risk assessment.

CILC is abbreviation of Crud Induced Localized Corrosion. When the crud is deposited on the cladding surface, the cladding temperature rises due to the decreased heat transfer ability which accelerates the corrosion of the cladding. Since CIPS has a close influence on the normal operation of the core, EPRI recommends performing CILC assessment as well as CIPS assessment. Because CILC is highly dependent on local crud thickness and mass evaporation rate, EPRI proposes a three-step CILC risk assessment [3].

In this paper, the method of Monte-Carlo CIPS and CILC risk assessment were applied to OPR1000 with HIPER16^{TM} fuel.

2. Methods and Results

In this paper, the variables for analyzing are as follows:

- The number of fuel assemblies in core: 177
- The number of grids: 13
- Axial length: 165 in.

To assess the CIPS and CILC risks, BOA Code version 4.0 [2] was used. The CIPS and CILC risks were analyzed about three cases as shown in below:
(1) No reactor trip & No Zinc injection (NTNZ)
(2) Reactor trip & No Zinc injection (TNZ)
(3) Reactor trip & Zinc injection (TZ)
The ultrasonic fuel cleaning was applied and input variable about it was changed following the manual [2].

2.1 Monte-Carlo CIPS risk assessment

The thresholds of Monte-Carlo CIPS [1, 2] are as follows:

- Mild to moderate CIPS: 230 ~ 450 g (0.5 ~ 1.0 lbm)
- Severe CIPS: 450 g ~ (1.0 lbm ~)

The process of Monte-Carlo CIPS risk assessment is as followed. First, designer prepares the BOA input for Monte-Carlo CIPS and performs the Monte-Carlo CIPS. If Boron mass of all cases are under 1 lbm, there are no Severe CIPS in this cycle. When severe CIPS is determined to occur, like the boron mass is over 1 lbm, it is recommended to carry out the re-design to decrease the crud deposition. If there are no severe CIPS, the designer has to evaluate probability of Mild CIPS. If the number of events which boron mass over 0.5 lbm are over 5, it is recommended to advise plant management of potential risk of Mild CIPS.

Fig. 1 shows the results about non-statistical CIPS. In case of non-statistical CIPS for OPR1000, all cases didn't exceed the threshold as shown in Fig. 1.

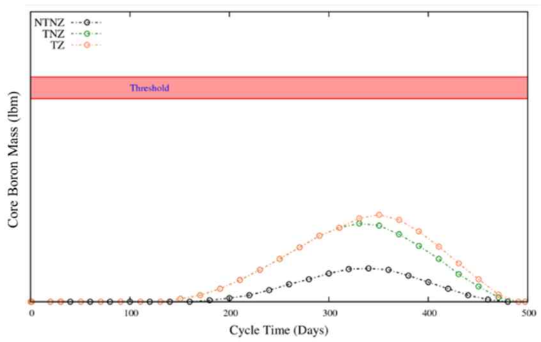

Fig. 1. The results of non-statistical CIPS

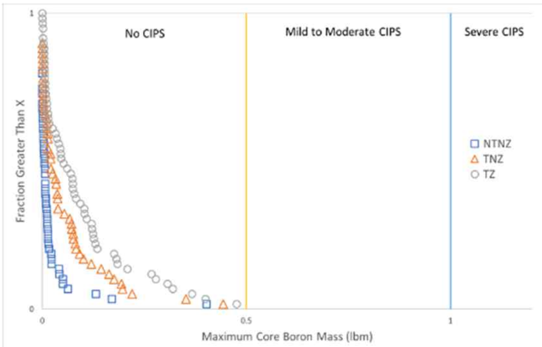

Fig. 2. The results of Monte-Carlo CIPS

Fig. 2 shows the CIPS calculation result with applying the Monte-Carlo method. Since the core boron mass didn't exceed 1 lbm, it could be said that severe CIPS occurrence probability was under 5 % in this core model. Also, since the core boron mass didn't exceed 0.5 lbm, it could be judged that Mild CIPS occurrence probability was under 10 % in all cases.

2.2 CILC risk assessment

CILC risk assessment is required under the following conditions [3].

First of all, the maximum crud thickness is over 3 mils (76 microns) or 0.75 mils (19 microns) over than prior cycle. Fig. 3 shows the maximum crud thickness versus cycle time. The maximum crud thickness of all cases was under 3 mils. Second, when a period of zero mass evaporation rate is greater than 75 % of the total cycle, the CILC risk assessment is required. Fig. 4 shows the mass evaporation rate versus cycle time. Zero mass evaporation rate period is shortly shown in trip case, TNZ and TZ. Third, the utility desires to evaluate CILC risk, CILC risk assessment is executed.

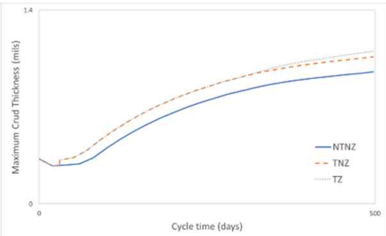

Fig. 3. Maximum crud thickness versus cycle time

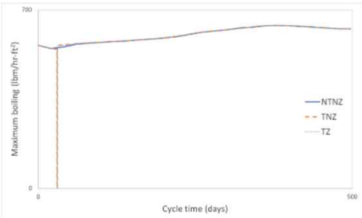

Fig. 4. Mass evaporation rate versus cycle time

CILC risk assessment process has 3 steps. First, the designer performs the CILC risk assessment step 1 with appropriate BOA code input. If the output is over the threshold of step 1, the designer should perform the step 2 or redesign the core. Step 2 or step 3 is performed the same way. The designer has to check the output with threshold of corresponding steps, and if over, perform the next step or redesign the core.

CILC analysis step 1 is called Tier 1 BOA analysis with hotspots. Before performing the Tier 1, the BOA code input was prepared. The main difference with CIPS input was setting the hotspot location. Hotspot is a node right under the grid which located more than 100 inches from the start of the heating length [3]. In HIPER16^{TM} fuel, there are 3 grids located more than 100 inches from the start of the heating length. After selecting the hotspot, the hotspot factors are applied for all assemblies to conservatively evaluate crud deposition.

The results of CILC risk assessment Tier 1 is shown in Fig. 5. In tier 1, the CILC risk is evaluated with the leading channel technique. The leading channel technique is checking the period being in top 5 which mass evaporation rate of specific channel. If the period is over 90 % of total cycle, it make increasing CILC occurrence. In Fig. 5, it could be seen that the mass evaporation rate of the selected leading channel occupies the top 5 for more than 90 % of the total cycle. There were some overlapping nodes like 55, 95, 131 and 109 in each cases, but all cases showed the similar trends.

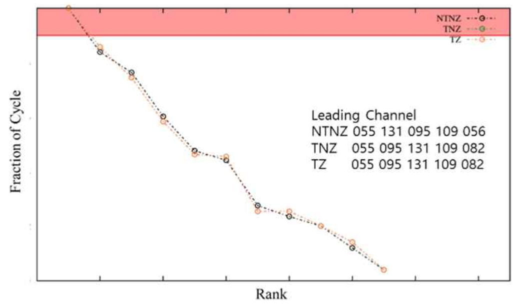

Fig. 5 The results of leading channel selection

CILC risk assessment step 2 is called BOA Tier 2 subchannel analysis. In this step, the fine mesh modeling was used. To use the fine mesh modeling, the target node has to be selected.

The AOA files are remade for fine mesh modeling. The remade AOA files are made up of channel, axial node, rod surface group, heat transfer surface, axial elevation, heat flux, local pressure, local fluid temperature, local mass flux, hydraulic diameter, heat transfer ratio and surface area fraction. The heat transfer surface number is defined that the specific rod divided in 4 with neighboring subchannels. The local pressure, temperature and mass flux is defined through the subchannel analysis code.

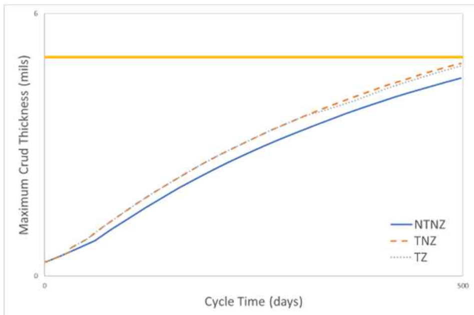

Fig. 6. The results of CILC risk assessment Tier 2

Fig. 6 shows the results of CILC risk assessment Tier 2 subchannel analysis. The graph represents the maximum crud thickness versus cycle time. A bold yellow line represents the threshold of CILC analysis step 2, 5 mils. The maximum crud thickness was under the 5 mils about all cases. The maximum crud thickness of cases TNZ and TZ were greater than NTNZ value. The values of TNZ and TZ had the same crud thickness before the zinc injection. After the zinc injection, the crud thickness of TZ was slightly thicker than TNZ case.

CILC risk assessment step 3 is called BOA Tier 4 analysis. It had to be preceded to perform tier4 that the 20 azimuthal CFD (Computational Fluid Dynamics) determined heat transfer coefficient with the subchannel.

CFD analysis was performed with model that composed in 8.5 by 8.5 rods as shown in Fig. 7. In this figure, the orange colored rods had relatively high heat flux, then green colored rods after and outer rods had the lowest heat flux. For CFD analysis, ANSYS Fluent Version 2020 R2 was used.

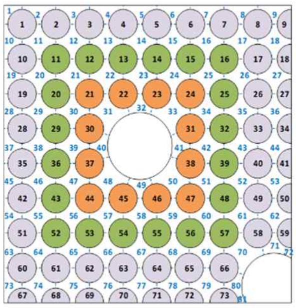

Fig. 7. 8.5 by 8.5 modeling for Tier 4

The heat transfer coefficient rate is defined as heat transfer coefficient of CFD over heat transfer coefficient. The heat transfer coefficient of CFD is calculated as shown.

$$HTR_{i,j,k,l} = \frac{HTC_{CFD_{i,j,k,l}}}{HTC_{i,j,k,l}} = \frac{\dfrac{q'_{i,j,k,l}}{T_{CFD_{i,j,k,l}} - T_{b_{i,j,k,l}}}}{HTC_{i,j,k,l}}$$

where, *HTR*: Heat transfer coefficient ratio
HTC: Heat transfer coefficient [Btu/hr-ft^2-F°]
i : 1/4 assembly ID
j : axial node ID
k : rod ID
l : surface ID
q'' : heat flux [Btu/hr-ft^2]
T_{CFD} : surface temperature calculated by CFD [°F]
T_b : bulk temperature calculated by subchannel analysis code [°F]

Fig. 8 is example of heat transfer coefficient rate about specific rod. In this model, the heat transfer rates about all rods in 8.5 by 8.5 model were calculated. It is hard to derive a representative distribution because of flow mixing by mixing vane. It is needed to applied the appropriate heat transfer rate for each rod where large amount of crud is expected to be deposited.

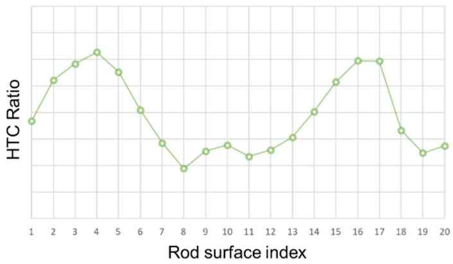

Fig. 8. Heat transfer rate about specific rod

To perform the Tier 4, the AOA files were modified with heat transfer rate. The number of heat transfer surface was changed which was 4 in Tier 2 to 20. After that, the heat transfer rate was applied appropriately for each rod index. The result of Tier 4 calculation by applying the corresponding AOA files is shown in Fig. 9. Fig. 9 represents the feed maximum crud thickness about Tier 1, 2 and 4 in NTNZ case. The crud thickness of Tier 4 is similar to Tier 2, and all results are not exceeded the threshold.

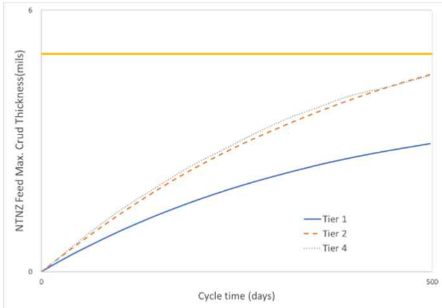

Fig. 9. Feed maximum crud thickness about Tier 1, 2 and 4 in NTNZ case

3. Conclusions

The method of Monte-Carlo CIPS and CILC risk assessment were applied to OPR1000 with HIPER16^{TM}. The results of Monte-Carlo CIPS risk assessment are as follows. The maximum core boron mass doesn't exceed 0.5 lbm and the maximum crud thickness doesn't exceed 3 mils. Period of zero mass evaporation rate is less than 75 % of the total cycle.

In CILC risk assessment Tier 1, the period being in top 5 which mass evaporation rate of specific channel was over 90 % of total cycle. In Tier 2, the maximum crud thickness was not exceeded 5 mils. The CFD analysis for Tier 4 was performed for HIPER16^{TM} 8.5 by 8.5 model. Heat transfer rate were calculated about all rods in this model. With the heat transfer rate, the AOA files were modified and executed the BOA code with Tier 4 input. The results of CILC risk assessment, the crud thickness about Tier 4 was similar to Tier 2.

REFERENCES

[1] EPRI, Boron-Induced Offset Anomaly (BOA) Risk Assessment Tool Version 3.1, User's Manual, 3002000831, 2013.

[2] EPRI, Boron-induced Offset Anomaly (BOA) Risk Assessment Tool Version 4.0, User's Manual, 3002012131, 2017.

[3] EPRI, Crud Induced Localized Corrosion Risk Assessment Methodology, 3002013303_Redacted, 2019.