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Thermal hydraulic-Mechanic Integrated Simulation for Advanced Cladding Thermal Shock Fracture Analysis during Reflood Phase in LBLOCA

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1. Introduction

In spite of suitability of zirconium-based alloy (zircaloy (Zr)) for nuclear fuel cladding material, its BDBA (Beyond Design Based Accident) tolerance has become a major safety issue after Fukushima accident.

One of the most promising alternative is changing the nuclear fuel cladding material to very high oxidation resistant material (SiC, FeCrAl, and so on). That concept for enhanced safety of LWR called Advanced Accident-Tolerance Fuel Cladding (ATF cladding, ATF) [1] is researched actively.

However, current nuclear fuel cladding design criteria for zircaloy cannot be apply to ATF directly because those criteria are mainly based on limiting their oxidation. So, the new methodology for ATF design criteria is necessary.

In this study, stress based analysis methodology for ATF cladding design criteria is suggested. By simulating LBLOCA scenario of SiC cladding which is the one of the most promising candidate of ATF. Also we'll confirm our result briefly through comparing some facts from other experiments.

2. Methods and results

According to Lee et al., [2] in LBLOCA condition, the most probable breakaway region of SiC cladding is near the point where the boiling mode changes. We simulated thermal stress profile of SiC cladding in LBLOCA scenario and solved the failure probability density function. Then we could find the probability of breakaway and the most dangerous region along the time. If that region is located near the position where changing boiling mode, we can conclude that this stress based approach can predict the behavior of ATF cladding under accident condition.

To achieve the purpose, in this study we designed experiment as following 3 steps:

1. Get cladding temperature field and boiling mode data along the time.
2. Calculate stress profile to use cladding temperature profile from step 1.
3. Obtain failure probability density function from the stress profile from step 2 to use Weibull statistics model.

Because there is no code to do those whole steps, we used 3 different codes to simulate this situation step by step. Those are MARS/RELAP 3D, ANSYS and in-house failure analysis codes.

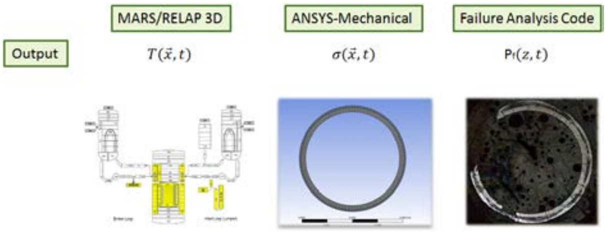

Figure 1. Simulation Conceptual Diagram

2.1 MARS/RELAP 3D results

From the recent research [3], inserting convection heat transfer coefficients along the position correctly is important to predict cladding's behavior well. So, in this study, we used the temperature and heat transfer coefficient profile of cladding under LBLOCA from the result of MARS/RELAP 3D code. It gives slightly precise data along the time and position. Authors simulated the cold leg broken LBLOCA scenario. We inserted every conditions (Broken time, fuel geometry, assembly geometry and so on) exactly same as ordinary plant that using Zr-4 cladding except cladding material properties.

Alternative cladding material properties are from the value of SiC-Duplex. The temperature, heat transfer coefficient and boiling mode profile from MARS/RELAP 3D along the time and position are in Figure 2, Figure 3 and Figure 4.

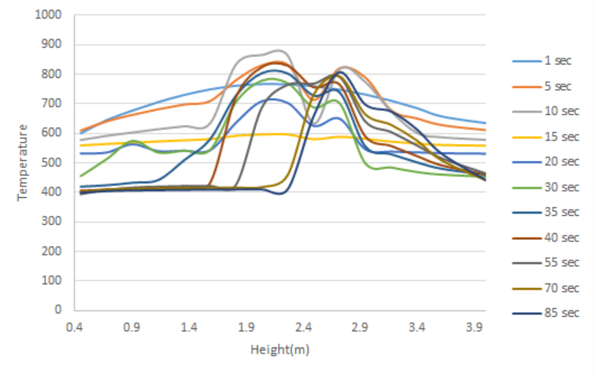

Figure 2. Temperature profile from MARS/RELAP 3D along the time and z-axis position

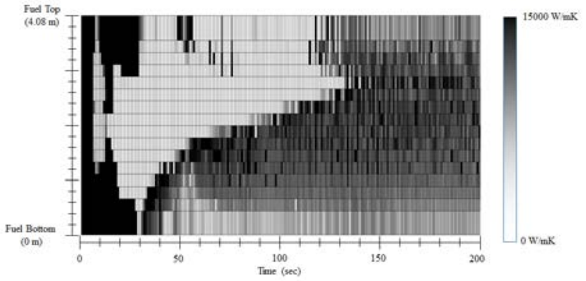

Figure 3. Convection heat transfer coefficient profile from MARS/RELAP 3D along the time and z-axis position

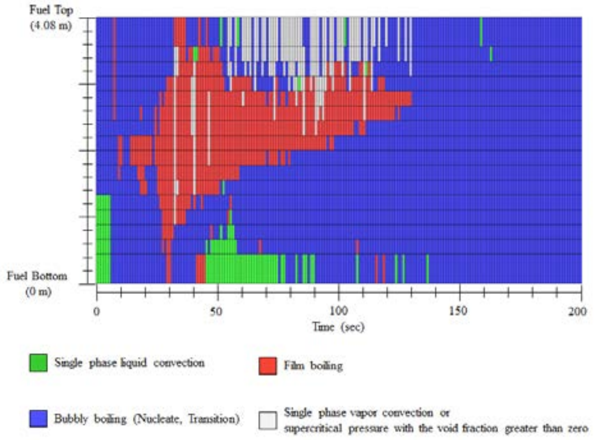

Figure 4. Boiling mode profile from MARS/RELAP 3D along the time and z-axis position

2.2 ANSYS-Mechanical results

Next, the cladding inner temperature profile was inserted to ANSYS-Fluent and ANSYS-Mechanical to find stress profile.

The most serious issue of this step is the mesh sensitivity and convergence problem. Figure 5 shows the relationship between final results and the number of the meshes.

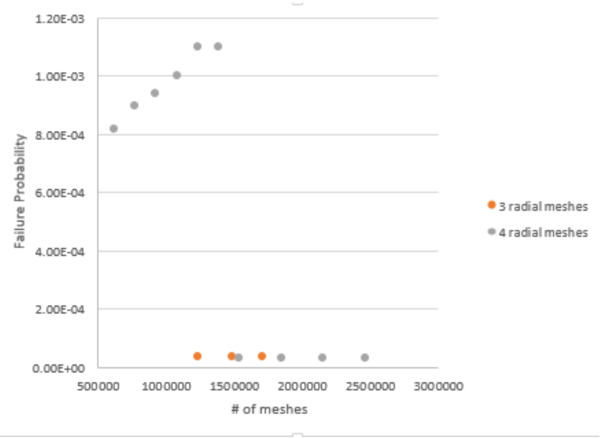

Figure 5. Relationship between final results and the number of the meshes

From these tests, we can say more than 1.0E7 meshes could provide suitable results. This experiment used meshes divided in 4 radially and in 600 axially, which has 1.85E7 meshes.

2.3 In-house failure probability code results

Using this stress profiles, probability and most dangerous region could be found by the Weibull Statistics Model. Weibull statics model for ceramic given as Equation 1.

$$P_s(V) = \exp\left[-\frac{1}{V_0}\int_V \left[\left(\frac{\sigma_\theta(\vec{r})-\sigma_u}{\sigma_0}\right)^m + \left(\frac{\sigma_z(\vec{r})-\sigma_u}{\sigma_0}\right)^m + \left(\frac{\sigma_r(\vec{r})-\sigma_u}{\sigma_0}\right)^m\right] dV\right] \quad (1)$$

Equation 1. Weibull Statistics Model for ceramics

The constants for SiC-Duplex are listed in Table 1.

Table 1. Weibull constants for SiC-Duplex

	Weibull Modulus	Chracteristic Strength (MPa)	Effective Volume (1E-4 m^3)
CVD-SiC	7.5	369	6.36
Composite-SiC	17.5	290	11.184

By this method, failure probability of SiC Duplex cladding under LBLOCA along the time is Figure 6 and Figure 7.

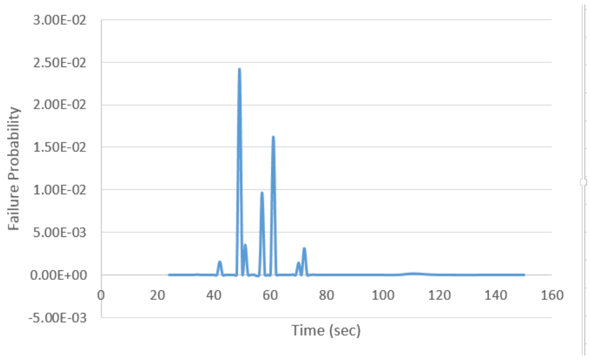

Figure 6. Failure probability of SiC-Duplex along the time

3. Discussion

Figure 7 shows the locations which boiling mode changes and the most dangerous position along the time together. The most dangerous position determined the location that has highest probability density of failure along the z axis by in-house Failure Analysis Code. By this picture, we can see that the most delicate point was located near where the boiling mode changed, as expected.

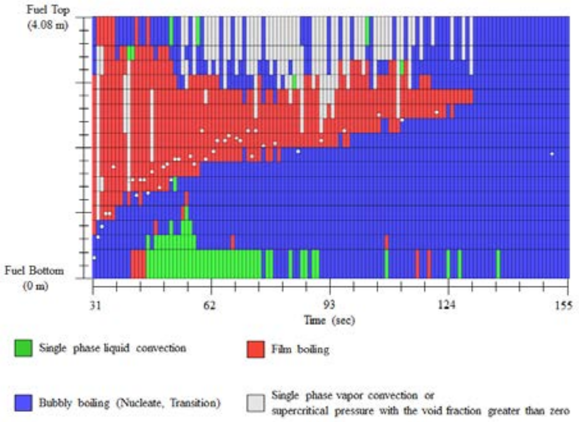

Figure 7. Locations which is changing boiling mode (background) and most dangerous position (point) along the time together.

Also this simulation can predict the behavior of SiC cladding under LBLOCA. Especially, it shows the most dangerous moment and position.

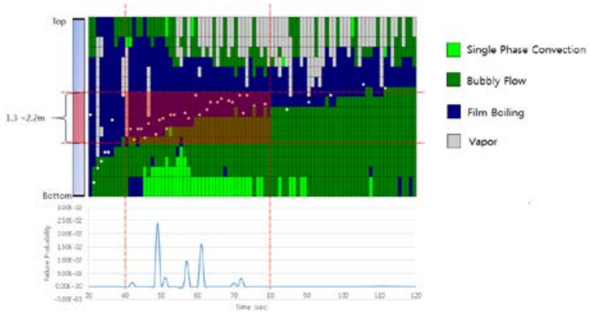

Figure 8. Simulated the most dangerous time and location of SiC-duplex cladding during LBLOCA

4. Conclusion

This study suggested thermal hydraulic-mechanical integrated stress based methodology for analyzing the behavior of ATF type claddings by SiC-Duplex cladding LBLOCA simulation. Also, this paper showed that this methodology could predict real experimental result well.

This result is validating now. Some of results show good performance with 1-D failure analysis code for SiC fuel cladding that already developed and validated by Lee et al,. [3]. It will present in meeting.

Furthermore, this simulation presented the possibility of understanding the behavior of cladding deeper. If designer can predict the dangerous region and the time precisely, it may be helpful for designing nuclear fuel cladding geometry and set safety criteria.

REFERENCES

[1] F. Goldner, Development Strategy for Advanced LWR Fuels with Enhanced Accident Tolerance, Enhanced Accident Tolerant LWR Fuels National Metrics Workshop, Germantown, MD, October 2012.

[2] 2015. Youho Lee, Thomas J. McKrell, Mujid S. Kazimi. Thermal Shock Fracture of Hot Silicon Carbide Immersed in Water. Journal of Nuclear Materials, 467, 172-180.

[3] 2015. Youho Lee, Jeong Ik Lee, Hee Cheon NO. Impacts of Transient Heat Transfer Modelling on Prediction of Advanced Cladding Fracture during LWR LBLOCA. Nuclear Engineering and Design.