Study on the Effect of Heatup Rate on Rupture Temperature Model of SPACE Code

Seung Wook Lee [a*], Chiwoong Choi [a], Kwi Seok Ha [a]
[a]*Korea Atomic Energy Research Institute, 989-111 Daedeok-daero, Yuseong-gu, Daejeon 3405, Rep. of Korea*
[*]*Corresponding author: nuclist@kaeri.re.kr*

1. Introduction

The fuel cladding rupture model of SPACE code is the same as the NUREG-0630 model [1] which is the function of the engineering hoop stresses and heatup rate of fuel cladding. Among the independent variables of this model, the heatup rate is a time derivative variable and its value is strongly sensitive to the time step size and change of cladding temperature. Current SPACE code adopts instant heatup rate, therefore, the heatup rate just before the cladding rupture is the most decisive factor to determine the rupture temperature, especially in the high hoop stress range.

In situation of fuel crumbling which can occur when fuel fragment, relocation and dispersal (FFRD) model is activated, the SPACE code reduces the fuel gap size. As a result, gap conductance is increased and cladding temperature is changed in an instant. Finally, big discrepancy of rupture temperature will be caused due to different heatup rate whether FFRD model is activated or not.

To avoid such an undesirable situation, time-averaged heatup rate is implemented into SPACE code as a user option instead of instant heatup rate and, its effect will be discussed in the following section.

2. Methods and Results

Cladding rupture temperature model of NUREG-0630 is as follows [1]:

$$T_R = 4233 - \frac{20.4\,S}{1+H} - \frac{8.51\times10^6\,S}{100(1+H)+2790\,S} \qquad (1)$$

In Eq. (1), T_R is the cladding rupture temperature in K, S is the engineering hoop stress in kpsi and, H is the normalized heatup rate between 0 (0 K/s) and 1 (28 K/s).

In order to investigate the effect of heatup rate on the rupture temperature in detail, experimental data with well-controlled cladding wall temperature is required. NRC-Studsvik LOCA test [2] fits in with this purpose. The test apparatus is designed to externally heat a 0.3 m long, pressurized, irradiated fuel rodlet up to 1,473 K by infrared radiation. The fuel rodlets are heated in a flowing steam environment from 573 K to a target temperature of 1,473 K at a rate of 5 K/s. The rodlet temperature is measured with a thermocouple located 50 mm above the axial mid plane. The test segment is pressurized with helium. The apparatus used for the NRC-Studsvik LOCA test is shown in Fig. 1.

There are 6 test cases in NRC-Studsvik LOCA test and Test 192 has been selected to investigate the effect of heatup rate. The initial and boundary conditions of Test 192 are shown in Table I.

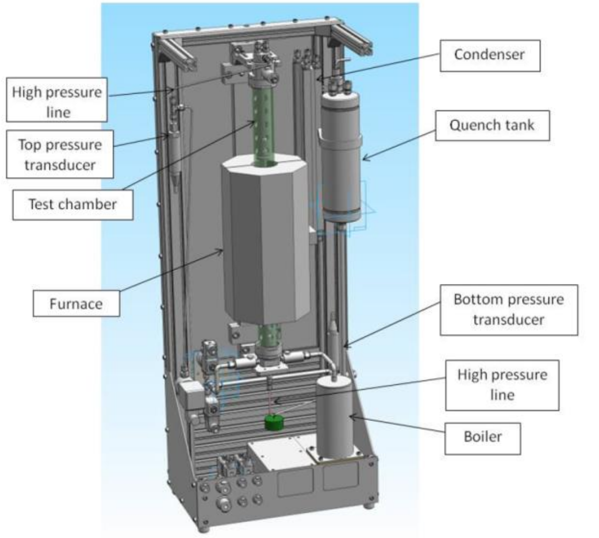

Fig. 1. Schematic of apparatus for NRC-Studsvik LOCA test [2]

Table I: Initial conditions & boundary conditions of NRC-Studsvik LOCA Test 192 [2]

Properties	Value
Rod average burnup (MWd/kgU)	68.2
Rod internal pressure at 573 K (bar)	82
Average oxide thickness [μm]	25~30
Average heatup rate [K/s]	5.0
Peak cladding temperature [K]	1458
Rupture temperature [K]	973
Rupture pressure [bar]	81

2.1 Time-averaged Heatup Rate Model

For time-averaged heatup rate model, time duration required for averaging is specified by user input. Time and instant heatup rate are cumulated for the time duration. In addition, instant heatup rate and time step size at each step are saved in the additional array which has the number of elements corresponding to two divided by minimum value among the maximum time step sizes in the time cards.

Average heatup rate is determined when cumulated time exceeds the user-specified time by input. And then, cumulated time is reduced until it becomes lower than user-specified time by subtracting the value of the foremost element in the array of time step. Cumulated heatup rate is also corrected in a similar manner. After correction of cumulated values, both arrays of time step and instant heatup rate are updated by replacing the fore elements with the next elements in order. Finally, the calculation of time-averaged heatup rate is completed and goes to the next step.

2.2 Simulation of NRC-Studsvik LOCA Test 192

NRC-Studsvik LOCA Test 192 was simulated with SPACE. Fuel rodlet of 0.3 m height consists of 15 axial nodes and temperature boundary condition is applied at right side of each node. Boundary temperature of each node is determined by the parabolic function as a function of node height [3]. Radial mesh consists of 16 intervals of pellet, single interval of gap, 2 intervals of cladding and single interval of oxide.

There are six cases in SPACE simulation as shown in Table II. Simulation includes 4 cases of time-averaged heatup rate with different user-specified time and two cases of instant heatup rate to investigate the effects of FFRD [4] and heatup rate on the rupture temperature.

The maximum time step is set to 0.01 s in all cases, so that the number of elements of the array for saving data is 200.

Table II: Summary of simulation cases

Case	**FFRD model**	**Heatup rate model**	**Duration for averaging (s)**
0	N/A	instant	-
1	applied	instant	-
2	applied	average	0.1
3	applied	average	0.5
4	applied	average	1.0
5	applied	average	2.0

2.3 Simulation Results

Table III summaries the simulation results focusing on the time, cladding temperature (Tc), rupture temperature (Tr), hoop stress (HS) and heatup rate (HR) at rupture.

In Case-0, where fuel crumbling which may cause the sudden change of cladding temperature is not expected because FFRD model is not applied, heatup rate agrees well with the experiment result and, Tc and Tr are almost same. However, in Case-1, 2 and 3, where FFRD model with heatup rate of instant or short duration (0.1 s ~ 0.5 s) is applied, the heatup rates at rupture are far from the measured data due to rapid increase of gap conductance. Because normalized heatup rates less than zero is reset to zero in Eq. (1), the heatup rates of these cases are close to zero. Therefore, the rupture temperatures in these cases are lower than cladding temperatures by 14 ~ 16 K due to low heatup rate. In contrast to case of short duration, the results of Case-4 and 5 agree very well with Case-0 because heatup rates of these cases are the same as that of Case-0 due to long duration for averaging. Case-5 shows little difference compared with Case-0 and 4, so that 1 second is long enough to estimate precise average heatup rate in Test 192.

Table III: Summary of simulation results

Case / Parameter	Case-0	Case-1	Case-2
Time (s)	1158.6	1150.7	1150.7
Tc (K)	981.1	937.3	937.2
Tr (K)	981.1	920.9	921.0
HS (kpsi)	12.42	13.25	13.24
HR (K/s)	5.4	-125.5	-6.5
Case / Parameter	**Case-3**	**Case-4**	**Case-5**
Time (s)	1150.6	1158.7	1158.7
Tc (K)	935.5	981.4	981.4
Tr (K)	921.2	981.4	981.4
HS (kpsi)	13.24	12.40	12.40
HR (K/s)	2.36E-3	5.4	5.4

Fig. 2 shows the relationship of the hoop stress and the rupture temperature by the Eq. (1). Two blue and red lines are upper (H=1) and lower (H=0) bound and, 5 K/s (H=0.18) in Eq. (1), respectively. The red circle is the results of Case-0, 4 and 5 and, the red triangle is the results of Case-1, 2 and 3. The blue triangle is the measured data which is out of range of the correlation. As shown in the figure, the effect of heatup rate on the rupture temperature becomes larger in the high hoop stress region than low hoop stress region.

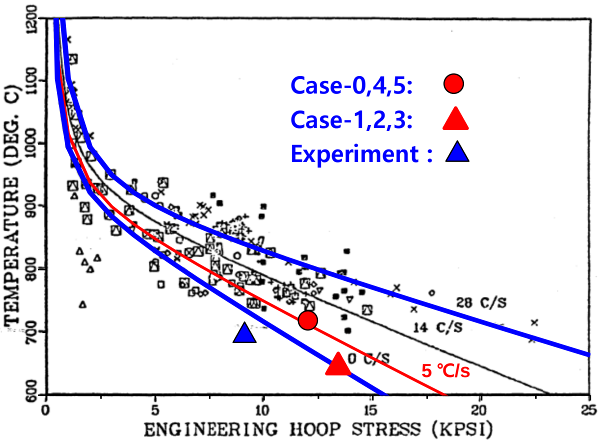

Fig. 2. Correlation of rupture temperature as a function of engineering hoop stress and heatup rate [1]

The reason why the estimation of accurate rupture temperature is important is that the rupture strain is determined by rupture temperature in NUREG-0630 model. Fig. 3 shows the comparison of the strain of cladding between measured data and simulation results along the axial height at the moment of rupture. From the figure, we can see the rupture strain of Case-1 is much smaller than Case-0 and 4 because Case-1 predicts much lower rupture temperature. Fig. 4 shows the comparison of burst strain between simulation and measured data. From the simulation results above, in order to predict the burst strain well, heatup rate should be estimated correctly using time-averaged value instead of instant value.

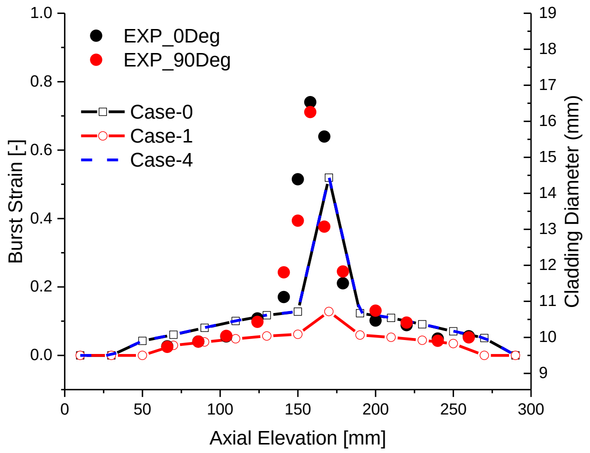

Fig. 3. Comparison of axial strain

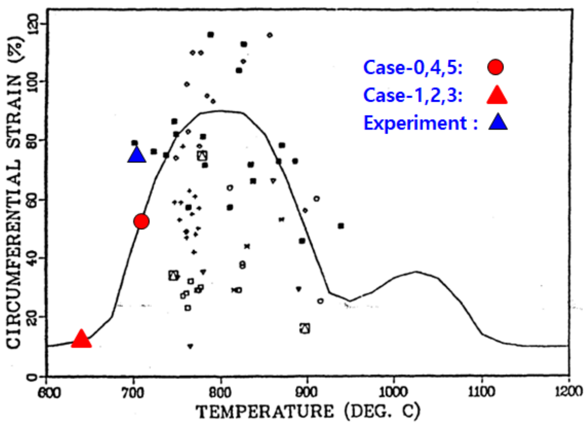

Fig. 4. Comparison of burst strain in each case [1]

3. Conclusions

The fuel cladding rupture temperature model of SPACE based on the NUREG-0630 model is strongly dependent on the heatup rate at rupture, especially in the high hoop stress range. In addition, when fuel rupture occurs together with fuel crumbling which causes drastic change of heatup rate, the accurate prediction of heatup rate is more important to estimate the rupture strain.

For a precise estimation of heatup rate, time-averaged heatup rate model was newly implemented into SPACE. From the validation against NRC-Studsvik LOCA test data, it agreed well with measured data compared with current instant heatup rate model. The recommended time duration for averaging was 1 second.

As a further work, we will simulate a postulated LOCA in commercial nuclear plant to investigate the effectiveness of the time-averaged heatup rate model.

ACKNOWLEDGEMENT

This work was supported by the Korea Hydro & Nuclear Power (KHNP) (A19LP05, Establishment of optimal evaluation system for safety analysis of OPR1000and Westinghouse type nuclear power plant (1)).

REFERENCES

[1] D. A. Powers and R. O. Meyer, Cladding Swelling and Rupture Models for LOCA Analysis, NUREG-0630, U.S. NRC, 1980.

[2] Michelle E. Flanagan, Post-Test Examination Results from Integral, High-Burup, Fueled LOCA Tests at Sudsvik Nuclear Laboratory, NUREG-2160, U.S. NRC, 2013.

[3] Jernkvist, L. O., Computational assessment of LOCA simulation tests on high burnup fuel rods in Halden and Studsvik, Stral Sakerhets Myndigheten SSM report 2017:12, 2017.

[4] Chiwoong Choi et al., Design, Implementation and Verification of FFRD Model in SPACE, A19LP05-A-1-RD-003R3, KAERI, 2021.