*Transactions of the Korean Nuclear Society Autumn Meeting*
*Gyeongju, Korea, October 26-27, 2017*

# Study on the ballooning calculation in FRAPTRAN code during LOCA

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## 1. Introduction

Numerous operational and retrofit design changes were applied to LWRs after loss of coolant accident (LOCA) at Three Mile Island. These specific design features and upgrades were primarily associated with maintaining adequate core cooling in the event that the primary cooling system is not functional. Especially, ballooning in LOCA leads to flow blockage at fuel assemblies. It is a very important phenomenon with respect to loss of core coolability.

Fuel designers and safety authorities rely heavily on fuel performance codes since they require minimal costs in comparison with the costs of an experiment or an unexpected fuel rod failure. The typical performance codes are FRAPCON and FRAPTRAN corresponding to the normal operating and the design-based accident (DBA) condition respectively. As safety under DBA is focused especially, there is a demand for development and improvement of the performance code. In order to understand how to describe the ballooning phenomenon during LOCA, we analyze the ballooning calculation in FRAPTRAN[1].

## 2. Ballooning sub-module

### *2.1 Perturbation theory for ballooning deformation*

BALON2 code in FRAPTRAN is used to express the ballooning deformation during LOCA. If the condition of occurrence of ballooning is satisfied during the analysis of performance core, the ballooning deformation is calculated based on the flowchart shown in Fig. 1. First, local stresses are calculated using the pressure, temperatures, midwall radii and wall thickness. Then, the given time step size is checked to see if it is short enough to prevent significant change in the local stresses during the time step. Cladding temperatures are recalculated to account for effects of the deformation during the previous time step in cladding temperature. The effects of annealing are also considered for flowchart. Next, all nodes are checked for failure. If cladding failure has not occurred, the description of the cladding texture is update and the effective strain prior to deformation is calculated. The dimension components are calculated from the effective strain and new dimensions at the end of the time step was defined under the assumption that bending is applied. If it has remaining part of time step, the next time step processes with the previous calculated data.

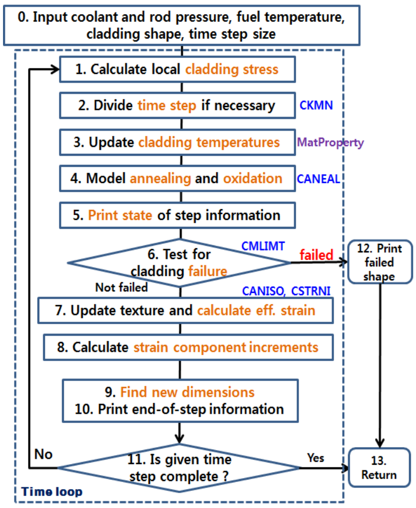


Fig. 1. Sequence of BALON2 model calculations. [2]

The perturbation theory is applied to express large deformation during ballooning in FRAPTRAN code. The hoop stress was reconstructed through the perturbation theory as Eq. (1). The hoop stress of cladding is expressed by adding effect of shape change on stress, Eq (3) to typical hoop stress, Eq (2) induced by thick-wall theory.

$$\sigma_{\theta\theta} = \sigma_{\theta\theta,a} + \sigma_{\theta\theta,\delta} \qquad (1)$$

$$\sigma_{\theta\theta,a} \approx \frac{P_i - P_o}{t_{ave}} r_{ave} - \frac{P_i + P_o}{2} \qquad (2)$$

$$\sigma_{\theta\theta,\delta} \approx \frac{P_i - P_o}{t_{ave}}\delta - r_{ave}\frac{(P_i - P_o)}{t_{ave}^{\ 2}}h_\delta + \frac{P_i - P_o}{t_{ave}}\frac{\partial^2\delta}{\partial\theta_o^2} + \frac{\sigma_{zz}}{\left(e^{\varepsilon_z}\right)^2} r_{ave}\frac{\partial^2\delta}{\partial z_o^2} \qquad (3)$$

$$\delta = r - r_{ave},\quad h_\delta = t - t_{ave}$$

### *2.2 Find new dimensions of ballooning shape*

Hagrman [2] described that the calculated radial displacement assumption through only perturbation theory did not match the data unless the failure stress was reduced by a factor of 0.6. He claimed that another assumption was needed to present the effect of bending due to different changes in cladding length during ballooning.

By inputting the curvature value ($Z_{bend}$) as shown in Eq. 4, additional displacement due to bending could be imparted. In this way, it is possible to calculate the deformed shape of the final cladding tube.

$$X_{ave} \approx \frac{Z_{bend}{}^{2}}{8r_0}\frac{\left[\exp\left(\varepsilon_{z_L}\right)-\exp\left(\varepsilon_{z_R}\right)\right]}{\left[\exp\left(\varepsilon_{\theta_R}\right)+\exp\left(\varepsilon_{\theta_L}\right)\right]} \qquad (4)$$

*2.3 Calculated results according to bending effect*

We used the FRAPTRAN input data based on the experiment to evaluate the influence of bending assumption.

Table I: Calculated results at ballooning initiation

| State | Time [s] | Avg. Cladding Temp. [K] | Avg. radius [mm] | Maximum radius[mm] |
|---|---|---|---|---|
| Initial ballooning | 156.06 | 957.663 | 5.511 | 5.511 |

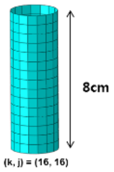


Fig. 2. Ballooning model in FRAPTRAN

In BALON2 code, we perform a thermal-mechanics analysis using a 16 x 16 cylindrical mesh, as in Figure 2, which has a node points of fuel rod where ballooning begins. The calculated result is visualized with PARAVIEW[3] which is open source. Figure 3 shows the deformation shape of cladding at burst state depending on the value of $Z_{bend}$. In FRAPTRAN, the default value of $Z_{bend}$ is 0.1.

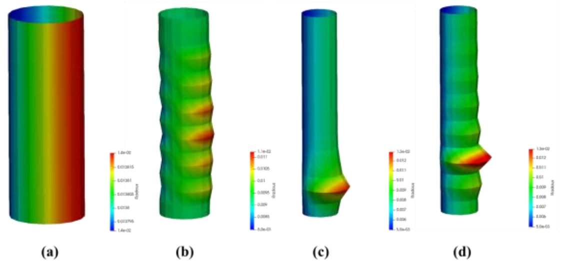


Fig. 3. Deformation results at burst state (a) $Z_{bend}$ = 0, (b) $Z_{bend}$ = 0.05, (c) $Z_{bend}$ = 1.0(default), and (d) $Z_{bend}$ = 2.0.

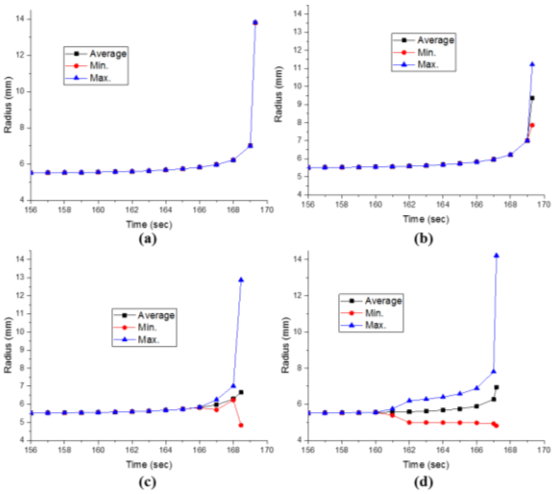


Fig. 4. Calculated radii of cladding (a) $Z_{bend}$ = 0, (b) $Z_{bend}$ = 0.05, (c) $Z_{bend}$ = 1.0(default), and (d) $Z_{bend}$ = 2.0.

In the case where the bending effect is not reflected, as shown in FIG. 4 (a), all the regions expand to substantially the same. Conversely, when considering the bending effect, as shown in FIG. 4 (b),(c),(d), variations of radius occur along circumferential and axial direction. The average radius of cladding without bending effect is greater than that with bending effect and the burst is delayed if bending is not considered. The bending term in BALON2 is useful to represent effectively the ballooning phenomenon which happen large deformation during short time. It is observed that the amount of deformation increases sharply before burst occurs, as the material of the cladding tube observed under LOCA condition is softened as the temperature of the cladding tube increases as shown in Fig. 5. In particular, when the temperature exceeds 1000 K, a softening phenomenon occurs to a large extent.

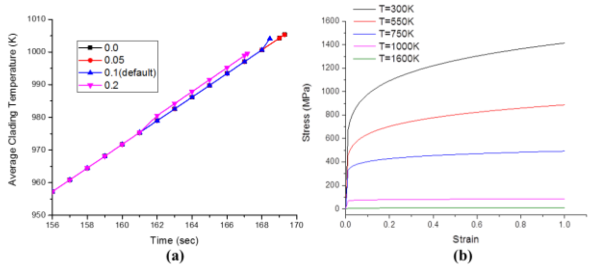


Fig. 5. (a) Calculated Cladding temperature and (b) Strain-stress curve during calculation

## 3. Conclusions

This paper is written to establish a working basis for the progress of the understanding the ballooning calculation in FRAPTRAN code. A comparison about bending effect was performed.

1) Perturbation theory and bending assumption are applied to express the ballooning phenomenon in FRAPTRAN code

2) In the case where the bending effect is not taken into consideration, local deformation and non-uniformity at the surface of the cladding are not expressed, so that uniform and large deformation of cladding is induced.

## ACKNOWLEDGEMENTS

This work has been carried out under the Nuclear R&D Program supported by the Ministry of Science and ICT. (NRF-2017M2A8A4015024)

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