Preliminary analysis for the Swelling and Densification Phenomena of a Dual Cooled Fuel Rod

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1. Introduction

A dual cooled fuel rod consists of a coaxial inner and an outer cladding tube and annular pellets. Two coolant passages and two gaps between a pellet and cladding tubes are distinct features of a dual cooled fuel. There are three major concerns such as a different elongation of the inner/outer cladding tubes, a heat split and an irradiation elongation of the pellets. In the case of a heat split, swelling, densification, thermal expansion and creep of the pellets and a creep of the cladding tubes are the causes. Because there is one gap between a pellet and a cladding tube in a solid fuel, deformation direction of a pellet is always one way. But the deformation direction of an annular pellet is a concern because it could expand both inward and outward. In this regard, one gap could become a gap contact faster than another. If a gap is closed, the thermal resistance between a pellet and a cladding tube lessens. Then, heat split phenomenon happens. It could be a critical problem threatening the integrity of dual cooled fuels. It is necessary to study in which direction an annular pellet expands and to develop a method to maintain the difference of the gap conductance of the inner and outer gaps.

In this paper, a quasi-static analysis method is established to predict the deformation direction of pellets during a swelling and densification.

2. Conservative equations

Swelling and densification phenomena are problems with burnup-dependent material responses. So, a quasi-static analysis, the VISCO analysis, in ABAQUS/Standard v.6.7-1[1] is used. Volume change ratio due to swelling and densification could be calculated by the conservative Eq. (1). Constants ($\Delta\rho_{sat}$, τ) are obtained by in-pile test results [2].

$$\Delta V / V_0 \cong -\Delta\rho_{sat}[1-\exp(-BU/\tau)] + 0.1\times BU \qquad (1)$$

Here are,

$\Delta\rho_{sat}$: Maximum densification, %TD
BU : burnup, GWd/tU
τ : burnup coefficient

Burnup corresponding to EFPD (E; effective full power days) are calculated by Eq. (2). It is an empirical fomula about a fuel rod's peak burnup in OPR-1000 reactor [3].

$$BU = -0.56116 + (0.05362\times E) - (7.81e-6)E^2 \qquad (2)$$

3. Analysis procedure and FE models

At the VISCO analysis, total analysis time matches total EFPD. Analysis is divided into some increments; total time is divided into some increments. ABAQUS solves displacement of all nodes by using volume change ratio about every increment. This ratio is calculated by the FORTRAN subroutine coded to produce burnup and volume change ratios corresponding to given increments.

To verify the usability of the FE model, solid type pellet is created at first. Then, an annular pellet and inner/outer cladding tubes are modeled as shown in Fig. 1. This schematic drawing used a tentative geometry data of a 12x12 dual cooled fuel. A few 8-node linear brick elements (C3D8R) are used for a pellet and two cladding tubes. The elastic-plastic characteristic values of Zircaloy-4 are used for the material properties. The pellet's materials are referred to MATPRO [4].

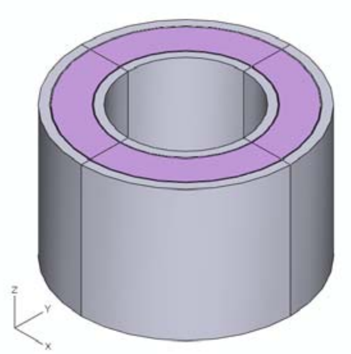

Fig. 1 An annular pellet and inner/outer cladding tubes.

Cylindrical coordinate is used in the analysis. The D.O.F. in a circumferential direction of all components is fixed to prohibit rotation of components during the analysis and a symmetry condition is applied in Z-direction.

3. The results of analysis

Figure 2 shows a comparison of the volume change ratios obtained by using ABAQUS and Eq. (1). According to this graph, the coded FORTRAN subroutine precisely simulates the swelling and densification phenomena of a solid pellet.

To analyze the deformation of a dual cooled fuel rod by the swelling and densification phenomena of a pellet, it is assumed that a volume change ratio and a burup corresponding to EFPD are the same as those of a solid fuel case. So, the same subroutine is used for a dual cooled fuel, again.

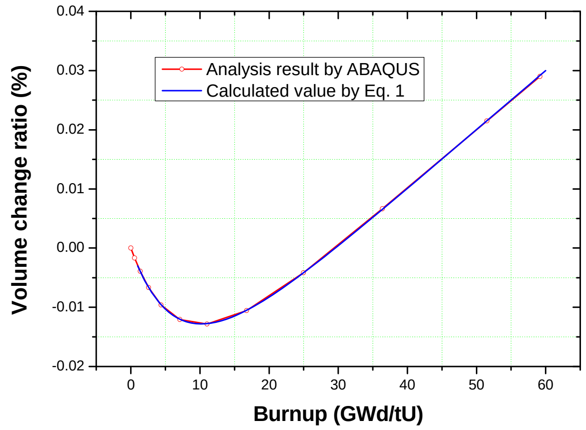

Fig. 2 Comparison of volume change ratios (%).

The radial displacements of some nodes are shown in Fig. 3. The positions of the nodes are below;

· # 7 : a node on inner tube positioned 0 deg.
· # 12 : a node on pellet's inner edge positioned 0 deg.
· # 11 : a node on pellet's outer edge positioned 0 deg.
· # 4 : a node on outer tube positioned 0 deg.

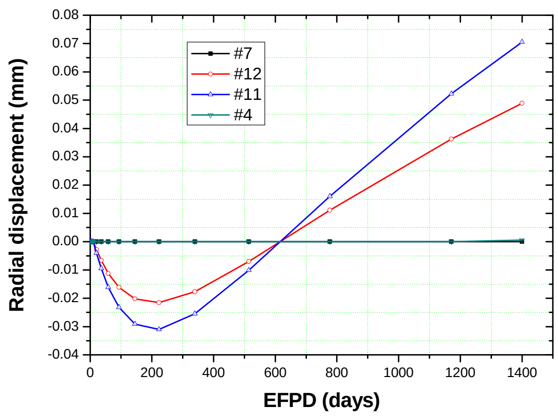

Fig. 3 Radial displacement of four nodes positioned 0 deg.

Pellet's outer edge is deformed more than its inner edge during the whole EFPD. Final radial displacements of the inner and outer edges of an annular pellet due to swelling and densification phenomena are 489, 705 ㎛, respectively. Because the initial gap thickness between the pellet and cladding is 700 ㎛, contact between the pellet and outer tube has just happened as shown Fig. 4. In summary, the deformation direction of the inner/outer edges of a pellet is toward an outer cladding tube in the case of the swelling and densification phenomena

4. Conclusion

A FORTRAN subroutine for calculating a volume change ratio is coded to predict the deformation of a dual cooled fuel rod accommodating a swelling and densification of a pellet. It is certified that both the inner and outer edges of an annular pellet expand outward when considering the swelling and densification phenomena. Because the displacement of a pellet is almost the same as the initial gap between the pellet and tubes, it is regarded that an interaction between the pellet and tubes does not happen.

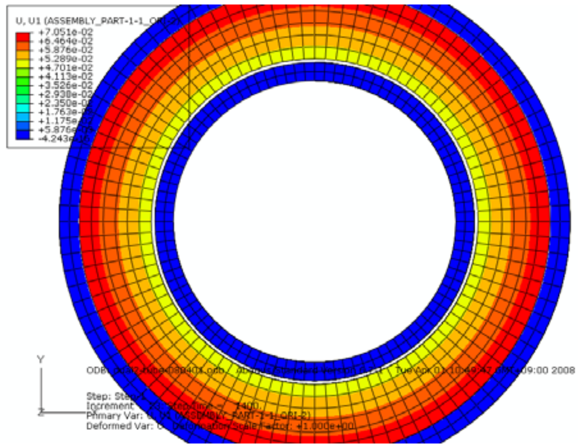

Fig. 4 Radial displacement after the swelling and densification analysis (mm).

Presently, the established method will be extended to add other phenomena of fuel rods such as a thermal expansion of a pellet, and a creep of both a pellet and cladding tubes, etc.

ACKNOWLEDGEMENTS

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REFERENCES

[1] H.D. Hibbit, G.I. Karlsson and E.P. Sorensen, ABAQUS Analysis User's Manual(version 6.7-1), 2007.
[2] Y.Harada, S.Doi, Irradiation behavior of large grain UO2 fuel rod by active powder, Journal of Nuclear Science and Technology, Vol. 35, p. 411~418, 1998.
[3] Private letter from Y.S.Yang.
[4] MATPRO – A Library of Materials Properties for Light-Water-Reactor Accident Analysis, NUREG/CR-6150, Vol. 4, Rev. 2.