Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 17-18, 2018

Effects of Pressure Tube Deformation on the Reactivity for CANDU6 Reactors

E.H. Ryu [1*] and J.Y. Jung [1]
[a]*Korea Atomic Energy Research Institute, 1045 Daedeok-daero, Yuseong-gu, Daejon, 34057, Korea*
[*]*Corresponding author: ryueh@kaeri.re.kr*

1. Introduction

All nuclear reactors have an unique and common condition in that the components are under high irradiation conditions. In addition, they also suffer from thermal load, high pressure and large weight. Owing to these rough circumstances, materials composing the components may deform their original shape.

For a PWR, this is generally called as bowing. Because the rod and assembly length may increase during the life cycle of a PWR, lateral displacement occurs. For the case of bowing, however, it is generally known that the resulting effect is not too significant because the function of the fuel assembly is dramatically improved, and the amount of displacement is not great [1][2]. For an SFR, this is called a flowering phenomenon, which causes assembly compaction or expansions. Such displaced assemblies result in reactivity changes of a negative direction. In addition, the amount of reactivity is known to be large. Thus, experiment such as PHENIX, are conducted to quantitatively study the flowering and lucidate its mechanism [3].

In this research, the pressure tube will be discussed intensively, which is a key component in a CANDU reactor because it separates the pressure boundary and holds onto large force that arises from the pressure difference between systems. In addition, the pressure tube is exposed to the extremely high irradiation conditions owing to its location and high thermal load from a coolant originating from fuel.

There are four main phenomena regarding pressure tube deformation such as the expansion of the radial and axial direction, sagging, and thinning. Among these phenomena, the radial expansion and axial sagging are dominant factors affecting pressure tube deformation. In the future, axial sagging will be discussed through detailed 3-D modeling and improved Finite Element Method (FEM) code capability. For now, using the 2-D FEM code, the 2-D radial expansion is sorely discussed here.

2. Phenomenon of Radial Expansion of Pressure Tube

In this section, the pressure tube dimensions are introduced briefly to a sense about scale and modeling. Also, the phenomena of pressure tube deformation, and the contributions of each phenomenon are summarized for the analysis. Finally, to know the importance of the pressure tube, the relation between pressure tube aging and CANDU reactor safety margin is analyzed.

2.1 Pressure Tube in CANDU

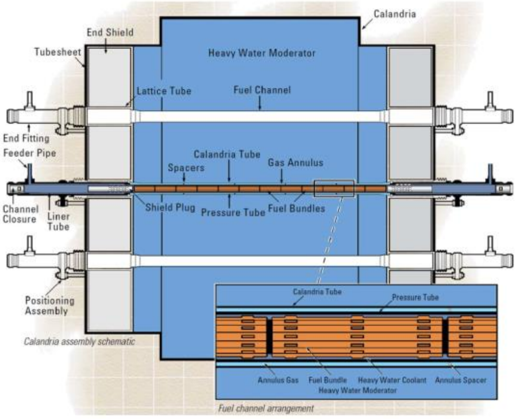

Fig. 1. CANDU Reactor Structure

The inside diameter of a pressure tube is 10.3378cm, the average pressure tube wall thickness is 0.4343cm, and the length of the pressure tube is about 6.3m, including end shield regions of 30cm. The material is Zr-2.5% Nb [4], and thus the pressure tube should be taken into account for a hydrogen generation because of an exothermic reaction of zirconium with steam.

2.2 Phenomenon of Radial Expansion and Modeling

Occasionally, radial expansion is called diametral expansion or radial creep. It is defined as an increase in length of the circumference, mainly owing to the irradiation creep. Thus, a high power channel has a larger increase in circumference compared with a low power region. Thus, central bundles in the axial direction have a larger diameter compared with those of other directions.

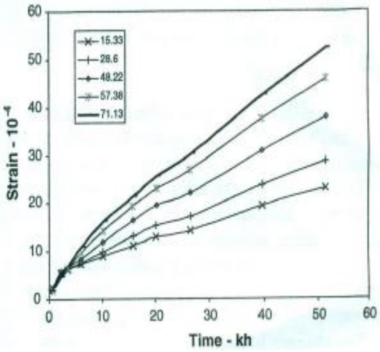

Fig. 2. Strain as a Function of Time for Fast Neutron Fluxes

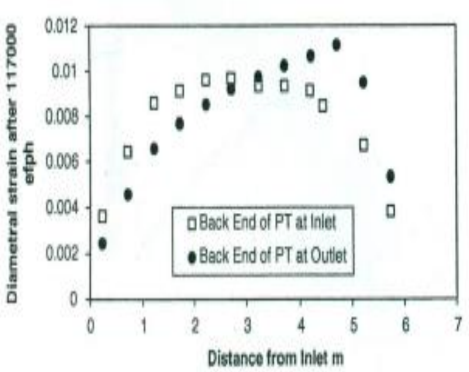

Fig. 3. Comparison of Diameter Profiles along Pressure Tubes with Two Loading Categories

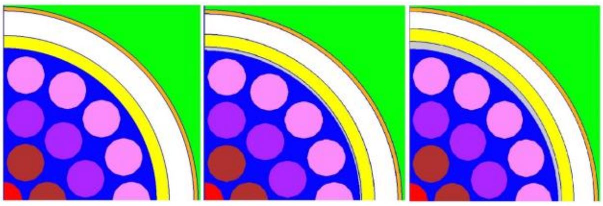

Fig. 4. Increase of Bypass Region for Creep Rate 0, 2.5% and 5.0%

Through Fig. 2, it can be confirmed that the strain increases with the fast neutron flux strength and time. In the process of rolling to produce a pressure tube, the direction is determined. In Fig. 3, it can be verified that, depending on the position of the back end of the pressure tube, the diametral creep tendency changes [5].

Although the pressure itself merely increases its diameter, there is a higher amount of coolant and a greater fuel weight. Thus, the center of the pressure tube changes with its axial position at the same time. In addition, the fuel displacement of its center position is relatively large compared with the pressure tube center displacement, and the bypass flow forms an upper region of the channel. These two additional deformations will be reflected through a future 3-D analysis. It seems that the upper region suddenly balloons compared with the lower region in a current 2-D analysis [6]. As shown in Fig. 4, the size of a bypass region can be approximately compared with the other regions.

2.3 Radial Expansion and Operational Margin

During the reactor operation, the diameter of the pressure tube continuously increases. From a reactor physics point of view, this causes a power asymmetry inside the channel because of the difference in neutron spectrum. From a thermal-hydraulic point of view, this causes a reduction in the cool down capability because of an increase in the bypass flow inside the channel. Thus the operational margin also decreases. Depending on the decrease in operation margin, the power should correspondingly decrease to secure a level of safety. In Fig. 5, the reduction of the trip set point for the reactor operation period is denoted as a continuously decreasing curve.

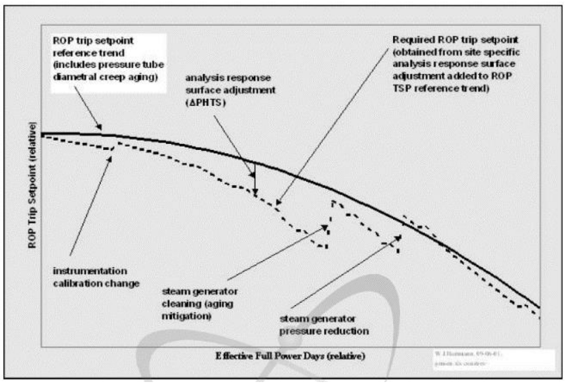

Fig. 5. Reduction Trend of Operational Margin wrt PT diameter expansion

In an average sense, about a 1% power reduction occurs for every year in a CANDU reactor. The major contributor for this 1% reduction is known to be pressure tube, among many other components. In addition, among the four mentioned mechanisms of pressure tube deformation, radial expansion and axial sagging are the most dominant factor for pressure tube aging. In Fig. 6, we can find the reason why the power should be reduced.

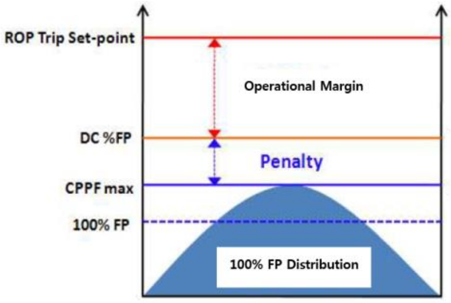

Fig. 6 CANDU ROP Trip Set Point and Operational Margin

2.4 TRIAINA Code Description

TRIAINA is a finite element code for the analysis about arbitrary geometry. The reactor physics codes generally deals with the structured geometry. Thus FDM is widely used for the basic numerical method. But depending on the shape of assembly, the code should be changed every time. But by using the finite element based code, we only need to change the geometry model alone. In addition, it can be used for the lattice analysis although it is obvious that the solution accuracy will be is lower than the transport solution. Same as this case, the pressure tube problem can not be solved with FDM code or something else. Thus it’s merit generally comes from the geometrical reason. Also, mapping and higher order solution can be selectable depending on the problems.

3. Numerical Result of 2-D Radial Expansion

Once a radial expansion occurs, the channel inside the geometry is no longer structured. Because the creep generates an ellipse for a pressure tube, the finite element method can be utilized for this pressure tube problem. For now, the FEM SP3 solution for a reactor physics calculation is possible for a 2D problem [8]. The TRIAINA code and linear basis function are used for the analysis. A total of three cases were analyzed with an average triangle pitch of about 0.173cm [9]. The multiplication factors for three cases are 1.11227, 1.11114, and 1.11005, respectively. This tendency is natural, because the spectrum hardens because of up-scattering owing to a high coolant temperature. Of course, the fission density near the top region decreases, and thus the fission density far from the top region relatively increases. In Fig. 7, the changes in relative pin power can be confirmed, and the rate of change is almost linear with respect to the creep rate. This power asymmetry can affect the heat transfer and void generation in the channel.

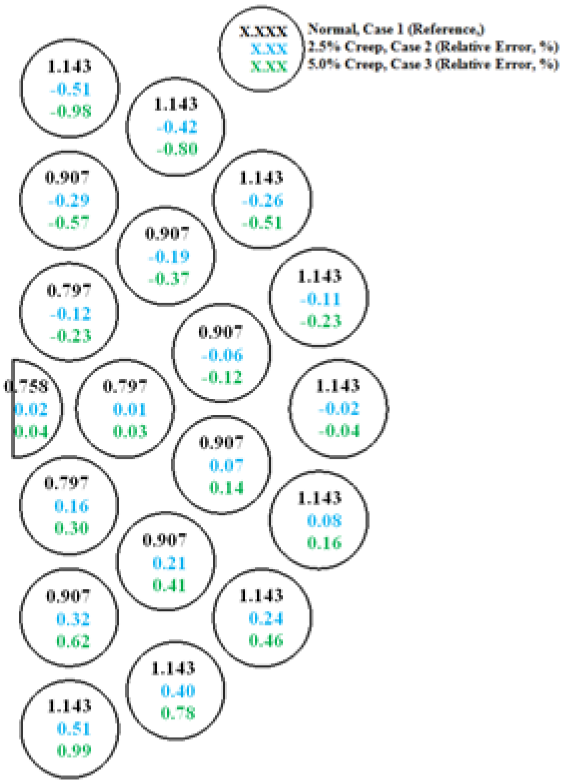

Fig. 7 Relative Errors of Pin Power with Creep of the TRIAINA-SP3 Code

4. Conclusions and Future Works

In this research, the FEM solution is compared with the McCARD solution for normal conditions, and the results for a creep situation are calculated using the FEM code. As a result, a 1mk change per 2.5% creep was observed for the lattice calculation, as reported in another thesis [10]. In addition, a pin power asymmetry is observed. Because this result is merely from radial expansion only, the combined effect with sagging should be investigated. CATIA modeling based on the observed data is underway, and a 3D FEM code is being prepared based on a modification for periodic boundary conditions.

5. Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea Government (Ministry of Science, ICT, and Future Planning) (No. NRF-2017M2A8A4017282).

REFERENCES

[1] S.Y. Jeon, K.S. Lee, J.H. Kim, H.K. Kim, J.R. Park, An Investigation on the Structural Behavior of the PWR Fuel Assembly due to Irradiation, KNS Spring Meeting, 2007.

[2] S.Y. Jeon, N.G. Park, Y.K. Jang, J.M, Suh, and K.L. Jeon, An Investigation on the Bow Characteristics of the PWR Fuel Assembly, KNS Autumn Meeting, 2011.

[3] B. Fontaine, G. Prulhiere, A. Vasile, P. Masoni, P. Singh, Description and Preliminary results of PHENIX core flowering test, Nuclear Instruments and Methods In Physics Research, Vol.505, p.159, 2003.

[4] KHNP, “CANDU 6 Generating Station Physics Design Manual”, 2009.

[5] J.Y. Jung, Status of CANDU Pressure Tube Deformation Technology, KAERI/AR-956, 2012.

[6] H.S. Kim, Neutronics Impact of Pressure Tube Creep in a CANDU Lattice, KAERI/TR-3701, 2008.

[7] J.Y. Jung et al., Development of Core Technology of PHWR Safety Enhancement and Evaluation, KAERI/RR-3777, 2014.

[8] E.H.Ryu et al., The Effects of the Treatment of the Periodic Boundary Condition in TRIAINA Codes with a Pressure Tube Problem”, CANSAS(STNI), 2013.

[9] Geuzaine, C., Remacle, J., -F., “Gmsh: a three-dimensional finite element mesh generator with built-in pre- and post processing facilities”, Int. J. Num. Meth. Eng., 79, 1309, 2009.

[10] Ilas G. et al, “Impact of Pressure Tube Aging on Physics Parameters of a CANDU Lattice Cell”, Proceedings of Advances in Nuclear Fuel Management III(ANFM 2003), SA, USA, 2003.