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Optimization for the Prediction using Results of Gap Measurements between Fuel Channels and LINs

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APSTRACT

Pressurized heavy water reactor (PHWR) designed to refuel in service produces the energy led by nuclear fission. Fuel channel consists of the pressure tube which is directly contacted with fuels, the passage of reactor coolant, the calandria tube which is contacted with moderator, rolled joint with calandria, the spacer which is not to contact between pressure tube (PT) and calandria tube (CT), etc. Liquid Poison Injection Nozzles (LIN) aligned 90 degree horizontally with the fuel channels gradually sag due to irradiation creep during the plant operation. Fuel channels shall not contact with calandria vessel internal components before the next periodic inspection interval. KHNP-CRI developed the visual inspection equipment and measured the gaps between fuel channels and LINs. In this paper, the gaps were predicted using the results of the in-service inspection results of pressure tube sag and reviewed the difference of results between the analytical prediction and the visual inspection.

INTRODUCTION

Pressurized heavy water reactor (PHWR) designed to refuel in service produces the energy led by nuclear fission. Fuel channel consists of the pressure tube which is directly contacted with fuels, the passage of reactor coolant, the calandria tube which is contacted with moderator, rolled joint with calandria, the spacer which is not to contact with pressure tube, calandria tube, etc. as shown in Fig. 1.

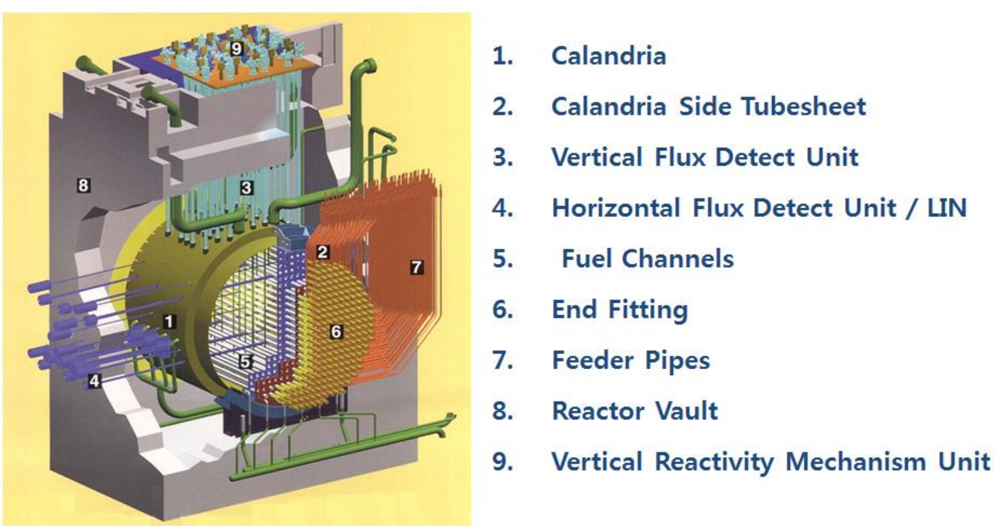
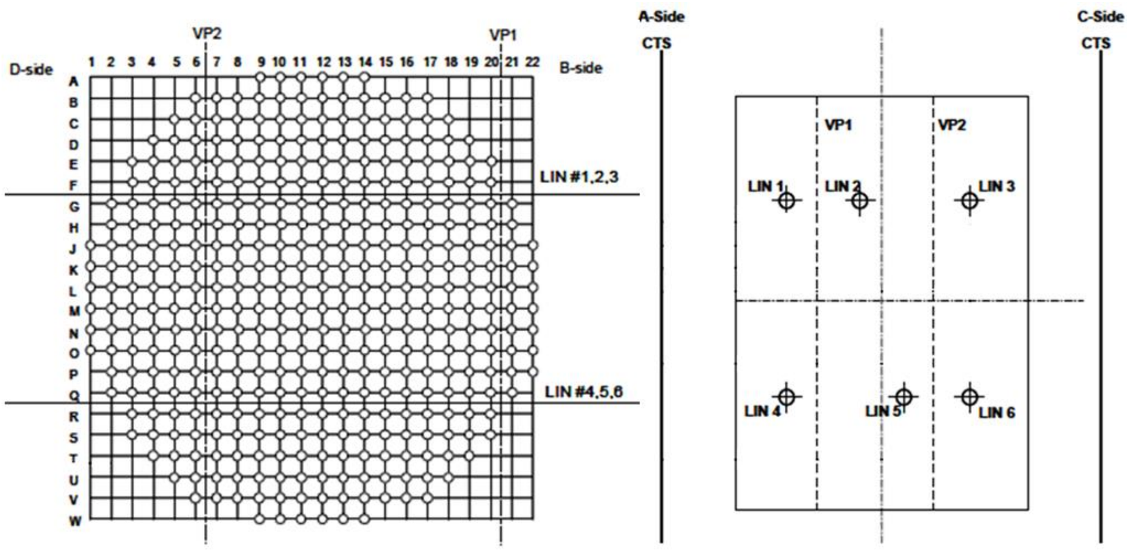


Figure 1. Configuration of PHWR

Liquid Poison Injection Nozzles (LINs) aligned 90 degree horizontally with the fuel channels gradually sag due to irradiation creep during the plant operation (Fidleris, 1988). LINs are installed between calandria tubes (CTs) in rows F and G and between CTs in rows Q and R. LIN 2 and 5 are installed near the center of the Calandria assembly, as shown in Figure 2. When the sag of fuel channel is large enough, the calandria tube can possibly contact the LINs, which CANADIAN Standards Association (CSA) N285.4 states that there is no fuel channel (calandria tube) contact with calandria vessel internal components/parts.



(a) Front View (C-Side) (b) Side View(D-Side)

Figure 2. Positions of Calandria Tubes and LINs on PHWR

The contact between the calandria tubes and the LINs during the operation of PHWR can not observe the requirement of the CSA standard for the safe operation of the plant. It is therefore necessary to confirm the gap between the calandria tubes and the LINs. There are several ports to insert measuring equipment into the calandria, that is, through liquid injection nozzle itself (Abucay et al., 1995) or horizontal flux detector guide tube (Goszczynski and Mitchell, 1996), vertical flux detector guide tube or viewing ports.

Visual inspection for the measurement of gaps between calandria tubes and LINs which can be vertically inserted into calandria through viewing ports was developed and applied for the Wolsong NPP. Similar measurement methods through viewing ports using a mechanical tool developed by Atomic Energy Canada Limited and using a ultrasonic testing developed by Korea Electric Power Research Institute(Tae Ryong Kim and Seok Man Sohn, 2004) were applied to Wolsong NPP.

The sag of fuel channels due to creep was computed (Pettigrew and Lambert, 1979), in order to confirm the fuel loading into fuel channel. Creep deformation of fuel channels for the evaluation of fuel channel sag and the contact between calandria tube and liquid injection nozzle was developed. Creep deformation evaluation uses classical beam theory. The prediction of the sag is conservative. Sag results of pressure tube and gap between pressure tube and calandria tube were used to predict realistically the gaps between calandria tubes and LINs.

In this paper, the prediction of gaps between calandria tubes and LINs are optimized using the results of the in-service inspection of fuel channel and reviewed the difference of results between the prediction and the visual inspection.

PT SAG and PT-CT GAP MEASUREMENT

CSA N285.4 states that the licensee shall demonstrate that there is no contact between the pressure tube and the calandria tube at the end of the next periodic inspection interval. There are two options of measurements to demonstrate no contact between the pressure tube and the calandria tube: (a) Detection of spacers and calculation of sag, or (b) Measurement of pressure tube to calandria tube gap. The simple inspection is to show that the spacers are in their design locations. If spacers remain in their design locations, contact is not expected before the end life of pressure tubes. The other inspection is to detect the gap between the pressure tube and the calandria tube directly.

During the periodic inspection on the Wolsong PHWR NPPs, the sag of pressure tubes and the gap between pressure tubes and calandria tubes have been measured since the start of the plants operation. For the inspected channel example, the measured values of maximum pressure tube sag are as like Figure 3. There is a difference in the change rate of sag between the pressure tube and calandria tube. The gap between calandria tube and LINs can be calculated with the results of the periodic inspection.

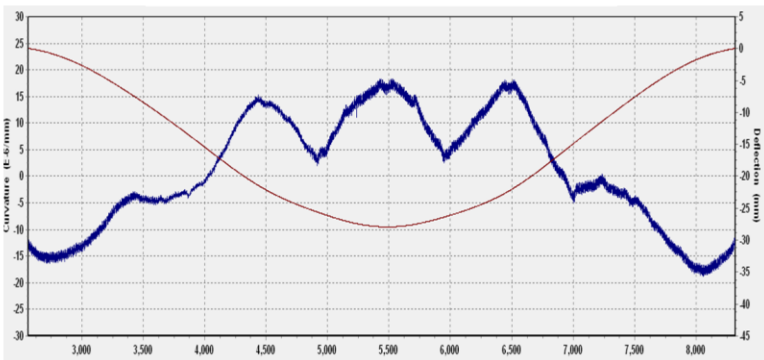
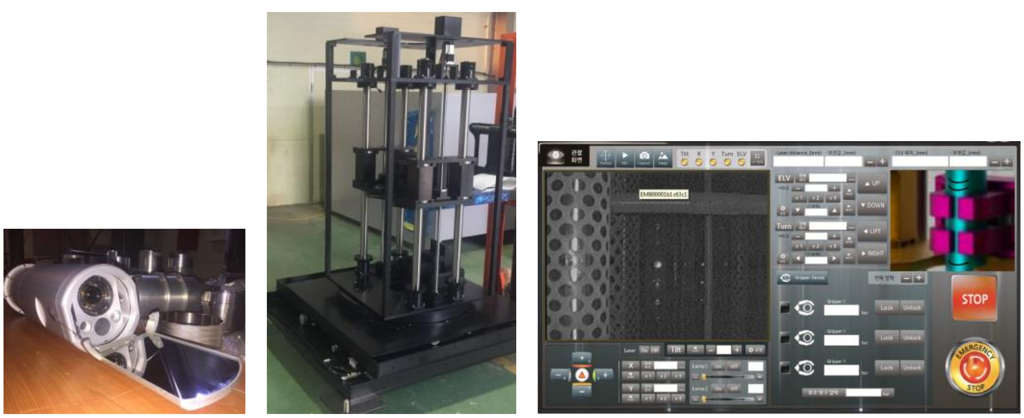


Figure 3. Sag of Fuel Channel Inspection on PHWR

VISUAL INSPECTION of PT-CT Gap

The visual inspection equipment was developed to measure the gaps between calandria tubes and LINs. This inspection equipment is based on a radiation-hardened camera and vision software and supported in a mechanical drive unit mounted on the viewing port, which is established as the reference plane between the reactor and the inspection system. The mechanical drive unit consists of moving module, booms, controller module, and inspection head like as figure 4.



(a) Inspection Head (b) Mechanical Drive Unit (c) Operating Software

Figure 4. Inspection Results of Fuel Channel on PHWR

FUEL CHANNEL SAG PREDICTION

The deflection curvatures of pressure tube and calandria tube of this analysis is same as that of early research results about fuel channel sag prediction, as follows.

$$\frac{d^2Y_p(x,t_n)}{dx^2} = M_p(x,t_n)BIP(x,t_n) + \sum_{t=t_1}^{t_{n-1}} M_p(x,t)\Delta C_p(x,t) \tag{1}$$

$$\frac{d^2Y_c(x,t_n)}{dx^2} = M_c(x,t_n)BIC(x,t_n) + \sum_{t=t_1}^{t_{n-1}} M_c(x,t)\Delta C_c(x,t) \tag{2}$$

Where, $\Delta C_p(x,t) = \dot{C}_p(x,t)\Delta t / \mathrm{I}_p$

$\Delta C_c(x,t) = \dot{C}_c(x,t)\Delta t / \mathrm{I}_c$

$BIP(x,t_n) = 1/E_p\mathrm{I}_p + \Delta C_p(x,t)$

$BIC(x,t_n) = 1/E_c\mathrm{I}_c + \Delta C_c(x,t)$

Where Y, M, $\dot{C}$, x, t, E and I are vertical displacement, section moment, irradiation creep coefficient, axial position, operation time, elastic modulus and moment of inertia, respectively. Subscript "p" and "c" means pressure tube and calandria tube, respectively. The irradiation creep coefficients are defined as follows, in which following creep coefficients were used according to previous research results.

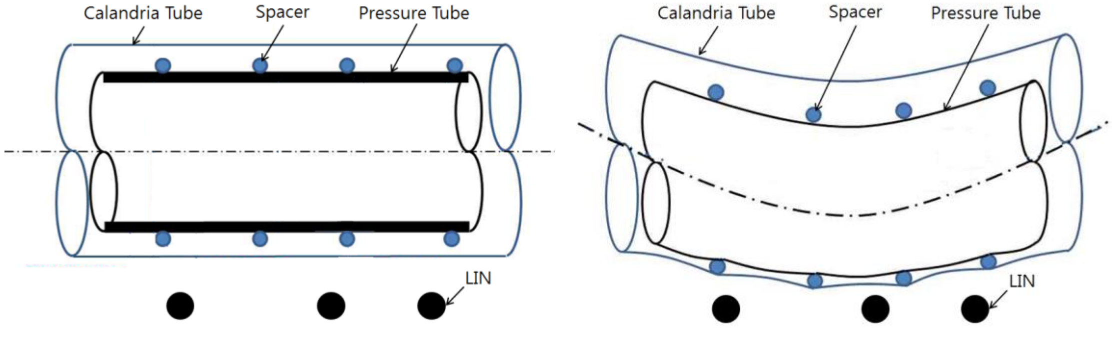
$$\dot{\varepsilon}_b = \dot{C}\sigma_b \tag{3}$$

$$\dot{C}_p(x,t) = \left[3\times10^{-4}t^{-\frac{2}{3}} + 6\times10^{-23}\phi(x)\right]e^{\frac{-4700}{T(x)}} \quad \text{[/h/MPa]} \tag{4}$$

$$\dot{C}_c(x,t) = 1.16\times10^{-27}\phi(x) \quad \text{[/h/MPa]} \tag{5}$$

Where $\dot{\varepsilon}_b$ is creep bending strain rate, σ_b is bending stress, t is time [hour], ϕ is fast neutron fluence (>1MeV) [n/m2/sec] and T is temperature [K].

In this calculation, nonlinear behaviors of gap between pressure tube and calandria tube were calculated as like figure 5.



(a) Installment of Fuel Channel (b) Sag of Fuel Channel

Fig. 5 CANDU fuel channel sagging deformation

OPTIMIZATION of PT SAG

The prediction of PT sag was optimized using the results of the in-service inspection of fuel channel. The creep correction factor was determined to match the inspection results of pressure tube with the analytical prediction results. The optimal creep correction factor of a unit analyzed is 0.88 as seen in Fig. 6.

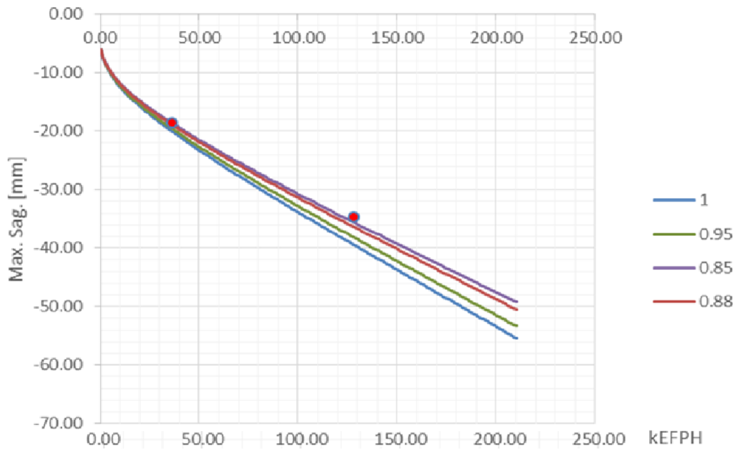


Fig. 6 Optimized Sag Prediction of Pressure Tube

Maximum creep sag of calandria tube at the end of plant design life (210,000 EFPH) was evaluated in the same manner as above. There is no contact between the calandria tubes and LINs. As results of measurement of the gap between calandria tubes and LINs using the developed visual inspection equipment, it is confirmed that the gap of the visual inspection is agreed well with the predicted gap as shown in figure 7. However, more visual inspection results are required to predict the practical gap prediction.

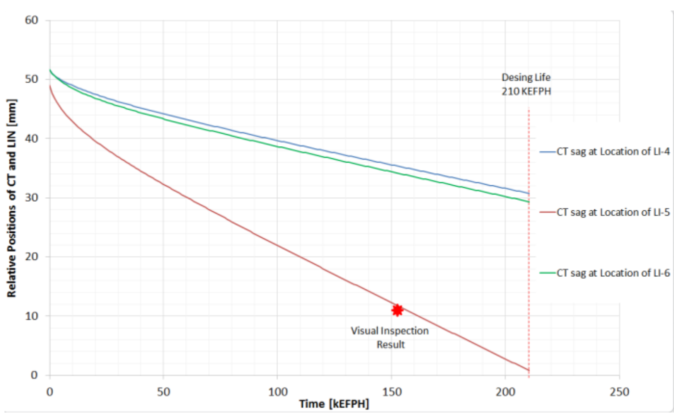


Fig. 7 Optimized Sag Prediction of Pressure Tube

CONCLUSION

Visual inspection equipment was developed for the measurement of the gap between the calandria tubes and LINs through viewing ports at Wolsong PHWR NPP. The gaps were predicted using the results of the in-service inspection of pressure tube sag and were optimized to determine the creep correction factor.

It was confirmed that the predicted gap using inservice inspection results was useful. But more visual inspection results are required to predict the practical gap prediction.

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