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Performance Evaluation of Modified 37-element Fuels during Demonstration Irradiation

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1. Introduction

As a CANDU reactor ages, the thermal margin in CHF is reduced due to an aging phenomena such as pressure tube (PT) diametral creep, which increases bypass coolant flow to the fuel bundle in the channel. Therefore, to shut down an aged CANDU reactor safely, the utility should consider a reduction of the thermal margin and undertake proper procedures such as a reduction of the Regional Overpower Protection system's Trip Set Point (ROP TSP). For some utilities, the reduction of the ROP TSP means a decrease of normal full power level from 100%FP.

Korea Hydro & Nuclear Power Co. Ltd. (KHNP) decided to load the 37M fuel bundle into the Wolsong NPP site in 2013. The modified 37-element (37M) fuel bundle was developed by Canadian utilities, which is the same as the existing 37-element (37R) fuel bundle but for smaller center pin diameter. So, the center pin sub-channel flow area is much larger. However, this small change has caused CHF of the 37M fuel bundle to go up to 16.9%[1] with aging. At present, KHNP is preparing to submit a Final Safety Analysis Report including information on the 37M full loading core and the 37R-to-37M transition core status. In the licensing process for approval of test fuel loading, the Korean regulatory body requested the demonstration irradiation (DI) results because the 37M fuel loading into a CANDU-6 reactor except CANDU reactors is the first time in the world. So, sixteen 37M test fuel bundles were loaded in two selected fuel channels at Wolsong NPP Unit 4 in October 2014. During the test period, KHNP had to predict various fuel performances for the 37M test bundles. For that purpose, KHNP has developed an automatic work procedure connecting plant site data systems, the reactor physics code, thermal-hydraulic codes and fuel performance analysis code.

This paper shows how to manage these codes and calculated historical features of the representative fuel pins in the fuel channels with 37M fuel bundles.

2. Required Computer Codes

To evaluate detailed fuel pin performance, fuel channel conditions reflecting reactor operational status with Effective Full Power Day (EFPD) should be provided. These are bundle average power, bundle average burnup, pin power sharing factor, pin burnup sharing factor, pin to coolant heat transfer data, coolant temperature and pressure around pin. Some of these are not measurable data but should be obtained based on the measured thermal-hydraulic data, such as the reactor inlet header (RIH) temperature and the reactor outlet header (ROH) pressure, etc. Also, some of these essential data should be calculated by computer codes such as RFSP, NUCIRC and CATHENA. Each code's model is described briefly in this section.

2.1 RFSP

The RFSP code [2] is a computer program that generates bundle-wise power and burnup distribution for all 380 fuel channels based on the three dimensional two group static diffusion equation. By virtue of the specific burnup-dependent cross section table set for the 37M channel prepared using the WIMS-IST code [3], the bundle averaged power and burnup distribution of each 37M and 37R channel can be obtained for any operational condition. Using the new cross section table set, simple modifications of the RFSP input file can make the RFSP simulate the reactor core during the DI period. Power and burnup levels of the 48 fuel bundles of the four channels can be easily extracted from RFSP outputs. From them an input file can be made for the integration utility, R2E[4], in which bundle average values are divided into pin-wise data according to the power and burnup sharing factors, conservatively estimated by the RFSP.

2.2 CATHENA and NUCIRC

The CATHENA (Canadian Algorithm for THErmalhydraulic Network Analysis) code [5] is a one-dimensional, two fluid thermal-hydraulic computer code for analysis of postulated accidents in CANDU reactors. It solves six conservation equations for gas and liquid phases and also constitutive relations for mass, momentum, and energy transfer between liquid and gas phases and between walls and fluids. CATHENA code was used as a main thermalhydraulic code in the R2E utility, because the NUCIRC code [6] is not able to separately simulate each fuel pin and to simulate a fuel channel with both of 37R and 37M fuel bundles.

At the beginning of the DI sixteen 37R fuel bundles of a hot channel (A channel) and a cold channel (B channel) were replaced by sixteen 37M fuel bundles in Oct. 2014. So, each of the two channels had eight bundles of 37M in the upstream and four bundles of 37R in the downstream. Another hot and cold fuel channels (C and D channels) having all 37R fuel bundles and positioned symmetrically to the A and B channels, were also considered for comparison.

To produce required thermalhydraulic data, four CATHENA base single channel models were needed for the four fuel channels. Therefore, CATHENA base single channel models excluding several specific data, such as pin power, measured thermalhydraulic data, etc., were prepared. The thermal-hydraulic nodes of the four fuel channels were produced by the CATGEN6 utility [8, 9]. Pressure tube diametral creep and inlet feeder orifice degradation for each of the four channels were predicted by the NUCIRC code in order to reflect the aging conditions in the channel models. Coolant pressure and temperature measured at the RIHs and pressure measured at ROHs of Wolsong NPP Unit 4 were used as boundary conditions in the channel models. Also, void fraction of ROH of each channel was estimated based on NUCIRC code calculation results and also applied as a boundary condition. Each CATHENA channel model was adjusted to predict channel flow with a flow difference less than 3% between results of CATHENA and NUCIRC.

The utility R2E generates a specific CATHENA model applying specific operational data to the base models.

2.3 ELESTRES

The fuel performance code, ELESTRES (ELEment Simulation and sTRESses)-IST [7] models the on-power thermal, mechanical and micro-structural behavior of the CANDU fuel elements under normal operating conditions. The results are also provided to a fuel transient performance simulation for the evaluation of fuel integrity during accident condition. It is assumed that all the pins on the same ring at a given bundle location have the same initial fuel conditions. Therefore, for the 37M and 37R bundles, only four pins in a bundle were evaluated for fuel performance.

The available fission product inventory in a fuel pin depends on the configuration of the pin powers and burnups in the reactor core at the time of evaluation. Generally, daily power distribution of a CANDU-6 reactor dramatically varies during normal refueling life, so in the case of safety analysis, the fuel performance is evaluated with very conservative power history (or overpower history) with burnup. For 37R fuel bundles, the conservative power history was used. However, it was not used for 37M fuel bundles because the R2E utility code recorded all the power and burnup history from Oct. 2014 to each evaluation time every ~ 1 EFPD during the DI period.

3. Method for Integrating Individual Codes

KHNP developed a utility code, R2E, scripted with the Perl language and operated in a MS Windows environment. The overall data flows in the R2E code are shown in Figure 1.

The first task in the process is to gather fuel channels' boundary condition data over time. A total of 62 sets of plant data from several detectors installed in the reactor headers were saved in a file, and their averaged values, as boundary conditions for the CATHENA code, were inputted into "power_burnup.dat", which is the main input file of the R2E script. Bundle-wise power and burnup data extracted from the RFSP output were also used as the main R2E input. The next task was to run the CATHENA code. Based on the pre-determined CATHENA single channel base model, the R2E manipulated the measured thermalhydraulic channel boundary conditions and the current pin-wise axial power distribution to reflect operational status. From the output of the four CATHENA channels, the R2E extracts and re-evaluates 192 pin-wise thermal-hydraulic parameters, such as coolant pressures, coolant temperatures and heat transfer coefficients from sheath to coolant. The final task was to run the ELESTRES code. The R2E generates ELESTRES inputs for the 192 individual pins (=4 pins/bundle * 12 bundles/channel * 4 channels) reflecting operational powers, burnups and thermalhydraulic boundary conditions and runs the ELESTRES code to calculate all of the detailed information of interest. The R2E summarizes these outputs in a file, SUMMARY_EFPD, and makes electronic files containing key parameter trends.

As mentioned above, for the C and D channels it would be easy to obtain fuel performance predictions from running the R2E just as for the case of 37M test bundles if power and burnup histories and thermal-hydraulic boundary conditions for all bundles in C and D channels were known. However, it is difficult to make historical bundle-wise power and burnup data for the 37R fuel bundles using the ELESTRES code coupled with CATHENA because large amount of calculations are needed. Therefore, for all of the 37R bundles in A, B, C and D channels, the initial condition was determined using the overpower history curve and the averaged bundle thermalhydraulic conditions. These are the approaches that are used in safety analysis for conservatism.

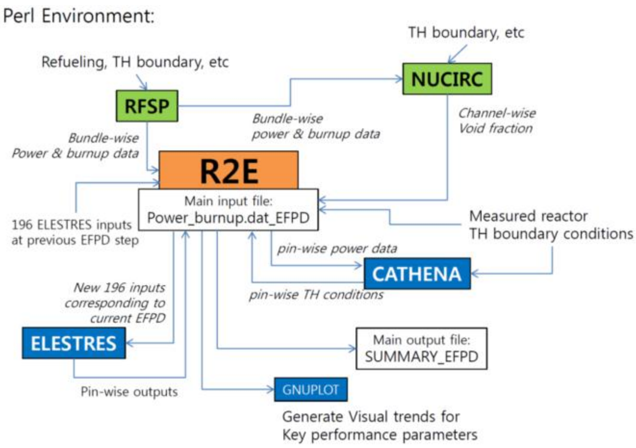


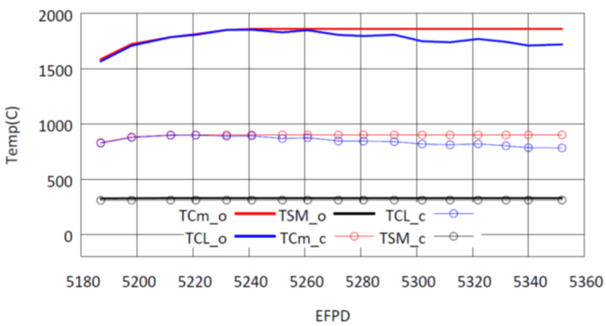
Fig. 1. Flow Diagram of Data in the R2E Utility

The R2E considers several uncertainties of the ELESTRES code to make a conservative estimate of 37M and 37R fuel tracking calculation during the DI. Each pin power was multiplied by a value of 1.08, which value contains a bundle power prediction uncertainty of

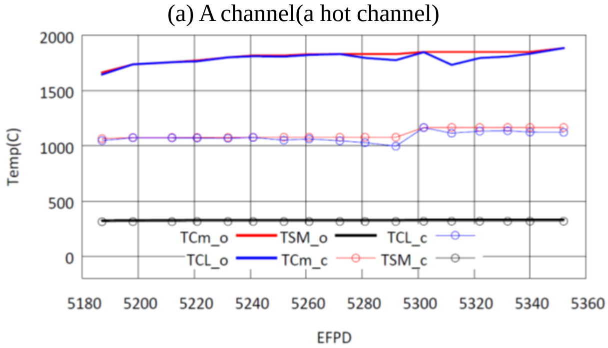
4.1% and a pin power variation of 4% caused by the thermal conductivity uncertainty of 6%. As for the strain rate, a total of 20% uncertainty was additionally applied so that the R2E produce a value that is 1.2 times the "calculated" strain of each pin. The calculated strain was obtained from the assumption of 8% power rise. The uncertainty of 20% was determined from the uncertainty parameters such as the oxide thermal conductivity, sheath thermal conductivity and expansion coefficient, fuel expansion coefficient and thermal conductivity. Detailed information on these was from NUREG/CR-7001 Table 4.5 [10].

4. 37M Fuel Bundles Performance Results

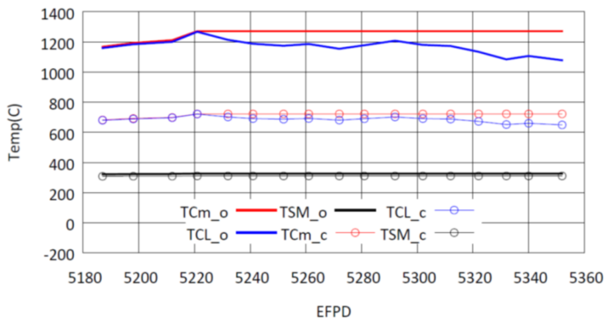
The fuel centerline and sheath surface temperature trends for outer and center pins of the hottest bundles (6th bundle from the inlet) of the four channels were shown in Figure 2. In the figure, TCm represents the maximum centerline temperature of a pin during the test period, TCL is the current fuel centerline temperature, and TSM is the maximum sheath surface temperature. The subscripts o and c indicate the outer and center pins, respectively. The fuel centerline and sheath temperature behaviors of each pin of the four channels were nearly the same as those of each of the other channels, and all values are well under the design criteria of 2840℃ (UO_2 melting temperature) and 1760℃(fuel sheath melting temperature), respectively. The small variations in pin power of the C and D channels at 5300 and 5340 EFPD, respectively, were caused by re-fueling at those channels.



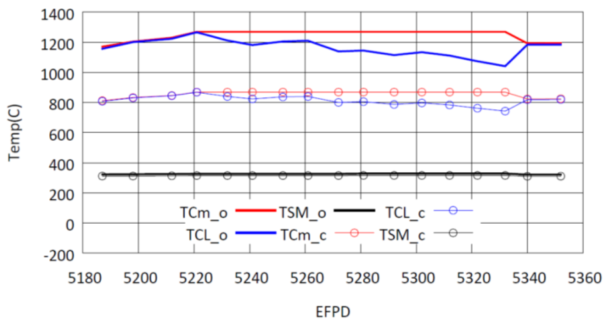
(a) A channel(a hot channel)



(b) C channel(another hot channel)



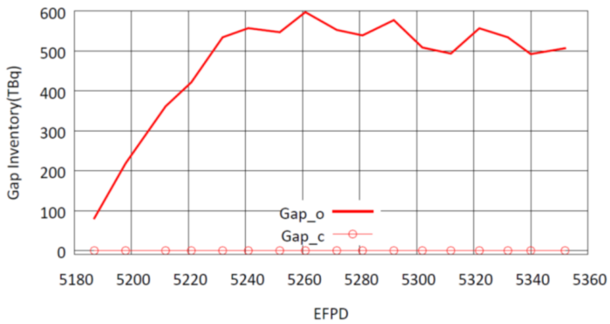
(c) B channel(a cold channel)



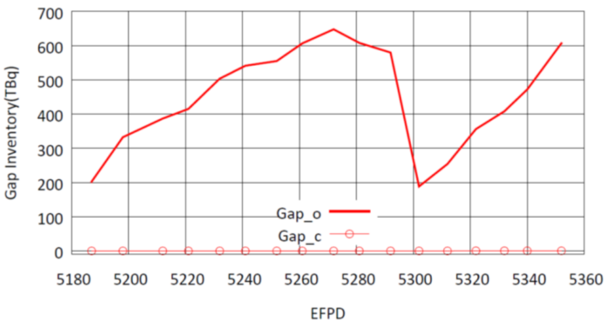
(d) D channel(another cold channel)

Fig. 2. Center and outer pin temperature variation

Inventories of the total set of fission products (which consisted of 31 isotopes, including I-131 and Xe-135 in gaps between the fuel pellets and the sheaths of each ring of bundle 6) accumulated during the DI were shown in Figure 3. These fission products inventories can change according to the pin power history and short-lived isotope concentration. A gap inventory for the outer ring of A channel in Figure 3(a) shows the typical inventory variation with time. Because of short-lived isotopes, gap inventory hit a peak early and then reached a saturated equilibrium condition. The refueling in the C channel creates a large discontinuity in the gap inventory history; however, the inventory behavior will follow the A channel's gap inventory curve. As for the gap inventory, there was no violation of the safety criterion. However the initial total gap inventories of the outer ring of bundle 6 of the modified O6 channel (the most conservative channel, and one that was intentionally modified) in the Large Break (LB) LOCA of the Wolsong NPP was ~ 1000 TBq, which satisfies the final dose criterion. Therefore, the evaluated 37M and 37R gap inventory trends indirectly satisfy the safety limits at every EFPD.



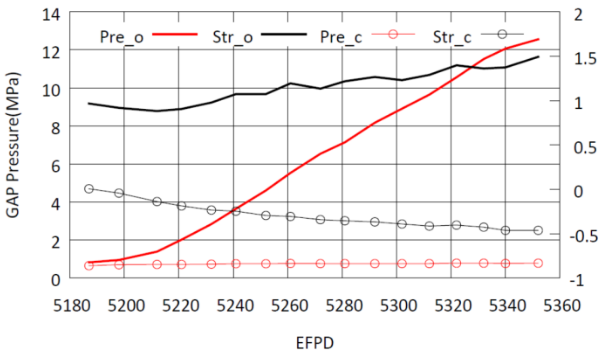
(a) A channel



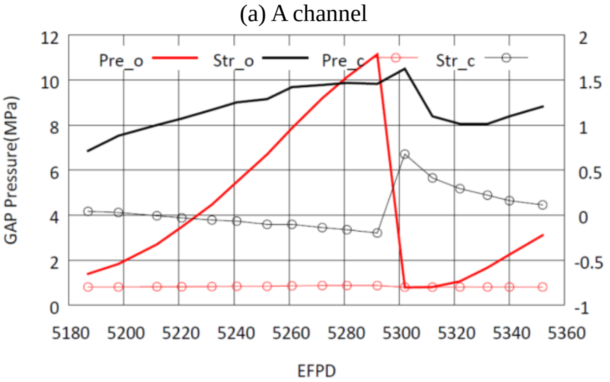
(b) C channel

Fig. 3. Ring and channel-wise gap inventory variation

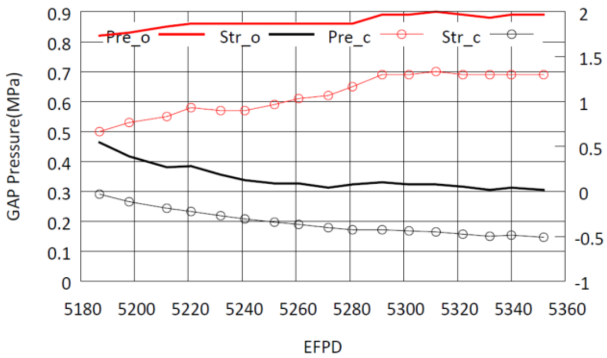
As for the sheath strain limit, there are two conservative sheath failure limits in the LB LOCA analysis. The first limit is "No excessive diametral strain." This condition conservatively assumes that fuel will fail when the average sheath strain reaches 5% and the sheath temperatures are lower than 1000℃. The second limit is "No significant cracks in the surface oxide". Because reduced sheath thickness under the crack tip can result in localized stresses and strains, leading to sheath failure, it is conservative to assume that sheath failure will occur when the calculated uniform sheath strains are higher than 2% and sheath temperatures are higher than 1000℃. The maximum sheath strains which reflected uncertainties appeared at the outer pins of bundle 6 of the A and C channels in Figure 4. No fuel sheath failure was expected. Even if the gap pressure on the outer pin went up to 13 MPa, the strain of the pin was still maintained less than 2% with an average sheath temperature of 400℃.



(a) A channel



(b) C channel



(c) B channel

Fig. 4. Ring and channel-wise Gap pressure and sheath strain variation

5. Conclusion

The fuel performance parameters, which had been monitored for 6 months, showed that the test 37M fuel bundles were being burnt with no significant or remarkable problems. Further, the behavior of the 37M fuel bundles was nearly the same as that of the existing 37R fuel bundles, and the parameters remain within the normal variation range for 37R fuel bundles; however, the thermal margin of the 37M fuel bundles was improved dramatically. Therefore, based on the conservatively monitored parameters, the 37M fuel can be loaded in a CANDU-6 reactor.

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