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Depletion Calculations of Adjuster Rods in Darlington

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Abstract

This paper describes the simulation methodology and reactivity worth calculated for aged adjuster rods in the Darlington core.

ORIGEN-S IST was applied to simulate the isotope transmutation process of the stainless steel and titanium adjusters. The compositions were used in DRAGON-IST to calculate the change in incremental properties of aged adjusters.

Pre-simulations of the reactivity worth of the stainless steel and titanium adjusters in Darlington were performed using RFSP-IST and the results showed that the titanium adjuster rods exhibit faster reactivity-worth drop than that of stainless steel rods.

Keywords: depletion calculations, aged adjuster rods.

1. Introduction

The work was done in support of the Darlington Refurbishment Project which requires an assessment of the reactivity worth of Adjuster Absorber rods (AAs) for the Darlington Nuclear Generating Station (DNGS). This assessment is focused on calculating the effect of neutron irradiation on the change in device compositions and on the reactivity worth of the AAs.

The results were used to assist Ontario Power Generation (OPG) in determining the suitability of the AAs for continued use in the Darlington units after refurbishment. The reactivity device worths were also calculated for the configurations corresponding to approximately the end of life of the initial cores, 195000 Equivalent Full Power Hour (EFPH)[1] and for the end of life of the refurbished cores, 405000 EFPH. The calculated results were compared with station measurements [1] that were taken at a recent station outage.

[1] EFPH represents the cumulative operation time at full power. One EFPH is equivalent to one hour of operation at 100% fission power.

2. Analysis scope

The scope of analysis is divided into three main activities; these are:

1. Calculations of incremental cross sections and average thermal flux values for the depletion calculations,
2. Depletion calculations, and
3. Full-core diffusion calculations.

2.1 Calculations of incremental cross sections and average thermal flux values required for the depletion calculations

The first step is the prerequisite work required as inputs to the depletion analysis used to calculate the isotopic compositions of the absorbers at different points in time. More specifically, it covers the development of supercell models to calculate the incremental cross sections representing the devices. Also covered are the full-core calculations that were used to calculate the average thermal flux values at the location of the AAs.

2.2 Depletion calculations

Depletion calculations used to calculate the change in compositions for each adjuster type from the beginning of life to 154008 EFPH and then out to 195000 EFPH. Depletion calculations were performed for each adjuster type and the compositions were used to update the material compositions in the supercell models to get the appropriate incremental cross sections.

2.3 Full-core diffusion calculations

The last activity was to calculate the reactivity worth of the AAs from the beginning of life to 154008 EFPH and then out to 195000 EFPH. The reactivity worths of the AAs were first determined and are reported for 154008 EFPH and 195000 EFPH of operation. The results were then used to interpolate/extrapolate the reactivity change to 166500 EFPH and 405000 EFPH, respectively.

3. Codes

The lattice cell calculations were based on the WIMS-IST code [2] and the supercell calculations were performed with the DRAGON-IST version 3.04T [3], [4]. The ORIGEN-S module [5] of the SCALE-5.1 package [6] was used to perform the depletion calculations based on the LWR data library for light elements and activation products that is distributed with the package. This library is routinely used in CANDU applications and is judged to be fully applicable in the current context. All the lattice and supercell calculations were performed with the WIMS-IST ENDF/B-VI data library [7].

The WIMS-IST based lattice properties were calculated with the Simple-Cell Method (SCM) [8] available in RFSP-IST [9] at the irradiation distribution equivalent to the time-average model with un-irradiated adjusters.

4. Assumptions

A number of analytical assumptions were made for the assessment of the reactivity worth of the AAs. The assumptions are discussed below:

- The depletion of the same adjuster types at different adjuster locations can be prorated based on the local flux profile within each adjuster component assuming there are no significant spectral changes between different adjuster locations. This allows one depletion calculation to be performed per adjuster type.
- Each adjuster can be modelled with a uniform isotopic composition along its length and representative of the average composition.
- Two sets of depletion calculations are performed, i.e. adjusters with titanium shim rods (Type 1 and Type 2)[2] and adjusters with stainless-steel shim rods (Type 3 and Type 4)[3]. Each set involves calculation of the shim-rod and the absorber-tube depletion.
- The reactivity worth of the adjusters at 166500 EFPH and 405000 EFPH can be interpolated/extrapolated based on the RFSP-IST simulations performed at 0, 154008 EFPH and 195000 EFPH. This allows an estimate of the adjuster worth over an extended irradiation period to be performed in 2 depletion time steps. Thermal neutron flux amplitude within each of these steps is assumed to be constant and the reactivity worth is assumed to change linearly as a function of EFPH.
- All DRAGON-IST and RFSP-IST calculations are performed at an average pressure-tube diametral creep of 2%.
- Each AA type is modeled with one set of incremental properties at a given irradiation.
- All other devices in the core are modeled with un-irradiated properties.

5. Calculation methodology

A multi-step process was involved to calculate the properties of the aged adjusters and their impact on the full-core calculations. The first step involved supercell calculations, followed by the second step where depletion calculations were performed. The last step involved full-core diffusion calculations.

5.1 Supercell calculations and average thermal flux values required for the depletion calculations

All DRAGON-IST input files were based on a 3-dimensional representation of two lattice pitch geometry with a one-bundle length in the axial direction and the reactivity device introduced between the two fuel bundles.

Incremental cross sections were calculated by subtracting the cross sections calculated with the device from the cross sections calculated for the reference case. The reference case consisted of a 3-dimensional representation of a two lattice pitch geometry without the reactivity device between the

[2] Adjusters Type 1 and 2 have a stainless steel absorber tube and a titanium shim rod (see Figure 1).
[3] Adjusters Type 3 and 4 have a stainless steel absorber tube and a stainless steel shim rod (see Figure 1).

two fuel channels. The incremental cross sections were calculated using a two-energy group convention with a cut-off at 0.625 eV and an upper limit of 10 MeV.

Four types of adjusters are used at DNGS and all have an outer stainless steel outer tube. Adjuster type 1 and 2 have a titanium shim rod located inside the outer tube and adjuster type 3 and 4 have a stainless steel shim rod located inside the outer tube. Figure 1 shows a typical configuration of an adjuster absorber.

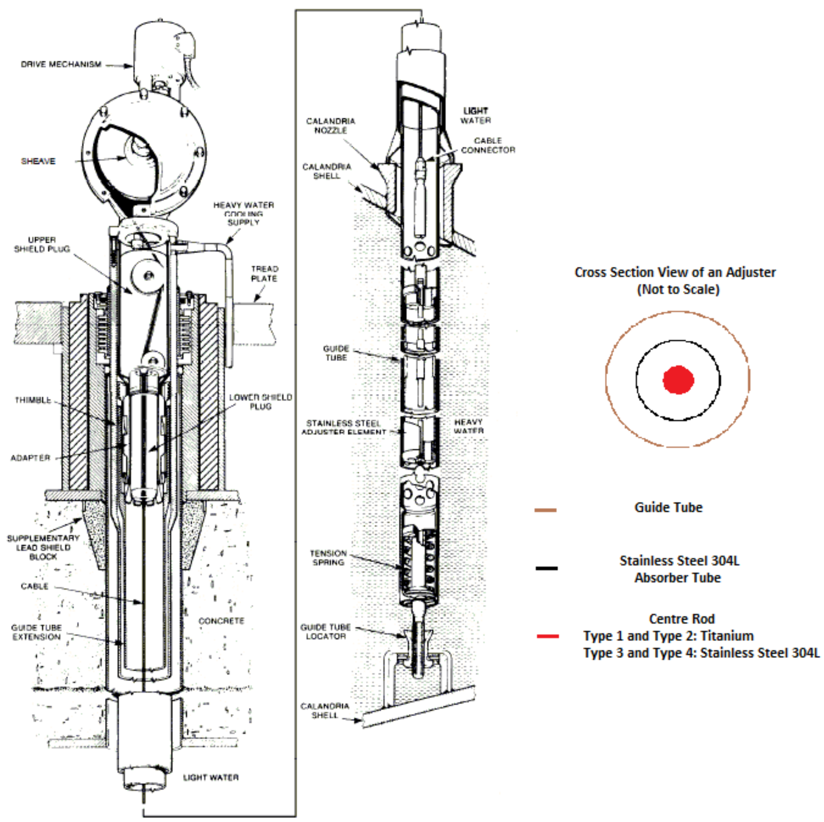

Figure 1 Configuration of an Adjuster Absorber

5.2 Average thermal flux values required for the depletion calculations

A time-average calculation was performed to calculate the burnup distribution in the core and extract the average thermal flux over each adjuster. The cell homogenized thermal flux was calculated with Equation 1.

$$\overline{\phi_a} = \frac{\sum_{x=1}^{nx}\sum_{y=1}^{nz}\sum_{z=1}^{nz} d_x \cdot d_y \cdot d_z \cdot \phi_{a,x,y,z}^{therm}}{\sum_{x=1}^{nx}\sum_{y=1}^{ny}\sum_{z=1}^{nz} d_x \cdot d_y \cdot d_z} \tag{1}$$

Where,

$\overline{\phi_a}$	cell homogenized thermal flux ($n/cm^2 \cdot s$) at the location of adjuster *a*
nx	number of meshes in the *x* direction along the adjuster
ny	number of meshes in the *y* direction along the adjuster
nz	number of meshes in the z direction along the adjuster

d_x, d_y, d_z mesh spacing in the *x, y* and *z* direction at location *x, y, z*

$\phi_{a,x,y,z}^{therm}$ thermal flux $n/cm^2 \cdot s$ at mesh location *x, y, z* for adjuster *a*

5.3 Depletion calculations

In order to provide the best approximation of the change in adjuster worth over long irradiation periods, the depletion calculations were performed using an iterative calculation procedure with the DRAGON-IST/RFSP-IST and ORIGEN-S codes. Two depletion calculations were performed, from 0 to 154008 EFPH. The isotopic compositions were used in DRAGON-IST to calculate the neutron fluxes in the absorber and the results were then used in ORIGEN-S to perform the depletion calculations from 154008 EFPH to 195000 EFPH. The results were then used in calculating the adjuster worths. The results of reactivity worths at 154008 EFPH and 195000 EPH were also used to interpolate the worth at 166500 EFPH and extrapolate the worth at 405000 EFPH. The assumption is that a linear extrapolation at 405000 EFPH provides a conservative calculation for the depletion of the adjuster.

5.3.1 Theory

The change in incremental cross sections of the adjusters over a long irradiation period was calculated by coupling the results of DRAGON-IST/RFSP-IST and ORIGEN-S. DRAGON-IST/RFSP-IST was used to calculate the physics properties of the device, i.e. local device flux profile, spectral flux information, and device absorption rates. The information was then input into ORIGEN-S to perform the detailed burnup calculation. To ensure consistency between the 2 code systems, the absorption rates were kept constant when data were passed between the codes. That is, the absorption reaction rates in the diffusion calculation were preserved when starting the burnup calculation and the total absorption cross section of the new compositions calculated using ORIGEN-S was also preserved when the compositions were passed back to DRAGON-IST.
This approach has been used in the industry for adjuster rod depletion. The theory of the depletion calculation can be summarized in the following equation.

$$\mathrm{V}_{\text{lattice}}^{\text{RFSP-IST}} \sum_i \left(\Delta \Sigma^{DRAGON-IST} \times \Phi^{RFSP-IST} \right)_i = \sum_j \left(\overline{\Sigma}_j^{ORIGEN-S} \times D_{th,j}^{DRAGON-IST} \times \overline{\Phi}_{th,j}^{ORIGEN-S} \times V_j \right) \quad (2)$$

The worth of the adjuster assembly is represented as the total absorption rate in the RFSP-IST lattice cell $V_{lattice}^{RFSP-IST}$ and was calculated as the sum (over energy group *i* of the product of the RFSP-IST fluxes $\Phi^{RFSP-IST}$ and the DRAGON-IST incremental cross section $\Delta\Sigma^{DRAGON-IST}$ on the left hand side of Equation 2.

The RFSP-IST absorption rate was matched with the sum of the product of the ORIGEN-S cross sections data $\overline{\Sigma}_j^{ORIGEN-S}$ and the required ORIGEN-S thermal flux $\overline{\Phi}_{th,j}^{ORIGEN-S}$ adjusted by the local flux depression factor $D_{th,j}^{DRAGON-IST}$ on the right hand side of Equation 2 summed over component *j*, where components comprise of the shim rod and the outer absorber tube.

5.3.2 Calculation steps

The stepwise approach used to execute the depletion calculation is summarized below.

1. The fast and thermal incremental cross sections were generated for the adjuster assembly at the beginning of life using DRAGON-IST, i.e. $\Delta\Sigma_{a,f}^{SR/OT}$ and $\Delta\Sigma_{a,th}^{SR/OT}$; where *SR* represents shim rod and *OT* represents outer absorber tube. The energy boundary between epi-thermal and thermal energy range is 0.625 eV.

2. Calculated the flux spectra in the shim rod and outer absorber tube of the adjuster assembly based on the DRAGON-IST supercell calculations; the spectra were represented as the ratio of the resonance-to-thermal flux, and the ratio of the fast-to-thermal flux, i.e.

$$\gamma_{res}^{SR/OT} = \Phi_{res}^{SR/OT} / \Phi_{th}^{SR/OT} \tag{3}$$
$$\gamma_{f}^{SR/OT} = \Phi_{f}^{SR/OT} / \Phi_{th}^{SR/OT} \tag{4}$$

Symbols $\Phi_{th}^{SR/OT}$, $\Phi_{res}^{SR/OT}$ and $\Phi_{f}^{SR/OT}$ are respectively the thermal, resonance, and fast neutron fluxes calculated by DRAGON-IST in the shim rod (*SR*) or the outer absorber tube (*OT*). The energy range of the fluxes are 0-0.625 eV for the thermal group, 0.625 eV-1.0 MeV for the resonance group, and 1.0 MeV-10 MeV for the fast group; these are the same energy groups that were used in the ORIGEN-S LWR 3-group cross section data library for light element activation calculations.

3. Time-averaged 2-group neutron fluxes were generated, i.e. Φ_{f}^{TA} and Φ_{th}^{TA} using RFSP-IST with the incremental cross sections calculated using DRAGON-IST in Step 1. The fluxes were volume-averaged over the RFSP lattice cell in which the adjuster assembly was represented.

4. The absorption reaction rates of the adjuster ($RR^{SR/OT}$) were calculated as the product of the RFSP-IST time-averaged 2-group fluxes and the DRAGON-IST incremental cross sections using the following equation.

$$RR^{SR/OT} = (\Delta\Sigma_{a,f}^{SR/OT}\Phi_{f}^{TA} + \Delta\Sigma_{a,th}^{SR/OT}\Phi_{th}^{TA})\ V \tag{5}$$

where,

V = lattice cell volume in DRAGON-IST and RFSP-IST

This involved calculating the absorption rates of the outer absorber tube and of the shim rod in the lattice cell.

5. 1-group macroscopic absorption cross section using microscopic cross sections $(\sigma_0, \sigma_{RI}, \sigma_f)$, in the LWRLIB library in ORIGEN-S were calculated using the following treatment:

$$\Sigma_{a}^{SR/OT} = \sum_i \frac{\rho_i}{A_i} N_A\, \sigma_{a,i}^{SR/OT} \tag{6}$$

where

$$\sigma_{a,i}^{SR/OT} = \sigma_{o,i}\sqrt{\frac{\pi T_0}{4T}} + \gamma_{res}^{SR/OT}\,\sigma_{RI,i} + \gamma_{f}^{SR/OT}\sigma_{f,i} \tag{7}$$

$\sigma_{o,i}$, $\sigma_{RI,i}$ and $\sigma_{f,i}$ are the thermal, resonance integral and fast group microscopic absorption cross sections for nuclide *i*, respectively

T_0 = 293.16K

T = 339.16K (moderator temperature)

ρ_i = partial density of nuclide *i*

A_i = atomic mass of nuclide *i*

N_A is Avogadro's number.

Individual 1-group nuclide cross sections $\sigma_{a,i}^{SR/OT}$ were weighted using the spectral coefficients (γ) derived in Step 2. All 1-group cross sections were summed.

6. The spatial thermal-neutron-flux depression factors were calculated in the shim rod and in the outer absorber tube. These are ratios of the local device thermal fluxes to the lattice-cell thermal flux calculated by DRAGON-IST as shown below.

$$D_{th}^{SR/OT} = \frac{\Phi_{th}^{SR/OT}}{\Phi_{th}^{cell}} \tag{8}$$

7. In order to reproduce the same device absorption rates in the RFSP-IST lattice cell, the thermal neutron flux Φ_{th} required as input in ORIGEN-S was calculated. This was done by dividing the RFSP-IST absorption reaction rates on the left hand side of Equation 5 by the one-group ORIGEN-S cross section in Equation 6 and the cell depression factor in Equation 8. That is,

$$\Phi_{th} = \frac{(\Delta\Sigma_{a,f}^{SR/OT}\Phi_f^{TA} + \Delta\Sigma_{a,th}^{SR/OT}\Phi_{th}^{TA})V}{D_{th}^{SR/OT}\,\Sigma_a^{SR/OT}\,V^{SR/OT}} \tag{9}$$

8. The change in nuclide compositions was calculated using ORIGEN-S with the thermal neutron flux calculated in Equation 9 and the 3-group spectral coefficients calculated in Step 2. The spectral coefficients represented as THERM, RES, and FAST were used to collapse the 3-group cross section in ORIGEN-S to a single group for use in the depletion calculation. In the calculation, it was assumed that the neutron-flux amplitude and spectrum remains unchanged from the start to the end of the irradiation interval.

9. The total absorption cross sections of the ORIGEN-S compositions at the end of the irradiation step were conserved using the available nuclides in the DRAGON-IST E65lib5 library. This was achieved by equating the sum of the macroscopic cross sections of

nuclides that were not in E65lib5 to the macroscopic cross section of the natural element using the equation below.

$$N_{Co}\,\sigma_{a,Co}^{SR/OT} = \sum_k N_k\,\sigma_{a,k}^{SR/OT} \tag{10}$$

Where,

N_k = atom density of nuclide k

k = nuclides not present in E65lib5 cross section library

σ_a = weighted absorption cross section calculated using Equation 7

The calculated N_{Co} was then added to the rest of the compositions available in E65lib5 which, in total, have the exact absorption properties as the ORIGEN-S compositions at the end of the irradiation step.

10. New incremental cross sections were calculated using DRAGON-IST and the new material compositions. A new set of spatial and spectral flux information in the shim rod and outer absorber tube were also calculated.

11. New lattice-cell absorption rates were calculated using RFSP-IST with the 2-group flux distributions generated by the new incremental cross sections.

12. Using the new incremental cross sections and absorption rates, steps 2 to 9 were repeated to calculate the new material compositions of the shim rod and outer absorber tube for the next irradiation time step of 195000 EFPH.

The resulting material compositions (at 195000 EFPH) were then employed in DRAGON-IST to calculate the new incremental cross sections, which were in turn used to estimate the new reactivity worth of the adjuster rods.

5.4 Full-core diffusion calculations

The depletion calculations performed with the ORIGEN-S computer code were used as inputs to the DRAGON-IST calculations. The results of the DRAGON-IST calculations provide incremental cross sections of the devices at 154008 EFPH and 195000 EFPH, which were used in RFSP-IST to calculate the reactivity worth of the AAs. The numerical values of reactivity worth calculated with RFSP-IST were used to interpolate the reactivity worth at 166500 EFPH and 405000 EFPH, respectively. The values of the reactivity worth of individual adjusters were also calculated at normal operating conditions for fresh adjusters and also at a burnout of 195000 EFPH.

Reactivity worths were calculated for all devices using two configurations. A reference configuration with the device withdrawn and the moderator poison concentration adjusted to have a critical configuration. A perturbed configuration with the device inserted in the core using the same moderator poison concentration.

Equation 11 was used to calculate the reactivity worth of each adjuster.

$$\rho_{dev} = \rho_{out} - \rho_{in} \tag{11}$$

Where,

ρ_{dev}	reactivity worth of the adjuster (mk)
ρ_{out}	excess reactivity calculated with RFSP-IST when the adjuster is withdrawn (mk)
ρ_{in}	excess reactivity calculated with RFSP-IST when the adjuster is inserted (mk)

6. Results

Table 1 lists the reactivity worths that were calculated for the individual adjusters at 154008 EFPH and 195000 EFPH. The results listed in Table 1 show that the reactivity worth of the devices is inversely proportional to the residence time spent in the reactor. The results listed in Table 1 also show that the Type 1 and Type 2 rods with the Titanium centre rods deplete faster compare to the Type 3 and Type 4 rods that have stainless steel centre rods.

Table 2 lists the reactivity values that were interpolated at 166500 EFPH and extrapolated to 405000 EFPH. The largest differences observed in the tables are for the adjusters that are located close to the centre of the core (with titanium shim rods) and located in a high neutron-flux region. At 405000 EFPH, the worths of adjusters 12 and 13 are reduced by 32.32% and 32.37% respectively.

7. Errors and uncertainties

The principal source of uncertainty is the assumed un-irradiated compositions of the different adjuster types used in the calculation. These uncertainties will impact the precision in local flux levels and the precision in nuclear transmutation and depletion over irradiation.

The uncertainties in cross sections are judged to be small since the light elements present in the adjusters are relatively common as structural or reactivity control materials in other reactor types, besides CANDU.

Another source of error comes from the use of only one time-average reference model to calculate the reactivity worth of the devices at different burnouts. In reality, the reduction in absorption rate in an absorber is compensated by the increase in refueling dwell time for the channels located within the neighborhood of the absorber.

8. Conclusions

The objective of this project was to support OPG initiative in determining the suitability of the adjuster rods for continued operation at the Darlington units after refurbishment. Using the RFSP/DRAGON-IST codes and the ORIGEN-S code the following conclusions can be made.

- At the end of their operating life, before refurbishment at 195000 EFPH, a maximum change in reactivity worth of -8.98% is expected for an adjuster with stainless steel shim rod and a maximum change in reactivity worth of -16.19% is expected for an adjuster with titanium shim rod,
- The titanium rods deplete faster compared to the stainless steel rods because of the higher absorption cross section in the main absorbing isotope in titanium, ^{48}Ti.

Table 1
Reactivity Worths Calculated for the Adjusters at 154008 EFPH and 195000 EFPH

Adjuster Number[4]	Adjuster Type	154008 EFPH		195000 EFPH	
		Worth (mk)	% differences to the Reference Case (0 EFPH)	Worth (mk)	% differences to the Reference Case (0 EFPH)
1	4	***Out of Core***	N.A.	***Out of Core***	N.A.
2	3	0.576	-6.04%	0.565	-7.83%
3	2	0.807	-11.61%	0.779	-14.68%
4	1	***Out of Core***	N.A.	***Out of Core***	N.A.
5	1	0.769	-12.91%	0.742	-15.97%
6	2	***Out of Core***	N.A.	***Out of Core***	N.A.
7	3	0.545	-6.03%	0.535	-7.76%
8	4	***Out of Core***	N.A.	***Out of Core***	N.A.
9	4	0.375	-6.95%	0.367	-8.93%
10	3	0.706	-6.24%	0.693	-7.97%
11	2	0.983	-11.76%	0.949	-14.81%
12	1	0.994	-13.04%	0.958	-16.19%
13	1	0.990	-13.01%	0.954	-16.17%
14	2	0.976	-11.83%	0.942	-14.91%
15	3	0.698	-6.06%	0.686	-7.67%
16	4	0.373	-6.98%	0.365	-8.98%
17	4	***Out of Core***	N.A.	***Out of Core***	N.A.
18	3	0.558	-6.06%	0.548	-7.74%
19	2	***Out of Core***	N.A.	***Out of Core***	N.A.
20	1	0.779	-12.96%	0.751	-16.09%
21	1	***Out of Core***	N.A.	***Out of Core***	N.A.
22	2	0.811	-11.75%	0.783	-14.80%
23	3	0.577	-5.87%	0.567	-7.50%
24	4	***Out of Core***	N.A.	***Out of Core***	N.A.

[4] *Type 1 and Type 2 have a titanium shim rod, Type 3 and Type 4 have stainless steel shim rod.*

Table 2
Reactivity Worths Calculated for the Adjusters at 166500 EFPH and 405000 EFPH

Adjuster Number[5]	Adjuster Type	166500 EFPH		405000 EFPH	
		Worth (mk)	% differences to the Reference Case (0 EFPH)	Worth (mk)	% differences to the Reference Case (0 EFPH)
1	4	***Out of Core***	N.A.	***Out of Core***	N.A.
2	3	0.573	-6.58%	0.509	-17.02%
3	2	0.798	-12.54%	0.636	-30.39%
4	1	***Out of Core***	N.A.	***Out of Core***	N.A.
5	1	0.761	-13.84%	0.604	-31.63%
6	2	***Out of Core***	N.A.	***Out of Core***	N.A.
7	3	0.542	-6.56%	0.484	-16.59%
8	4	***Out of Core***	N.A.	***Out of Core***	N.A.
9	4	0.373	-7.55%	0.326	-19.10%
10	3	0.702	-6.77%	0.626	-16.81%
11	2	0.973	-12.69%	0.775	-30.45%
12	1	0.983	-14.00%	0.774	-32.32%
13	1	0.979	-13.97%	0.770	-32.37%
14	2	0.966	-12.77%	0.768	-30.64%
15	3	0.694	-6.55%	0.625	-15.95%
16	4	0.371	-7.59%	0.324	-19.20%
17	4	***Out of Core***	N.A.	***Out of Core***	N.A.
18	3	0.555	-6.57%	0.497	-16.37%
19	2	***Out of Core***	N.A.	***Out of Core***	N.A.
20	1	0.770	-13.91%	0.608	-32.12%
21	1	***Out of Core***	N.A.	***Out of Core***	N.A.
22	2	0.802	-12.68%	0.640	-30.41%
23	3	0.574	-6.37%	0.516	-15.86%
24	4	***Out of Core***	N.A.	***Out of Core***	N.A.

[5] *Type 1 and Type 2 have a titanium shim rod, Type 3 and Type 4 have stainless steel shim rod.*

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10. References

[1] C. Banica and A. Sullivan, "Adjuster Rod Aging in Darlington's CANDU Reactors: Behaviour, Measurement and Implications for Operation", Proc. of 35th Annual Conference of the Canadian Nuclear Society, New-Brunswick, Canada, 2015 May 31-June3.

[2] J.D. Irish and S.R. Douglas, "Validation of WIMS-IST", Proc. of 23rd Annual Conference of Canadian Nuclear Society, Toronto, Canada, 2002 June 2-5.

[3] G. Marleau, A. Hébert and R. Roy, "A User Guide for DRAGON 3.04T", IGE-175, Rev. 5, August 2005.

[4] G. Marleau, "DRAGON Theory Manual, Part 1: Collision Probability Calculations", IGE-236, Rev. 1, October 2001.

[5] I.C. Gauld, O.W. Hermann, and R.W. Westfall, "ORIGEN-S: SCALE System Module to Calculate Fuel Depletion, Actinides Transmutation, Fission Product Buildup and Decay, and Associated Radiation Source Terms", ORNL/TM-2005/39, Version 6, Vol. II Sect. F7, January 2009.

[6] Oak Ridge National Laboratory, "SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation", ORNL/TM-2005/39, Version 5.1, Vols. I-III, November 2006.

[7] P.J. Laughton and I.C. Gauld, "The Derivation of Burnup-Chain and Pseudo-Fission-Product Nuclear Data for a WIMS-AECL ENDF/B-VI-Based Cross-Section Library", Proc. of 18th Annual Conference of Canadian Nuclear Society, Pembroke, Ontario, Canada, 1994 October.

[8] J.V. Donnelly, "Development of a Simple-Cell Model for Performing History-Based RFSP Simulations with WIMS-AECL", *Proceedings of the International Conference on the Physics of Nuclear Science and Technology*, Long Island, New York, p 343, American Nuclear Society, 1998 October 5-8.

[9] B. Rouben, "RFSP-IST, The Industry Standard Tool Computer Program for CANDU Reactor Core Design and Analysis", in Proceedings of the 13th Pacific Basin Nuclear Conference, Shenzhen, China, 2002 October 21-25.