Adjuster Rod Aging in Darlington's CANDU Reactors: Behaviour, Measurement and Implications for Operation

Constantin Banica[1] and Aaron Sullivan[1]
[1] Darlington Nuclear Generating Station, Ontario Power Generation, Ontario, Canada
(constantin.banica@opg.com)

Abstract

Presented are the simulation methodology and the results of reactivity worth measurements performed on adjuster rods in an equilibrium Darlington (large CANDU) core. Simulation had predicted the effect of neutron irradiation on device properties for adjuster rods of different construction and in-core residence times. The expected difference in the rate of irradiation-induced reactivity worth loss in rods containing titanium versus all stainless steel has been confirmed by comparing measured reactivity values for adjuster rods that differ in material construction and in-core service times. Also discussed are the method for conducting the measurements, and the accuracy of pre-simulation results.

1. Introduction

The Darlington Nuclear Generating Station is located on the North shore of Lake Ontario, about 70 km east of Toronto. It consists of four large CANDU Pressurized Heavy Water Reactors. Each Darlington reactor contains 480 fuel channels, each of which houses 13 natural uranium fuel bundles. The nominal thermal power of each reactor is 2776 MW; the net electrical output of each unit is 881 MW.

Each reactor's 480 fuel channels are arranged horizontally in a lattice consisting of 24 rows and 24 columns. The fuel string in each fuel channel is approximately six metres in length. These large CANDU reactors were initially designed with 24 vertical adjuster absorbers (AAs) to flatten the axial and radial flux profiles in the core. The AAs were arranged in eight rows (that run parallel to the fuel channels), each containing three rods. In the 1990s, early in the life of the Darlington station, the reactor design was changed to lock eight of the original 24 adjuster rods out of core, such that total AA reactivity was reduced to about 13 mk. [2]

Figure 1 shows this arrangement; the 16 in-service AAs are represented by green circles, while the 8 locked-out AAs are shown by red circles. When in their in-core operating positions, the vertical midpoints of the AAs lie on the horizontal mid-plane of the reactor, as shown in Figure 2.

There are four types of AAs, which differ in dimension and material of construction. The six Type 1 AAs occupy the positions closest to the centre of the core. The six positions adjacent to the Type 1 AAs contain Type 2 AAs. Similarly, six Type 3 AAs are adjacent to the Type 2 AAs, and six Type 4 AAs occupy the positions farthest from the centre of the core (Figure 1). The Type 1 and Type 2 AAs

[2] This design change was motivated by economical reasons (reduction in fuelling rate) and other reasons.

are the longest and consist of both stainless steel and titanium components[3], while the shorter Type 3 and Type 4 AAs are composed entirely of stainless steel (Figure 2).

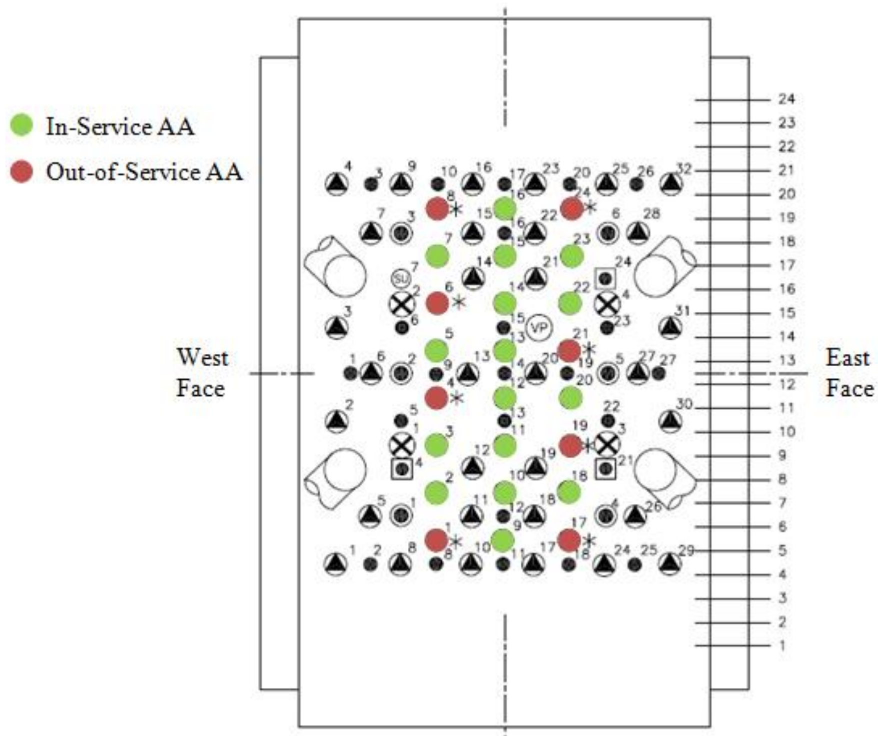

Figure 1: AA Arrangement in Darlington Reactors (Reactor Top View)

2. Indications of Adjuster Rod Aging

The Darlington reactors are not fitted with flux mapping detectors. Instead, agreement between the "real" flux distribution in the core and the simulated flux distribution from the core surveillance diffusion code is gauged by comparing the simulated and measured powers of 44 fuel channels in the core. Each of these 44 Fully INstrumented CHannels (FINCHs) (Figure 3) is fitted with instrumentation that measures the mass flow rate and enthalpy change of the coolant flowing through it, thereby measuring the thermal power of the channel. The difference between the simulated (S) and measured (M) powers of the FINCH is called the SORO[4]-FINCH Error (SFE=[S-M]/S). Thus, the 44 FINCH powers are used as validation data for the core simulation.

Analysis of SFE over the life of the station showed that, for all FINCHs, there was a subtle increasing or decreasing trend in this parameter, depending on the channel's location in the core (see Figure 5 and Section 7.1). The most centrally-located FINCHs exhibited increasing trends, while the trends for outer

[3] Titanium was incorporated into the design of the longest AAs to reduce their weight and, thus, the size of the associated drive motors.
[4] SORO (Simulation Of Reactor Simulation) is the diffusion code used at Darlington for licence compliance.

channels were decreasing. Based on predictions results in the 2003 COG study, [5] it was hypothesized that subtle changes observed in SFE are due to the change in AA reactivity worths.

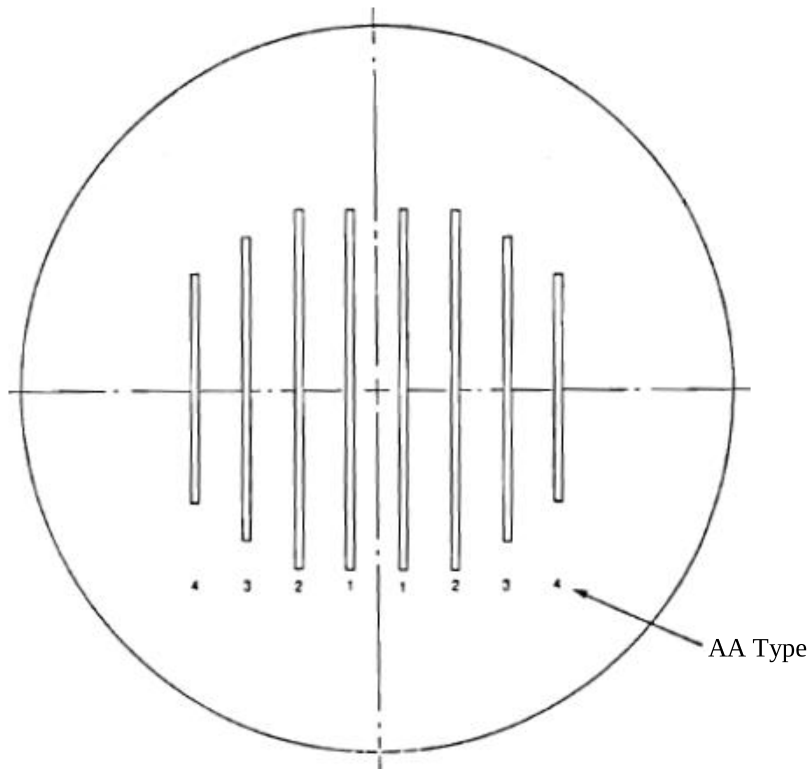

Figure 2: AA Type Arrangement (Reactor Face View)

3. Motivation for Simulation and Measurement of Adjuster Rod Reactivity Worth

There were three reasons for assessing the impact of AA aging: first, there is a constant need to properly model the aging core. Secondly, Darlington reactors are approaching the end of their initial commercial lives, and work is underway to determine the requirements of potential unit refurbishment. An important consideration in refurbishment planning is ensuring that reactivity devices can meet their design requirements over the second commercial life of the unit. Such a decision for refurbishment depends on how the device properties will have been affected by aging up to the time of refurbishment.

Thirdly, the AA reactivity available for poison override following a transient to 59%FP (e.g. a turbine trip) had to be confirmed for the aging reactors.

Evaluation of the post-refurbishment fitness for service of the AAs currently residing in the Darlington cores was performed in two parts. First, a simulation assessment was commissioned to quantify the effect of neutron irradiation on the AA compositions and reactivity worths. Second, in-

[5] Reference COG-03-2048

core reactivity worth measurements were performed on various AAs to confirm the results of the commissioned assessment.

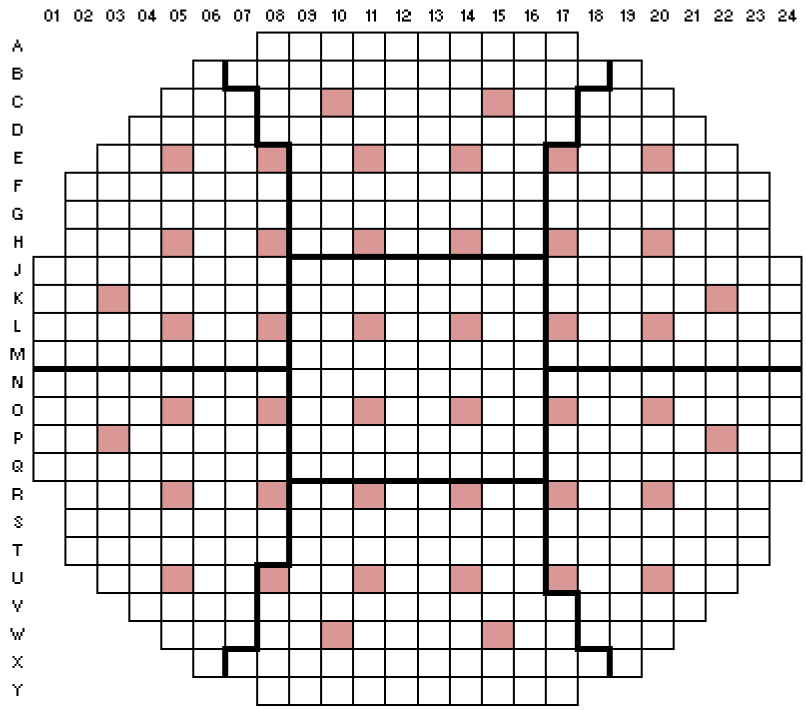

Figure 3: Arrangement of Darlington Unit FINCHs (Reactor East Face View)

4. Simulation of Adjuster Rod Reactivity Worth

An assessment[6] was performed to quantify the effect of neutron irradiation on AA and CA compositions and their associated reactivity worths. Device worth calculations were performed at three irradiation time steps (i.e., fresh, 154008 Effective Full Power Hours (EFPH) and 195000 EFPH).

Results predicted that the Type 1 and 2 AAs, which contain titanium and are centrally located in the core, could lose up to 16% of their reactivity worth by 195000 EFPH (i.e., by the end of life of the initial core); this rate of loss is about twice that predicted for the Type 2 and 3 AAs, which consist only of stainless steel and are less centrally located. Since the aging effect was shown to progress linearly, the loss of reactivity worth at the end of life of the refurbished core would be about twice that at the end of life of the initial core.

Table 1 shows the simulated percent loss of reactivity worth for each of the 16 in-service AAs at 166500 EFPH, under cold conditions, with all other rods fully withdrawn; these are the approximate

[6] The assessment was performed by B. Arsenault and K. Tsang of AMEC-NSS. Reference: paper titled "Depletion Calculations of Adjuster Rods in Darlington", to be presented at the CNS 7th International Conference on "Simulation Methods in Nuclear Engineering" (October 18-20, 2015 in Ottawa, Ontario).

reactor age and conditions under which the physical AA reactivity worth measurements were performed.

AA Type	AA	% Loss of Reactivity Worth	**AA Type**	AA	% Loss of Reactivity Worth
1 (Ti)	5	13.84	**3 (SS)**	2	6.58
	12	14.00		7	6.56
	13	13.97		10	6.77
	20	13.91		15	6.55
2 (Ti)	3	12.54		18	6.57
	11	12.69		23	6.37
	14	12.77	**4 (SS)**	9	7.55
	22	12.68		16	7.59

Table 1: Simulated Percent Loss of Reactivity Worth for In-Service AAs at 166500 EFPH

5. Measurement of Adjuster Rod Reactivity Worth

Reactivity worth measurements were performed for each of the 16 in-service AAs and three out-of-service AAs[7] (AAs 1, 4 and 6) in Darlington Unit 2, at an age of 165114 EFPH. This is the first time at OPG that reactivity device measurements were performed under equilibrium core conditions—all previous such measurements were performed as part of initial reactor commissioning.

The three out-of-service AAs that were measured were selected by virtue of their being of different AA types: AAs 1, 4 and 6 are of Type 4, 1 and 2, respectively; there are no out-of-service Type 3 AAs. Out-of-service AAs were included in the measurement campaign to provide direct comparison between AAs that were of the same type, but had incurred significantly different irradiations during their in-service lives (since the out-of-service AAs were permanently removed from the core in the mid-1990s, they've incurred about 18 operating years' worth of irradiation less than their in-service counterparts).

5.1 Reactor State

The AA measurements were performed under the following conditions:

[7] The AA measurement campaign was performed at the end of the unit outage, directly extending the outage duration. For this reason, only three out-of-service AAs were measured.

- Reactor was critical for about 22 hours following a planned 103 day maintenance outage.
- Reactor power was maintained at approximately -3.3 decades throughout the campaign.
- All reactivity device rods (i.e., Adjuster Absorbers, Control Absorbers and Shutoff Rods) were fully out of core, except for the rod being measured.
- The moderator contained approximately 1.2 mg Gd/kg D_2O (with all rods withdrawn).
- Moderator temperature at the calandria outlet was maintained at 36.0^{o}C; no variation in moderator temperature was observed for the duration of the measurements.
- Heat Transport System temperature was held steady (at around 64^{o}C) to within 0.1^{o}C in each of the four core passes throughout the measurement campaign.
- Parameters that significantly affect core reactivity were held constant during the measurements to isolate the reactivity effects of individual AA movements.

5.2 Adjuster Rod Worth Measurement Technique

Changes in bulk core reactivity were determined from the consequential change in the average fill level of all the liquid zone compartments in the core, which is referred to herein as Average Zone Level (AZL). For a given reactor state, the reactivity coefficient of AZL is nearly constant over the typical operating range for this parameter, so relative changes in core reactivity can be accurately determined from relative changes in AZL.

The main steps in the measurement workplan are described:

1. **Measurement of AA Bank Worth (withdrawn in design sequence):** All individual AA measurements were performed with all other reactivity device rods fully withdrawn from the core. This required removal of the 16 in-service AAs, which were in their normal in-core positions at the start of the campaign. This provided an opportunity to measure the reactivity worth of each AA bank, upon withdrawal from the core in design sequence[8], prior to the individual AA measurements.

   The withdrawal of the in-service AA banks was induced through the addition of sufficient gadolinium poison to the moderator to reduce the core reactivity below the point where the Reactor Regulating System (RRS) requested the withdrawal of a bank of AAs. After this was achieved, AZL was allowed to stabilize (and the AZL recorded) before the AA movement inhibit was removed and the first bank of AAs was removed under RRS control. Once the AAs were withdrawn, AZL was again allowed to stabilize before the post-withdrawal AZL was recorded.

[8] After eight AAs were permanently locked out of the core in the mid-1990s, the remaining 16 in-service AAs were arranged into eight two-rod banks. When required, the Reactor Regulating System moves each bank of AAs in turn in their designated design sequence; both AAs of a given bank are moved simultaneously.

The change in AZL effected by the withdrawal of the AA bank is a measure of the reactivity worth of the bank.

The process above was repeated for each of the remaining seven AA banks until all AAs were fully withdrawn from the core.

2. **Measurement of Individual AA Worth:** The worth of each measured AA was determined with all other rods fully withdrawn from the core. AZL was set to ~55% by adding or removing moderator gadolinium poison as required. Once AZL had stabilized, measurement of the first AA was performed by manually driving the rod to 100% insertion, allowing AZL to stabilize for 5 minutes, then manually withdrawing the rod to the fully withdrawn position and again allowing AZL to stabilize for 5 minutes. The AZL at the end of each stabilization period (before insertion, after insertion, and after withdrawal) was recorded to isolate the reactivity worth of the AA in terms of AZL change during both insertion and withdrawal. This process was repeated for each of the 16 in-service and 3 selected out-of-service AAs.

6. Adjuster Rod Reactivity - Results and Interpretation

6.1 Measurement Results for Symmetric In-Service and Out-of-Service AAs

Measurement results for two out-of-service AAs 4 and 6 are provided in column 3 of Table 2. For AAs 4 and 6, symmetric in-service AAs and their measured reactivity worths are provided in columns 4 and 5. Column 6 shows the percent difference in reactivity worth between each in-service AAs and its symmetric out-of-service AA[9]. This provides an indication of the magnitude of reactivity worth loss incurred by the symmetric in-service AAs between the time of the measurement and the AA reconfiguration in the mid-1990s—about 13.3% (average) and 10.6% for the Type 1 and 2 AAs, respectively.

Out of Service (OS) AA	AA Type	Measured OS AA Worth (%AZL)	Symmetric In-Service (IS) AAs	Measured Symmetric AA Worth (%AZL)	Difference: (IS-OS)/OS (%)	Simulated % Worth Reduction (31669 to 165114 EFPH)
4	1	15.8	5	13.8	-12.7	-11.1
			20	13.6	-13.9	-11.2
6	2	16.5	3	14.7	-10.6	-10.1

Table 2: Measurement Results for Out-of-Service and Symmetric In-Service AAs

[9] Percent difference is calculated as 100%*(in-service AA – out-of-service AA)/(out-of-service AA).

To compare the measured and simulated results, column 7 of Table 2 contains the simulated change in worth of each tabulated in-service AA between 31669 EFPH[10] and 165114 EFPH; these values were linearly interpolated from the simulated change in worth between 0 EFPH and 165114 EFPH. The data in columns 6 and 7 suggest the following about the simulated loss of reactivity worth Type 1 and 2 AAs: (1) it is supported by the results of physical measurement, and (2) it may slightly under-estimate the actual loss of reactivity worth.

6.2 Comparison of In-Service AA Measurement and Simulation Results

Table 3 compares the measured and simulated reactivity worths of the in-service AAs. In the table, the AAs are grouped based on symmetrical location in the core.

In-Service AAs in Symmetric Groups	AA Type	(M) Measurement Results (165114 EFPH)			(S) Simulation Results (165114 EFPH)			Difference of Group Ratios (%) ([M-S]/S)
		Individual Rod Worth (%AZL)	Group Average (%AZL)	Ratio: Worth of Group to Group 1b	Individual Rod Worth (mk)	Group Average (mk)	Ratio: Worth of Group to Group 1b	
5	1a (Ti)	13.750	13.650	0.796	0.762	0.767	0.780	2.0
20		13.550			0.771			
12	1b (Ti)	17.000	17.150	1.000	0.984	0.982	1.000	0.0
13		17.300			0.980			
3	2a (Ti)	14.650	15.225	0.888	0.799	0.801	0.816	8.8
22		15.800			0.803			
11	2b (Ti)	17.400	17.900	1.044	0.974	0.970	0.988	5.7
14		18.400			0.967			
2	3a (SS)	9.900	10.188	0.594	0.573	0.561	0.571	4.0
7		10.250			0.542			
18		9.300			0.555			
23		11.300			0.574			
10	3b (SS)	11.600	12.400	0.723	0.702	0.699	0.711	1.7
15		13.200			0.695			
9	4 (SS)	6.050	6.700	0.391	0.373	0.372	0.379	3.2
16		7.350			0.371			

Table 3: Comparison of Measured and Simulated Reactivity Worths of In-Service AAs

[10] AA1 and AA6 were permanently withdrawn from the core on 1996-Apr-17 at 31498 EFPH. AA4 was permanently withdrawn on 1996-May-03 at 31841.1 EFPH. Thus, the average reactor age at time of AA withdrawal is 31669 EFPH.

Columns 3 to 5 of Table 3 contain reactivity worth measurement data (i.e., individual rod worth, symmetric group average worth, and ratio of symmetric group average worth to average worth of symmetric group 1b[11]), while columns 6 to 8 contain the corresponding data from simulation.

Column 9 of Table 3 shows the percent difference[12] between the measured and simulated worth ratios for each symmetric AA group. The measured and simulated group worth ratios exhibit similar characteristics. Ignoring the reference group, the remaining AA groups take the same order when arranged by decreasing ratio, whether based on measured or simulated data; and the magnitudes of the ratios are similar, with the greatest difference being 8.8%. One measurement finding was that the measured average worth of the symmetric group 2b containing AAs 11 and 14 is greater than that of the heaviest simulated group 1b (containing AAs 12 and 13). The positive values in column 9 for all symmetric groups also suggest that the simulation over-predicted the aged reactivity worth of the group containing AAs 12 and 13, relative to other groups.

In other words, the central rods (initially the heaviest and expected to age the quickest) have lost slightly more reactivity than predicted by the initial depletion calculations. The current explanation is that average cell fluxes used for the initial pre-simulations (depletion calculations) were determined using initial (fresh) adjuster properties; self-consistency will need to be achieved in future post-simulations.

Figure 4 graphically presents the measured (blue) and simulated (red) individual AA worth data from Table 3; the y-axis shows the ratio of the AA worth to the sum of the measured or simulated individual in-service AA worths.

The data in Table 3 and Figure 4 suggest that the relative simulated change in worth between the various in-service AAs agrees with measurement, supporting the rates of reactivity worth loss determined in the simulation.

There is an opportunity to improve the accuracy of the simulated AA worths in a post-simulation by accounting for AA aging in the core model, as described above.

[11] The group containing AAs 12 and 13 was arbitrarily chosen as the reference group since these are the heaviest AA rods when fresh; AAs 12 and 13 are the most centrally located, and of the closest proximity of all grouped AAs.
[12] All percent differences are calculated as 100%*(Measured Value – Simulated Value)/(Simulated Value).

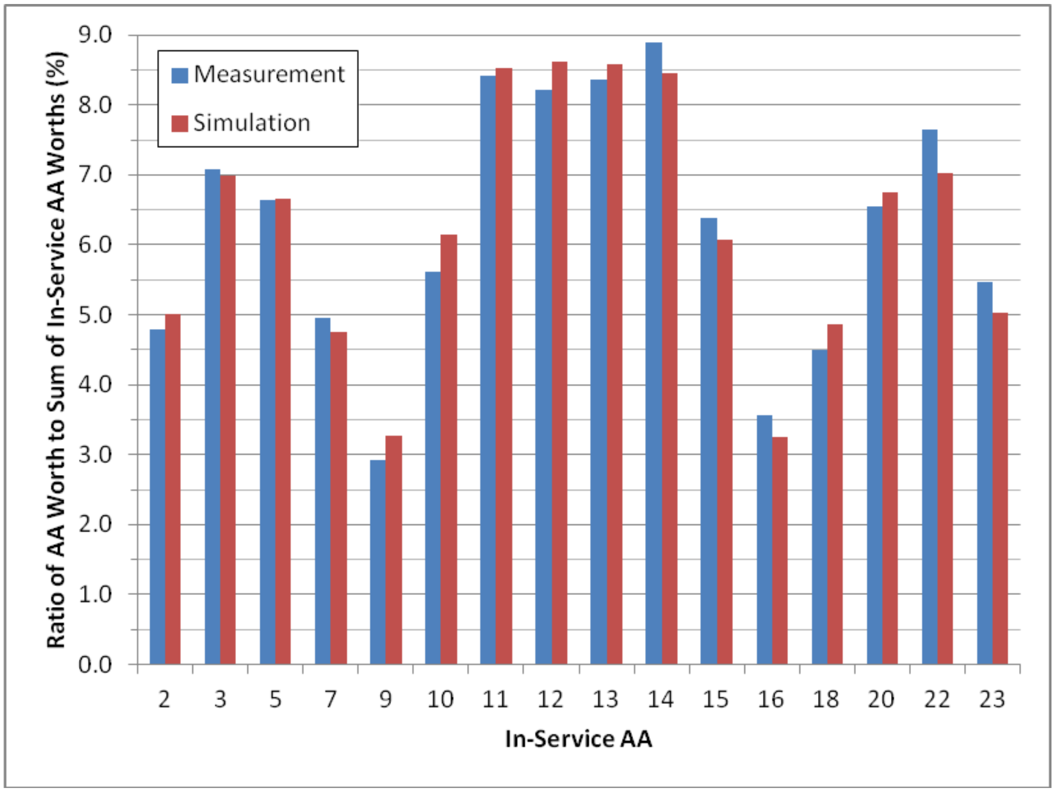

Figure 4: Comparison of Measured and Simulated Reactivity Worths of In-Service AAs

7. Accounting for Adjuster Rod Aging in Core Tracking Simulations

7.1 Routine Core Surveillance

The simulation results, showing the appreciable loss of AA reactivity worth with irradiation, provided an explanation for the slow divergence between routine core surveillance results and the measured FINCH powers discussed in section 2. Since the AA aging simulation predictions were confirmed by the AA worth measurement results, the core models used for core surveillance calculations were modified to introduce irradiation dependence to the AA incremental cross-sections, consistent with the aging simulation (previously, AA properties were fixed at their fresh, non-irradiated values).

The entire production history of each Darlington unit was re-run using the modified models. The percent difference between the SFEs calculated with the modified and original models for each individual FINCH in Unit 2 are plotted against production state (i.e., time) in Figure 5. The systematic change in these parameters is clearly observed. Increasing trends identify channels whose powers were increasingly under-estimated, as the AAs aged, by the core surveillance code with the fresh AA core model; the opposite is true of the decreasing trends.

In Figure 5, increasing trends are observed for centrally located FINCHs nearest to the Type 1 and 2 AAs, which exhibit the highest aging rate. Modelling AA aging (by reducing AA incremental cross-sections upon every SORO run) increases the neutron flux around these AAs, increasing the simulated power of the nearby FINCHs. The decreasing trends of the outer FINCHs is explained by the flux decrease toward the outside of the core when AA aging is accounted for; the faster aging central AAs lead to a higher central flux, thereby suppressing the flux at outer regions of the core. Figure 5 suggests the long-term behaviour of SFE is directly related to the FINCH's distance from the faster aging Type 1 and 2 AAs.

7.2 Safety Analysis

The demonstrated magnitude of the effect of AA aging on device properties is such that it must be considered in the aged core models developed for use in station Safety Analysis. Future analysis will necessarily account for this additional significant aging mechanism.

AA aging has been considered for new analysis in support of shim operation, currently underway for Darlington reactors.

7.3 Unit Refurbishment

Based on simulations and the confirmatory measurements, a decision was made to replace all 16 in-service AAs during unit refurbishment.

8. Conclusion

Overall, the in-service AA worth measurement results support the findings of the pre-simulation, which predict that AA aging can lead to an approximate reactivity worth loss of 16% in the most heavily irradiated rods by the end-of-life of the initial core. This aging mechanism is significant enough that it should be accounted for in core simulations used for both routine core surveillance and safety analysis. It also necessitates the replacement of the AAs as part of reactor refurbishment, to ensure they continue to provide adequate flux flattening and sufficient negative reactivity throughout the lifetime of the refurbished core.

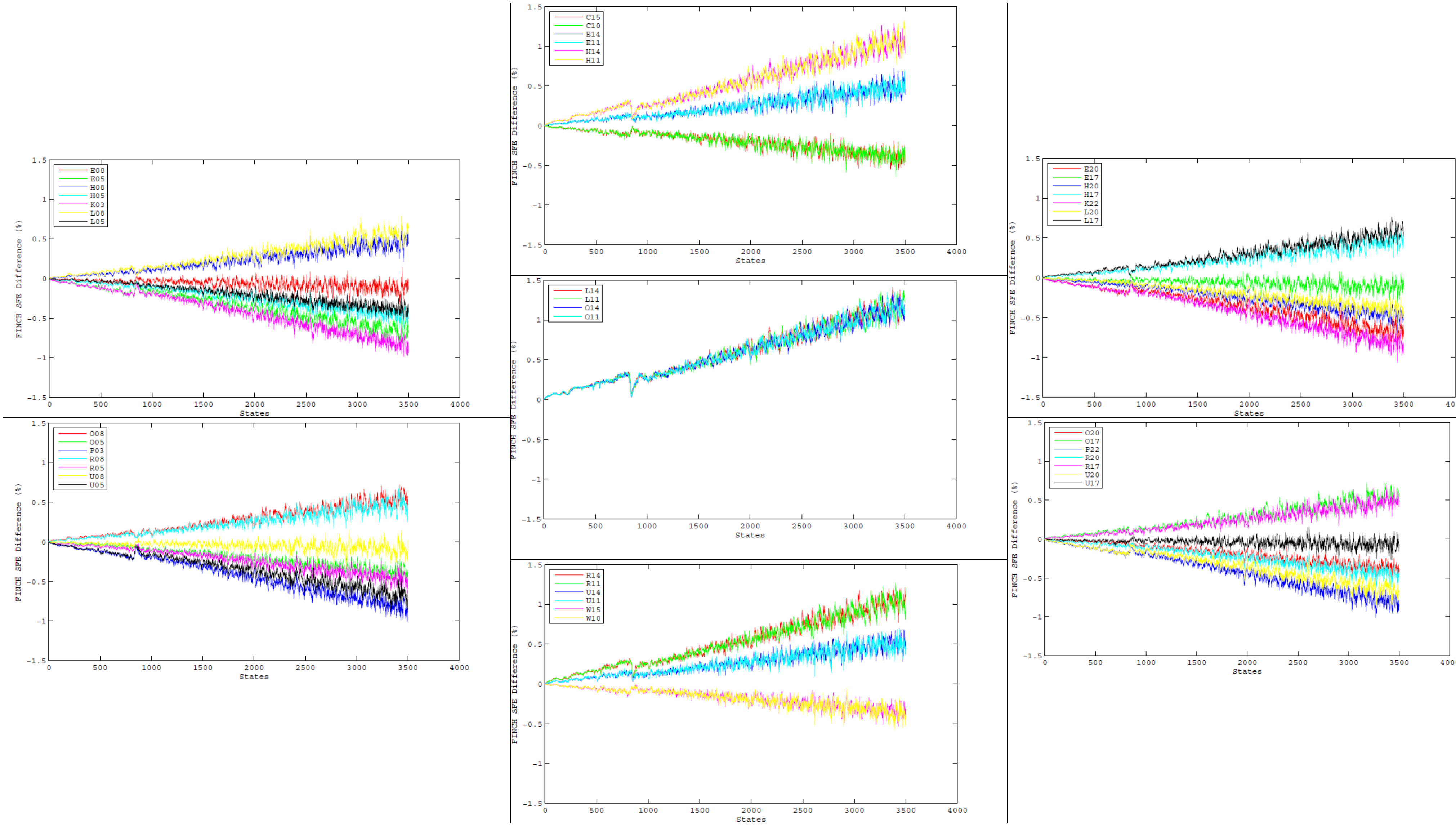

Figure 5: Percent Difference between SFEs Calculated using SORO Models with and without AA Aging over Unit 2 Production History (1990 to 2014)