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Validation of WIMS-AECL/RFSP Analysis of Moderator and Heat-Transport Temperature Reactivity Effects in Darlington Unit 2 During Commissioning

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ABSTRACT

The purpose of this analysis is to validate the calculation of reactivity effects associated with moderator temperature and heat-transport system (HTS) temperature variations relative to zone level changes in Unit 2 of the Darlington Nuclear Generating Station (DNGS). These reactivity effects were measured during Phase-B commissioning, and are here compared with calculations using the Reactor Fuelling Simulation Program (RFSP) and WIMS-AECL. This study is part of the project aimed at validating RFSP with WIMS-AECL-based data for CANDU® reactor analysis.

The temperature coefficients under consideration here have no safety significance, because of their small absolute magnitude, and because of the limited expected range of variation of either the coolant temperature or the moderator temperature during most accident conditions. The internal acceptance criterion at the station for the difference in coefficient value between prediction and measurement is 25%; thus the WIMS-AECL/RFSP results are acceptable.

1. INTRODUCTION

Ontario Power Generation (formerly Ontario Hydro) conducted Phase-B commissioning tests at Darlington Nuclear Generating Station (DNGS) Unit 2 during the commissioning of the reactor. These tests included moderator-temperature and heat-transport system (HTS) temperature reactivity effects. The purpose of the present analysis is to validate the moderator-temperature and HTS-temperature reactivity effects relative to zone level reactivity changes calculated by means of the Reactor Fuelling Simulation Program (RFSP) [1], using fuel tables from WIMS-AECL [2], for Phase-B commissioning conditions. The ENDF/B-V library was used in WIMS-AECL for this analysis.

It is important to note that "Phase-B commissioning" refers to a core with fresh fuel at zero power, where the heat-transport pumps are the only significant sources of heat. Nominal Phase-B commissioning parameters for DNGS Unit 2 are listed in Table 1.

2. METHODOLOGY

In this study, moderator-temperature and HTS-temperature reactivity effects relative to zone level reactivity changes were calculated for DNGS Unit 2 for Phase-B commissioning conditions and results were compared with measurements. Three different fuel types were present in the core during the tests. All fuel bundles were of the 37-element type. Four fuel tables are required for each diffusion calculation: 3 tables for the different fuel types and 1 table for the reflector properties. WIMS-AECL was used to perform the lattice-cell calculations for the different test conditions under consideration.

An operating reactor must always be critical. To maintain criticality, a change in reactivity that is due to a change in moderator temperature or HTS temperature is compensated by a change in average zone level (AZL). This is true as long as there are no other perturbations (such as adjuster-rod movements). Therefore, reactor criticality, which is maintained by balancing the reactivity between AZL and HTS temperature or AZL and moderator temperature, can be used as the basis for error analysis in this study.

2.1 Moderator-Temperature Reactivity Measurements and Calculations

In the tests involving moderator-temperature changes, the moderator temperature was raised from 31.2°C to 56.2°C in steps (shown in Table 2), while keeping the HTS temperature constant at about 265°C. The reactor was maintained critical by changing the zone fills: an increase in the AZL from 34.5% to 67.4% was required to compensate for the above increase in moderator temperature. The moderator-temperature reactivity coefficient is therefore positive under these conditions. This is mainly due to the high poison concentration in the moderator. Table 2 shows the measured values of moderator temperature and AZL for the various cases in the tests.

RFSP simulations, representing the moderator-temperature reactivity measurements, were performed (Table 2, Cases 1, 3-7). The AZL was changed in each simulation accordingly.

If there were perfect agreement between the calculation and the measurements, then the RFSP reactivity (column 4 of Table 2) would be identical in all cases, with each moderator-temperature change being exactly compensated by the corresponding zone-fill change. Any change in the RFSP reactivity (reported as non-zero in column 5 of Table 2) indicates a discrepancy between the simulation and the experiment. To quantify this discrepancy in a relative sense, we need to estimate the moderator-temperature and zone-fill reactivity changes separately.

To estimate the zone-fill reactivity, we used a calculated AZL reactivity coefficient. This coefficient was obtained by a simple RFSP simulation with moderator temperature kept constant at the reference value of 31.2°C while the AZL was increased from 34.5% to 67.4% (Case 2 in Table 2). A similar method was used to calculate the moderator-temperature coefficient of reactivity, where the moderator temperature was increased from 31.2°C to 56.2°C while the AZL was kept constant at 34.5% (Case 8 in Table 2).

The net fractional discrepancy between calculated moderator-temperature reactivities relative to AZL reactivity changes is then the change in RFSP reactivity (column 5 in Table 2) as a fraction of the average of AZL and moderator-temperature reactivity change (average of columns 6 and 7 of Table 2).

2.1.1 Moderator Poison Considerations

Table 1 shows the amount of poison in the moderator during Phase-B commissioning tests. It is important to look at the effect of moderator poison on moderator-temperature reactivity. The reason is that the volumetric concentration of poison changes as the moderator temperature changes. Independent WIMS-AECL/RFSP simulations were performed for moderator boron and gadolinium concentrations of 0 and 1 ppm. The resulting poison reactivity change was then used to estimate the reactivity change due solely to moderator temperature, after subtracting the effect of poison in the moderator. These results are discussed in Section 3.

2.2 Heat-Transport System Temperature Reactivity Measurements and Calculations

In the tests involving HTS-temperature changes, the measurements started at an HTS temperature of 85°C, while AZL was at 55% with all adjuster (ADJ) banks inserted. As the HTS temperature was increased to 135°C in steps (shown in Table 3), the reactor was maintained critical by changing the zone-fills. The AZL decreased to 20% at this time to compensate for the above change in HTS temperature. Thus the HTS-temperature reactivity coefficient is negative under these conditions. When the AZL dropped to 20%, the Reactor Regulating System (RRS) automatically withdrew adjuster (ADJ) bank A [1], which allowed the AZL to rise to 47.4%. The HTS temperature was then raised until it reached 195°C, and the AZL dropped to 18%, while ADJ bank A was out of the core. At this time, ADJ bank B [1] was also withdrawn by the RRS, allowing the AZL to rise to 46.2%. Repeating the same procedure as above, the HTS temperature was increased from 195°C to 265°C, while AZL dropped to 26.3%. Therefore, there are 3 distinct phases to these measurements: with all ADJ banks inserted, with ADJ bank A withdrawn, and with ADJ banks A and B withdrawn. Table 3 shows the measured values of HTS temperature and AZL for the various cases in the tests.

RFSP simulations, representing the HTS-temperature reactivity measurements, were performed (Table 3, Cases 1, 3-7, 9, 11-16, 18 and 20-26). The zone levels were changed in each simulation accordingly.

As before, if there were perfect agreement between the calculation and the measurements, then the RFSP reactivity (column 5 of Table 3) would be identical in all cases, with each HTS-temperature change being exactly compensated by the corresponding zone-fill change. Any change in the RFSP reactivity (reported as non-zero in column 6 of Table 3) indicates a difference between the simulation and the experiment. To quantify this difference in a relative sense, we need to estimate the HTS-temperature and zone-fill reactivity changes separately.

To estimate the zone-fill and HTS-temperature reactivities, we used the appropriate calculated reactivity coefficient. These coefficients were obtained using a method similar to that described in Section 2.1 (See Table 3).

The net fractional discrepancy between calculated HTS-temperature reactivities relative to AZL reactivity changes is then the change in RFSP reactivity (column 6 in Table 3) as a fraction of the average of AZL reactivity change and HTS-temperature reactivity change (average of columns 7 and 8 of Table 3).

3. RESULTS

The results of moderator-temperature and HTS-temperature reactivity calculations are presented in Tables 2 and 3, as well as in Figures 1 and 2, respectively.

3.1 Moderator-Temperature Reactivity

The AZL reactivities, for the moderator temperature case, were calculated using the simulations described as Case 2 in Table 2. This simulation results in a net reactivity decrease of 2.27 milli-k. Therefore, the AZL reactivity coefficient is about – 0.069 milli-k/%AZL. This value was used to calculate the AZL reactivities shown in Table 2. Similarly, Case 8 in Table 2 results in a net reactivity increase of 1.79 milli-k, resulting in a moderator-temperature reactivity coefficient of 0.072 milli-k/°C. This value was used to calculate the moderator-temperature reactivities shown in Table 2.

The discrepancies in calculated moderator-temperature reactivities relative to AZL reactivity changes are shown in the last column of Table 2. The results indicate that the moderator-temperature reactivities are underestimated by about 16% to 25% (average discrepancy of 23%).

Figure 1 shows that as the moderator temperature is increased the moderator-temperature reactivity also increases, while the AZL reactivity decreases. Table 2 shows that the discrepancy in moderator-temperature reactivity increases as moderator temperature is raised.

The effect of moderator poison on reactivity is also an important consideration. Independent WIMS-AECL/RFSP simulations were performed to calculate the coefficients of reactivity for boron and gadolinium, which were found to be −8.36 milli-k/ppm and −29.15 milli-k/ppm, respectively. Using poison concentrations from Phase-B conditions (Table 1), the total reactivity due to boron and gadolinium is calculated to be −74.97 milli-k.

It should be noted that as the moderator density changes, so does the poison volumetric density (while the poison concentration in ppm of course remains constant). Results show that poison densities vary by about 1% during the commissioning tests. Therefore, about 0.75 milli-k (= 0.01 x 74.97 milli-k) of moderator-poison reactivity change is due to the reduction in moderator density. In other words, about 40% of the moderator temperature reactivity (Table 2, Case 8) is associated with the change in poison density.

3.2 HTS-Temperature Reactivity

There were 3 separate sets of adjuster-rod configurations during the HTS-temperature reactivity measurements. Therefore, in the HTS-temperature reactivity calculations, we need to take the adjuster rods into account. Since calculation of adjuster-rod worth is not part of this study, the net reactivity for each of the 3 parts of this experiment was calculated separately (with all adjusters in-core, adjuster bank A withdrawn, and adjuster banks A and B withdrawn), using the initial configuration in each case for the reference reactivity. These 3 distinct parts are shown in Figure 2.

A method similar to that used in the moderator-temperature section, above, was used to calculate the AZL and HTS-temperature reactivities during the HTS reactivity measurements. It should be noted, however, that 3 separate AZL and HTS-temperature reactivity coefficients were calculated, corresponding to the 3 different adjuster-bank configurations. The AZL and HTS-temperature reactivity coefficients, along with the results of simulations at each HTS temperature, are shown in Table 3.

Figure 2 shows that, as the HTS temperature is increased, the HTS-temperature reactivity decreases while the AZL reactivity increases. As expected, the AZL reactivity coefficient increases as more adjuster banks are withdrawn from the core at higher HTS temperatures.

The results for the HTS-temperature reactivity (Table 3) were categorized into 3 separate sets, corresponding to the 3 different adjuster-bank configurations. These results indicate that for HTS temperature = 85°C to 135°C, the reactivities are overestimated by 38% to 14% (average value of 23%); for HTS temperature = 135°C to 195°C, the reactivities are overestimated by 20% to 0.4% (average value of 9%); and finally for HTS temperature = 195°C to 265°C, the reactivities are overestimated by 61% to 16% (average value of 27%). On the average, the HTS-temperature reactivities relative to AZL reactivity changes are overestimated by about 20%.

Note that the temperature coefficients discussed here are of small magnitude: approximately 0.07 milli-k/^{o}C for the moderator temperature, and approximately –0.02 to –0.04 milli-k/^{o}C for the HTS temperature. Thus their significance is minor, either in normal operation or even in accidents.

4. CONCLUSIONS

The temperature coefficients under consideration here have no safety significance, because of their small absolute magnitude, and because of the limited expected range of variation of either the coolant temperature or the moderator temperature during most accident conditions.

The results of reactivity calculations indicate that the moderator-temperature reactivities relative to AZL reactivity changes are, on the average, underestimated by about 23%, and that the HTS temperature reactivities relative to AZL reactivity changes are overestimated by about 20%. The internal acceptance criterion at the station for the difference in coefficient value between prediction and measurement is 25%; thus the WIMS-AECL/RFSP results are acceptable. This acceptance criterion recognizes the low safety significance of these coefficients and the difficulty in measuring them very accurately in power reactors, since the reactivity changes are small and the measurements are not made in the controlled conditions of a research reactor.

Please note that there are uncertainties in zone-controller level measurements and their nuclear properties which have a significant impact on the measurement of changes in reactivity.

It should be noted that during Phase-B commissioning conditions there is a relatively high concentration of neutron poisons in the moderator, which significantly affect moderator temperature coefficients. Separate validation is required for configurations with low moderator poison concentration and with equilibrium fuel.

The author would like to acknowledge that the data for this work was provided by Ontario Power Generation (formerly Ontario Hydro).

5. REFERENCES

1) B. Rouben, “An Overview of Current RFSP Code Capabilities for CANDU Core Analysis”, AECL Report AECL-11407, 1996 Jan.

2) J. V. Donnelly, “WIMS-AECL: A User’s Manual for the Chalk River Version of WIMS-AECL”, AECL Report AECL-8955, 1986.

Table 1: Nominal Phase-B Commissioning Parameters

Parameter	Value
Moderator Temperature (°C)	31.2
Coolant Temperature (°C)	265.0
Fuel Temperature (°C)	265.0
Moderator Boron Concentration (ppm)	0.18
Moderator Gadolinium Concentration (ppm)	2.52
Moderator Purity (atom %)	99.95
Coolant Purity (atom %)	98.75

Table 2: Results of Moderator-Temperature Reactivity Calculations

Case	Meas. Mod. T (°C)	Meas. AZL (%)	System Reactivity in RFSP (mk)	Net Reactivity Change in RFSP (mk)	Estimated AZL Reactivity Change (from Coefficient) (mk)	Estimated Mod. Temperature Reactivity Change (from Coefficient) (mk)	Discrepancy (%)
1	31.2	34.5	-11.87	0	0	0	0
3	36.5	40.9	-11.93	-0.07	-0.44	0.38	16.3
4	41.2	47.3	-12.06	-0.19	-0.88	0.72	23.9
5	46.2	54.0	-12.18	-0.31	-1.34	1.07	25.6
6	51.2	60.5	-12.28	-0.41	-1.79	1.43	25.7
7	56.2	67.4	-12.37	-0.51	-2.27	1.79	25.0
Cases 1 and 2 were used to calculate the AZL coefficient of reactivity = – 0.069 milli-k/%AZL Cases 1 and 8 were used to calculate the moderator-temperature coefficient of reactivity = + 0.072 milli-k/°C							
1	31.2	34.5	-11.87	0	0	0	0
2	31.2	67.4	-14.13	-2.27	-2.27	0	---
8	56.2	34.5	-10.08	1.79	0	1.79	---

Table 3: Results of Heat-Transport Temperature Reactivity Calculations

Case	Meas. HTS T (°C)	ADJ Conditions	Meas. AZL (%)	System Reactivity in RFSP (mk)	Net Reactivity Change in RFSP (mk)	Estimated AZL Reactivity Change (from Coeff.) (mk)	Estimated HTS Reactivity Change (from Coeff.) (mk)	Discrepancy (%)
1	85	All in	55.0	-7.68	0	0	0	0
3	95	All in	45.0	-7.47	0.22	0.70	-0.43	38.2
4	105	All in	38.0	-7.42	0.26	1.20	-0.87	25.6
5	115	All in	32.0	-7.42	0.26	1.62	-1.30	18.0
6	125	All in	25.0	-7.33	0.36	2.11	-1.74	18.6
7	135	All in	20.0	-7.37	0.32	2.47	-2.17	13.7
9	135	Bank A Out	47.4	-7.41	0	0	0	0
11	145	Bank A Out	41.0	-7.32	0.08	0.46	-0.36	20.5
12	155	Bank A Out	37.0	-7.37	0.03	0.75	-0.71	4.4
13	165	Bank A Out	31.0	-7.26	0.14	1.19	-1.07	12.6
14	175	Bank A Out	26.0	-7.20	0.20	1.55	-1.43	13.8
15	185	Bank A Out	22.0	-7.39	0.02	1.84	-1.78	1.0
16	195	Bank A Out	18.0	-7.40	0.01	2.13	-2.14	0.4
18	195	Banks A & B Out	46.2	-7.64	0	0	0	0
20	205	Banks A & B Out	39.7	-7.44	0.20	0.49	-0.18	61.2
21	215	Banks A & B Out	36.7	-7.45	0.19	0.71	-0.36	35.1
22	225	Banks A & B Out	34.5	-7.50	0.14	0.87	-0.54	19.3
23	235	Banks A & B Out	31.4	-7.46	0.18	1.11	-0.72	20.1
24	245	Banks A & B Out	28.4	-7.38	0.26	1.33	-0.90	23.2
25	255	Banks A & B Out	27.6	-7.44	0.20	1.39	-1.08	16.2
26	265	Banks A & B Out	26.3	-7.41	0.22	1.49	-1.26	16.4
AZL coefficient of reactivity = - 0.071 milli-k/%AZL (from Cases 1 and 2) (all ADJs in) HTS-temperature coefficient of reactivity = - 0.043 milli-k/°C (from Cases 1 and 8) (all ADJs in)								
1	85	All in	55.0	-7.68	0	0	0	0
2	85	All in	20.0	-5.22	2.47	2.47	0	-----
8	135	All in	55.0	-9.86	-2.17	0	-2.17	-----
AZL coefficient of reactivity = - 0.072 milli-k/%AZL (from Cases 9 and 10) (ADJ bank A out) HTS-temperature coefficient of reactivity = - 0.036 milli-k/°C (Cases 9 and 17) (ADJ bank A out)								
9	135	Bank A Out	47.4	-7.41	0	0	0	0
10	135	Bank A Out	18.0	-5.28	2.13	2.13	0	-----
17	195	Bank A Out	47.4	-9.55	-2.14	0	-2.14	-----
AZL coefficient of reactivity = - 0.075 milli-k/%AZL (form Cases 18 and 19) (ADJ banks A and B out) HTS-temperature coefficient of reactivity = - 0.018 milli-k/°C (from Cases 19 and 26) (ADJ banks A and B out)								
18	195	Banks A & B Out	46.2	-7.64	0	0	0	0
19	195	Banks A & B Out	26.3	-6.15	1.49	1.49	0	-----
26	265	Banks A & B Out	26.3	-7.41	0.22	1.49	-1.26	-----

Figure 1: Reactivity Change (mk) vs. Moderator Temperature (°C)

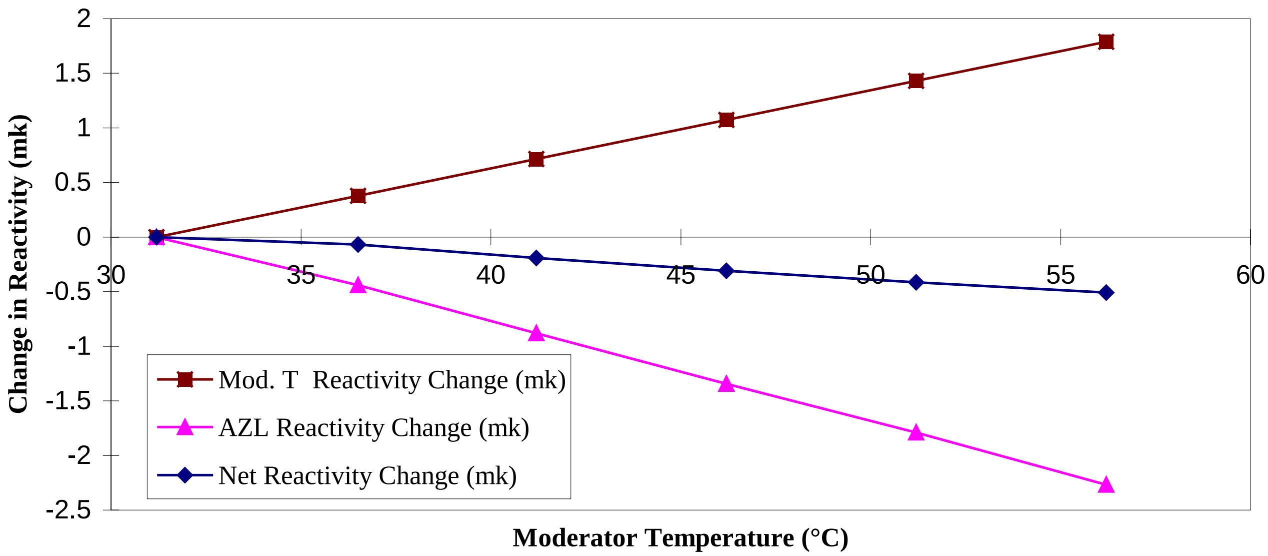

Figure 2: Reactivity Change (mk) vs. HTS Temperature (°C)