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Validation of Moderator-Level Reactivity Coefficient Using Station Data

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Abstract

The reactivity effect due to variations in the moderator level has been recognized as a reactor-physics phenomenon of importance during normal operation and accident analysis. The moderator-level reactivity coefficient is an important parameter in safety analysis of CANDU reactors, e.g., during Loss of Moderator Heat Sink as well as in the simulation of Reactor Regulating System action in CANDU reactors that use moderator level for reactivity control.

This paper presents the results of the validation exercise of the reactor-physics toolset using the measurements performed in Pickering Unit 4 in 2003. The capability of the code suite of predicting moderator-level reactivity effect was tested by comparing measured and predicted reactor-physics parameters.

Keywords: Code Validation, Reactor Physics Toolset, Moderator level

1. Introduction

The objective of this study is to validate the current reactor-physics code suite (RFSP/WIMS/DRAGON) against CANDU station data, and in particular the code prediction of the moderator-level reactivity effects. The results of the current validation exercise will address, at least in part, the validation gap of predicting the moderator-level reactivity effect.

In particular, the observed changes in reactivity induced by moderator-level changes were compared with those predicted by the reactor-physics code suite. The magnitude of reactivity insertion due to this effect was quantified by measuring the amount by which the Liquid Zone Control (LZC) level and hence the system reactivity was altered by the Reactor Regulating System (RRS) to maintain reactor criticality and keep reactor power at its setpoint.

2. Data Collection Requirements

As the moderator level changes in a CANDU reactor, the RRS acts to maintain a constant reactor power by adjusting LZC levels to compensate for the reactivity change due to the change in moderator level.

The calculation uncertainty increases with each additional reactivity effect that contributes to the overall core reactivity. Therefore, an effort was exercised during data collection in order to reduce the sources of uncertainty in the measured and predicted parameters contributing to core reactivity change during the moderator-level maneuver. This was achieved by keeping, as much as possible, the parameter changes to a minimum.

Specifically, during the measurements, the following conditions were observed:

1) Power changes and power maneuvers were avoided during the measurements. Therefore, there was no need to account for the reactivity effect associated with concentration changes of the saturating fission products.

2) Moderator-poison concentration was kept unchanged by valving out the moderator ion-exchange columns and by avoiding poison additions to the moderator. Removal of contaminants from either the Heat Transport System (HTS) or the moderator was avoided by shutting off the purification system.

3) Coolant and moderator isotopic purities were kept unchanged by avoiding any D_2O upgrading or downgrading of either the HTS or the moderator system.

4) Moderator temperature was controlled and kept constant during reactor operation at power.

5) The reactivity devices (other than the LZC) such as the adjuster rods and shutoff rods were kept in their normal locations in or out of the core during the measurements.

Therefore, the only parameters that were allowed to change during the moderator-levelmaneuver were the moderator level and the LZC levels. This allowed inferring the moderator-level reactivity coefficient from the measured change in moderator level and the compensatory change in the LZC levels. The sources of measurement uncertainty in the validation exercise was then limited to those due to the measurements of these two parameters.

3. Site Measurements

Measurements taken during Pickering AUnit 4 moderator-level maneuver were received from OPG, processed, and reviewed prior to its use in the current validation exercise (Reference [1]). These measurements were checked to ensure their consistency and completeness, and were then converted into an appropriate format that allows their use in the validation exercise.

3.1. Moderator and Zone Levels

The moderator-level measurements plotted in Figure 1 shows that the moderator level is decreased from approximately 7.95 m to 7.27 m over a time span of about 27 minutes. The level is held at the 7.27m level for approximately 13 minutes and then increased back to the original level in 5 minutes. The corresponding changes in AZL is also shown in.Figure 1**.** As expected, the changes in moderator level and zone level are consistent. As moderator level was decreased (or increased), the RRS acted by decreasing (or increasing) the LZC level in order to maintain criticality and keep reactor power at its setpoint.

3.2. Detector Flux Readings

The readings of the RRS in-core flux detectors and the Shutdown System A (SDSA)ion-chambers were also collected. As expected, thein-core detector readings decreased for detectors located at the top of the calandria and increased for detectors at the bottom, as the moderator level was reduced.

3.3. Other Reactor-Physics Parameters

The following is a summary of the other measurements taken during the moderator-level maneuver:

- The power setpoint and the linear power were held almost constant throughout the maneuver at approximately 28 % FP.
- The average coolant temperature was held almost constant, with temperature variations of about 1 ^{O}C throughout the duration of the moderator-level maneuver.Similarly, the average moderator temperature varied by less than 1 ^{O}C throughout the duration of the moderator-level maneuver.
- Moderator isotopic purity is relatively constant at 99.94 wt% based on three measurements over the course of a 17 day period,which spanned the duration of the moderator-level maneuver. HTS coolant purity measurement at approximately 22 hours before the test is considered applicable to the model level measurements. The coolant purity measured at that time was 99.19 wt%.
- The closest measurement of moderator boron concentration was taken minutes before the start of the moderator-level maneuver and there was no gadolinium present in the moderator in Pickering Unit 4 at the time of moderator-level maneuver.

4. Analysis Methodology and Assumptions

4.1. Analysis Methodology

The *SIMULATE module of the RFSP code (Reference [2]) was used to simulate the reactor conditionsduring moderator-level maneuver. This was done by simulating sets of pairs of reactor critical states: one before and one after amoderator-level change. The change in the measured LZC levels due to moderator-level change was used to calculate the reactivity change that was compared with the change in the predicted reactivity. The reactor condition that exists before the measurements was determined and used as the starting condition for the simulation using the reactor-physics codes.

The following steps were used in the RFSP simulation:

1. The simulation was started from equilibrium steady-state operating conditions using the Reference Data Set (RDS) of Pickering NGSA. The *SIMULATE module was used to produce the steady-state equilibrium conditions.

2. Operating conditions before and after a change in the moderator level took place (LZC levels, coolant and moderator temperatures, coolant density, coolant and moderator isotopic purities, moderator poison concentration, and locations of reactivity devices) were used as input to RFSP and the excess reactivity was calculated, as a rationality check of the RFSP model. Ideally, the predicted excess reactivity should be equal or close to zero.

3. The instantaneous fuel burnup (or irradiation) distribution that exists at the beginning of the moderator-level maneuver obtained from the Simulation of Reactor Operation code (SORO),

Reference [3], was used in order to model the power distribution as close as possible to the power distribution that exists at the time of the measurements.

4. Production of the basic cell nuclear cross sections using the WIMS code (Reference [4]) and Simple Cell Model, SCM (Reference [5]) used in the RFSP simulations were calculated to cover the range of parameters that existed before and after the moderator-level change. The incremental cross sections of the major reactivity devices located in the core during the measurements previously calculated, using DRAGON (Reference [6]), were used in the RFSP simulation.

5. The change in the moderator level was simulated in the RFSP model using two methods (Reference [7]): the Vacuum Boundary (VB) method and the fictitious Black Absorber (BA) method.

In the VB method, the plane where the neutron flux goes to zero is specified, with no extrapolation factor accounted for. Since the moderator-level maneuver took about 1 hour to execute, the power shape is expected to somewhat change due to changes in the corresponding xenon redistribution. To estimate the effect of xenon, two cases with the VB method were considered: one with xenon distribution kept unchanged (i.e. fuel compositions were not recalculated during the transient) and another with the fuel allowed to burn (hence xenon redistribution).

In the BA method, values of the black incremental absorption cross sections were obtained by multiplying the incremental absorption cross sections of the Shutoff Absorber (SA) by a factor of 100.

The corresponding predicted change in zone levels to keep the reactor critical as well as flux values interpolated at the locations of the in-core and out-of-core flux detectors were extracted from RFSP simulation results.

6. The changes in the measured LZC level experienced due to moderator-level changes was used to calculate the corresponding reactivity changes, which was then compared with the changes in reactivity predicted by RFSP.

7. In addition, the calculated and measured detector readings of the in-core and out-of-core flux detectors were also compared.

8. The zone-level reactivity worth was determined by simulating the draining of all zones simultaneously and calculating the change in the eigenvalue. The results of the LZC reactivity worth calculation are summarized in Figure 2. In the AZL range between 50% and 80%, the reactivity variation is linear and the slope of the reactivity was calculated as 0.035597 mk/%. This zone-level range was selected since it bounds the measured values of AZL in the current validation exercise.

9. Similarly, the moderator-level reactivity worth was calculated by simulating the draining of the moderator and calculating the change in the eigenvalue, using the vacuum boundary method. Moderator-level data between 7200 and 8000 mm were used in the analysis, which encompasses the range of Pickering A moderator-level measurements. Figure 3 shows the RFSP-predicted reactivity change due to moderator-level change.

The following second-order polynomial fit was used to quantify the RFSP-predicted change in reactivity as a function of moderator level:

$$y = -1.6699\text{E-06}\,(\text{ML})^2 + 2.6716\text{E-02}\,(\text{ML}) - 1.0683\text{E+02}$$

where

y = is the change in reactivity

ML = is the moderator level

A value of zero was used instead if the polynomial predicted a positive reactivity change (for moderator levels greater than approximately 7872 mm), which is an artifact of the polynomial fit and not an indication of RFSP predictions.

As expected, the reactivity effect due to moderator-level change is non-linear. Initially, reactivity change per unit change in moderator level is small, as the moderator-level change occurs in the reflector region where neutron flux importance is relatively small. As moderator-level gets closer to the fuel region, neutron flux importance becomes higher and the corresponding reactivity change per unit moderator-level change becomes larger.

*4.2. **Analysis Assumptions***

The following assumptions were made in the RFSP simulation:

1. The average moderator temperature was calculated from the arithmetic averaging of the measured inlet and outlet moderator temperatures. Similarly, the average coolant temperature was calculated from arithmetic averaging of the measured inlet and outlet header temperatures.

2. HTS coolant density was calculated from the measured HTS coolant temperatures and pressures by interpolating the property tables for heavy water documented in Reference [8].

3. The fuel temperature wascalculated internally by the RFSP code using the appropriate built-in fuel temperature-bundle power correlation for the 28-element fuel bundle.

4. The coolant density and coolant temperature were assumed to be uniform throughout the core in the *SIMULATE calculations. This simplifying assumption is considered acceptable since the effect of changing the moderator level (at the top of the calandria) is not expected to be significantly affected by the non-uniformity of the coolant temperature and density in the core. Similarly, the moderator temperature was also assumed spatially uniform.

5. The change in fuel burnup was considered to be negligible during the period between each two critical reactor states. This is a valid assumption since the measurements are to be taken over a short period of time. However, the maneuver was simulated both with and without fuel burnup.

6. Moderator temperature is effectively controlled at high temperatures and kept constant and stable throughout the measurements. This assumption was confirmed by the measurements.

7. Only static detector response was calculated in RFSP, i.e., no detector dynamics were accounted for in the RFSP calculations. As a result, in-core detectors should be expected to respond faster in RFSP simulations than in the measurements as they have some delays. However, ion chamber response in measurements and RFSP simulations are less affected by this assumption as the ion chambers are more prompt.

4.3. *Computer Codes and Platform*

The following are the code versions that were used in the current simulation:

- RFSP Code: Version rfsp-ist.REL_3-04-05LIN (Reference [3]).
- WIMS: Version 2-5d with Nuclear Data Library ENDF-B/VI (Reference [4]).
- WIMS Utilities: Version 2.0.1.2 (Reference [5]).

5. Results

5.1. *Channel Power Distribution*

A comparison is made between the channel power distribution predicted by RFSP using the SORO burnup (irradiation) distribution and the corresponding power distribution extracted from SORO output. The comparison showed that the calculated percentage differences in channel powers across the core have maximum and minimum values of 5.8 % and -3.1 %, respectively, with the differences in the central core region are of the order of 1 to 3%. This confirms the validity of the use of the SORO fuel irradiation distribution in the RFSP model

5.2. *Core Reactivity*

At any time during moderator-level maneuver, the reactor was critical. Calculated criticality discrepancies are due to:

- Systematic error related to uncertainty in the initial conditions,
- Accuracy of the nuclear data and reactor model, and
- Error in the reactivity variation related to the accuracy of the transient prediction.

Table 1summarizes the average reactivity variation and standard deviation during moderator-level maneuver. The table demonstrates that the three methods used in RFSP modeling of moderator-level change predicted about the same reactivity at the beginning of moderator-level maneuver of about -3.15 mk. The three methods also predicted about the same average reactivity variation during the maneuver (-0.07mk to -0.09 mk). Table 1 also demonstrates that there is a small improvement in reactivity prediction when fuel burnup during the transient is calculated. With the use of the black absorber method, spikes in the reactivity variation were observed and can be attributed to the smearing effect when moderator level crosses RFSP model mesh planes in the vertical direction.

5.3. *Detector Readings*

Tables 2 to 4 show the percentage differences between the measured and predicted detector ratios for the three methods used in modeling moderator-level changes in RFSP. The detector ratios are defined here as the ratio between the normalized detector readings after and before the moderator level is reduced by 70 cm and the ratio between the normalized detector readings after and before the moderator level is later increased by 70 cm.

Figure 4 shows a comparison of measured readings of one of the in-core detectors within NFM5 and Figure 5shows the measured readings from an ion chamber AV02E (ICB) during the moderator-level maneuver together with the corresponding predicted values assuming vacuum boundary method, with fuel burnup accounted for. Note that both in-core and out-of core detectors (NFM5-H6 and AV02E) are located in the bottom half of the core: NFM5-H6 is about 160 cm below the center of the core, whereas AV02E is 280 cm below the center of the core.

6. Conclusions

The following conclusions can be drawn from the current validation exercise:

- There is a good agreement between the measured and calculated reactivity.
- The best method for simulating moderator-level changes is the vacuum boundary method. The average reactivity difference is -0.07 ± 0.03 mk for a 70 cm moderator level movement to and from full.
- The reactivity difference is -0.09 ± 0.09 mk when black absorber is used to simulate moderator-level changes for a 70 cm moderator level movement to and from full.Smearing effect due to black absorber crosses RFSP model mesh planes in the vertical direction introduced errors. Therefore, it is not recommended to use the BA method for cases when moderator level does not coincide with mesh planes in the vertical direction.
- When the effect of the fuel burnup was accounted for in the simulations, little improvement in residual reactivity was realized. As expected, xenon effects during moderator-level maneuver had a small impact on core reactivity and detector responses, with the VB method.
- There is a good agreement in measured and calculated detector responses. With the best method (vacuum boundary and fuel burns during the transient) the average difference in the detector response is 0.14 ± 0.51 (%).

In summary, we conclude that the good agreement between the predicted and measured reactivity effect and responses of in-core and out-of-core detectors with small prediction bias demonstrated the capability of the reactor-physics codes of predicting moderator level reactivity effect in CANDU reactors.

7. Acknowledgement

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8. References

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Table 1: Reactivity Variation during Moderator-Level Maneuver

Case Description	Calculated Reactivity (mk)	Average reactivity variation during the transient (mk)	Standard Deviation (mk)
Moderator Level Simulated as Vacuum Boundary	-3.15	-0.07	0.03
Moderator Level Simulated as Black Absorber	-3.15	-0.09	0.09
Moderator Level Simulated as Vacuum Boundary with No Fuel Burnup	-3.14	-0.08	0.04

Table 2: Comparison between Measured and Predicted Detector Ratios

Vacuum Boundary Method

	Detector Ratios - Moderator Level Down by ~70 cm		Detector Ratios - Moderator Level Up by ~70 cm		Difference in detector ratios (%), Moderator Level Down by 70 cm	Difference in detector ratios (%), Moderator Level Up by 70 cm	Average difference in detector ratios (%)
	Measurements	Calculations	Measurements	Calculations			
Average	1.021	1.022	1.017	1.019	0.05	0.24	0.14
Standard Deviation	0.061	0.062	0.053	0.054	0.56	0.49	0.51

Table 3: Comparison between Measured and Predicted Detector Ratios

Vacuum Boundary Method with No Fuel Burnup during Transient

	Detector Ratios - Moderator Level Down by ~70 cm		Detector Ratios - Moderator Level Up by ~70 cm		Difference in detector ratios (%), Moderator Level Down by 70 cm	Difference in detector ratios (%), Moderator Level Up by 70 cm	Average difference in detector ratios (%)
	Measurements	Calculations	Measurements	Calculations			
Average	1.021	1.021	1.017	1.021	0.01	0.33	0.17
Standard Deviation	0.061	0.058	0.053	0.057	0.75	0.58	0.51

Table 4: Comparison between Measured and Predicted Detector Ratios

Black Absorber Method

	Detector Ratios - Moderator Level Down by ~70 cm		Detector Ratios - Moderator Level Up by ~70 cm		Difference in detector ratios (%), Moderator Level Down by 70 cm	Difference in detector ratios (%), Moderator Level Up by 70 cm	Average difference in detector ratios (%)
	Measurements	Calculations	Measurements	Calculations			
Average	1.021	1.023	1.017	1.021	0.16	0.34	0.25
Standard Deviation	0.061	0.069	0.053	0.061	1.04	0.93	0.97

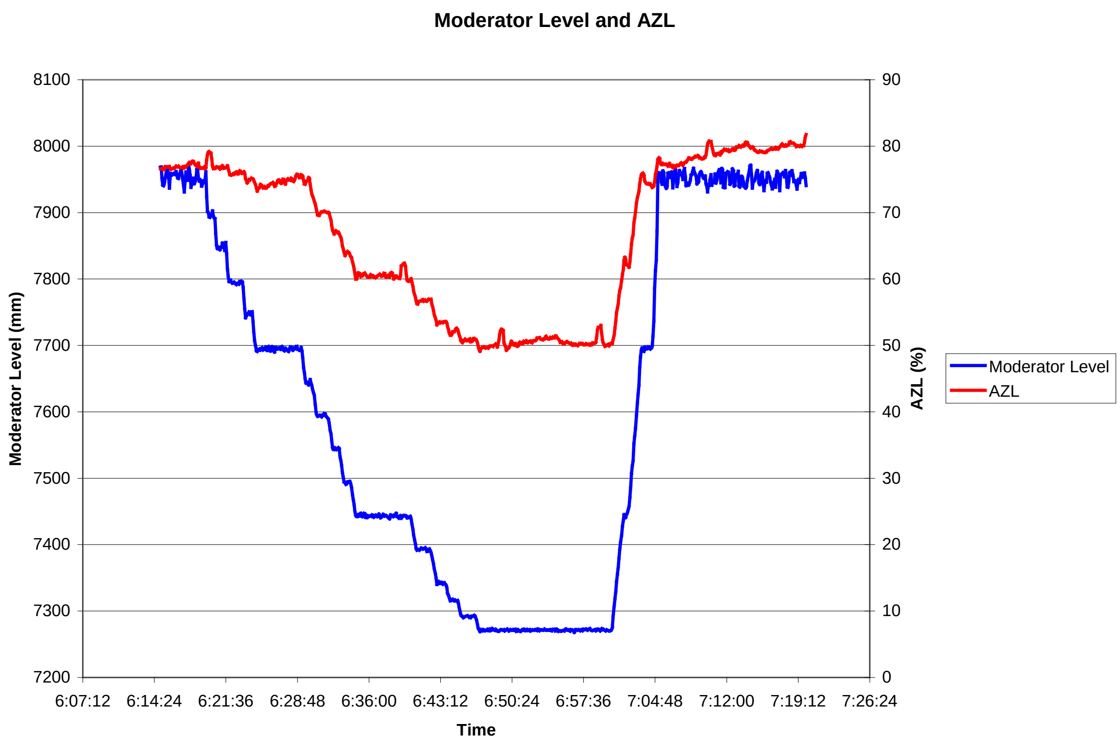

Figure 1: AZL and Moderator Level

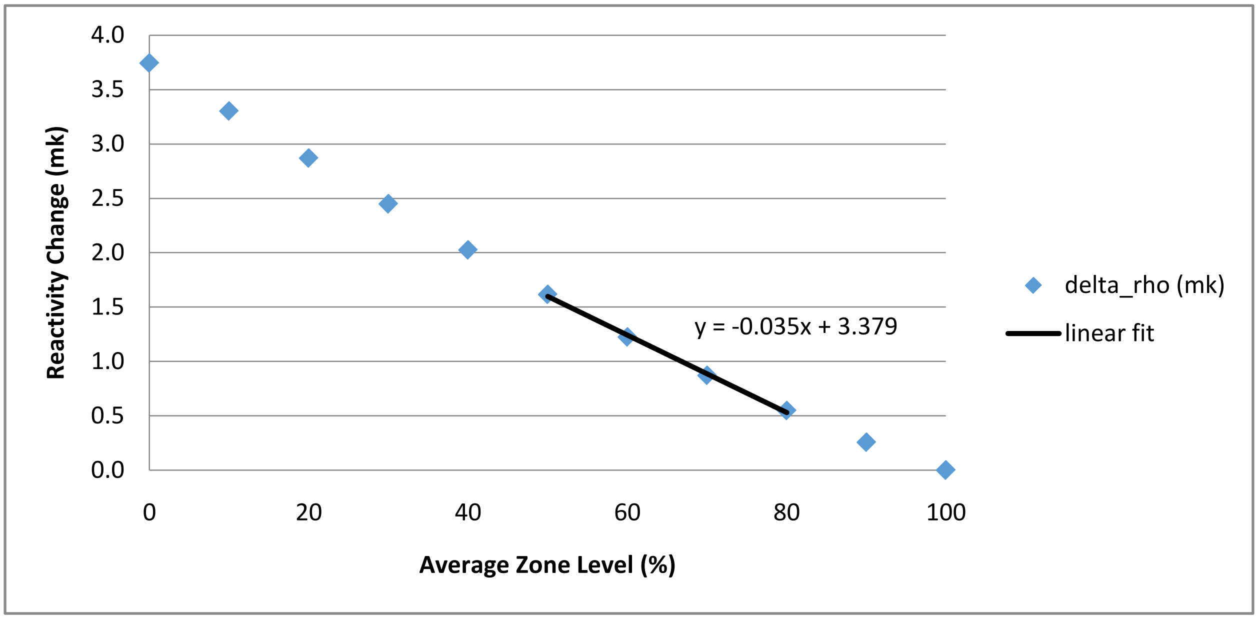

Figure 2:RFSP-Predicted Reactivity Change as a Function of AZL

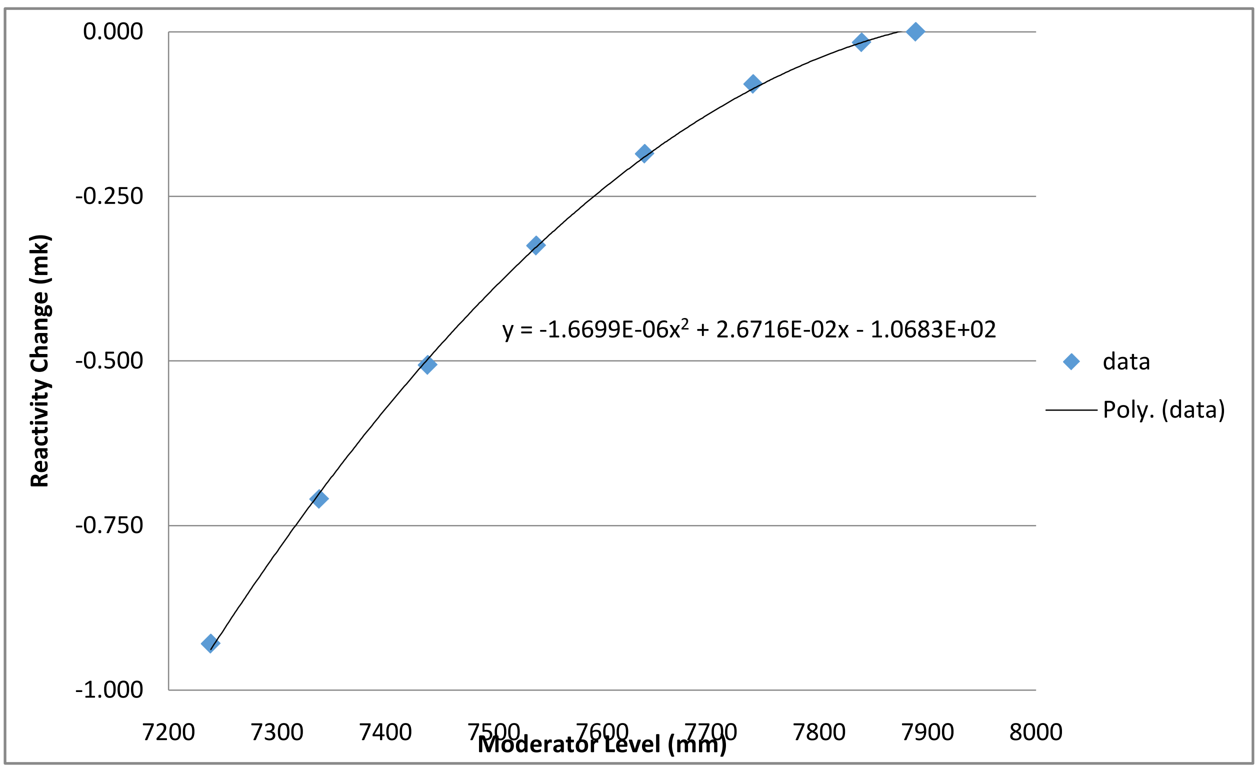

Figure 3: RFSP-predicted Reactivity Changes as a Function of Moderator-Level

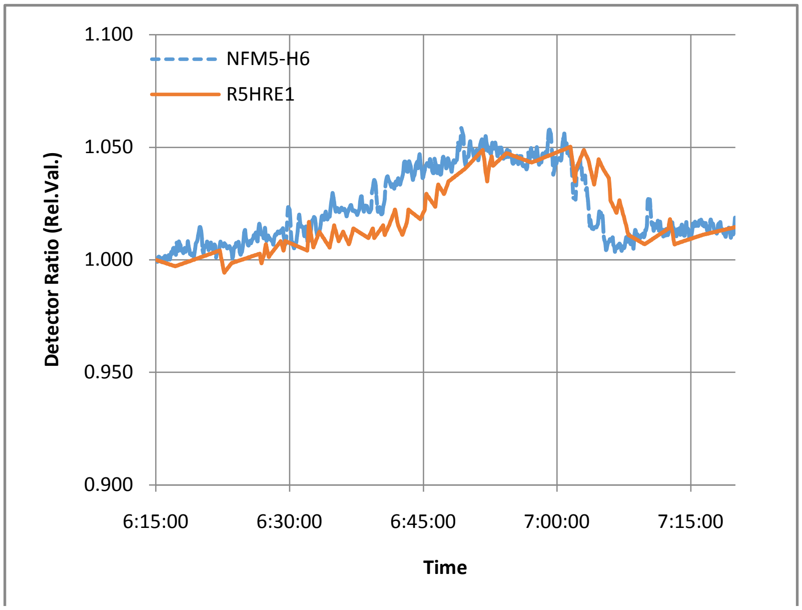

Figure 4: Measured and Calculated Detector Readings during Moderator-Level Maneuver - Detector NFM5-H6 (R5HRE1)

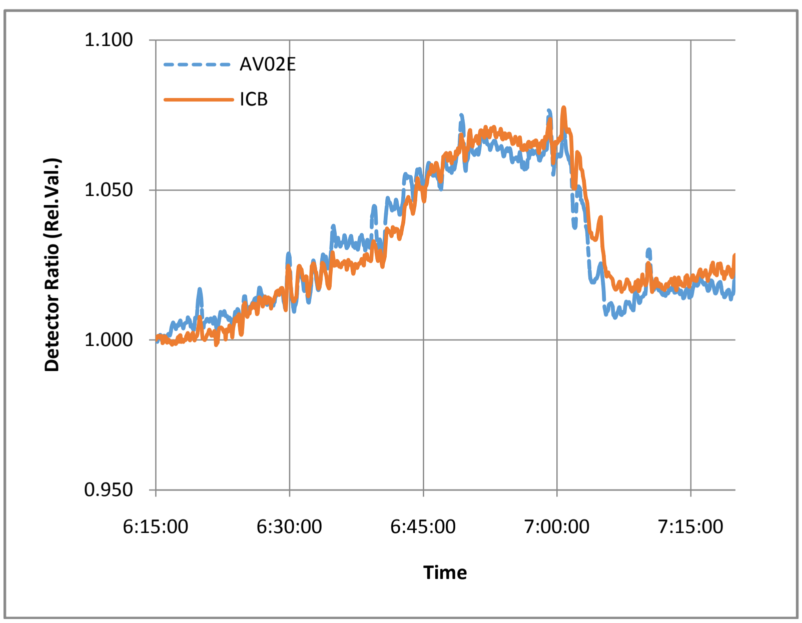

Figure 5: Measured and Calculated Detector Readings during Moderator-Level Maneuver–Ion Chamber AV02E (ICB)