REACTOR PHYSICS CODE SUITE VALIDATION USING STATION START-UP DATA: AN ASSESSMENT OF FEASIBILITY

I. Beith, G. Gavrus & Y. Parlatan
Nuclear Safety & Technology Department
Ontario Power Generation
889 Brock Rd.
Pickering, ON, Canada
ian.beith@opg.com; george.gavrus@opg.com; yuksel.parlatan@opg.com

M. Younis
Department of Reactor and Radiation Physics
AMEC-NSS
mohamed.younis@amec.com

Abstract

The feasibility of using Canada Deuterium Uranium (CANDU®) station warm-up measurements to validate Reactor Physics Industry Standard Toolset (RP-IST) predictions of combined coolant temperature, coolant density and fuel temperature induced reactivity effects was examined. The combined induced reactivity changes were quantified for several critical state transitions experienced during Heat Transport System (HTS) warm-up events at the Darlington Nuclear Generating Station (DNGS) in Ontario, Canada [1]. The magnitude of reactivity insertion due to increased coolant temperature (and hence increased fuel temperature and decreased coolant density) was quantified by measuring the amount by which the liquid zone control system reactivity was altered by the Reactor Regulating System (RRS) to maintain criticality. The events were then simulated with the RP-IST code suite and the predictions compared with the measurements. The results revealed a random prediction uncertainty of approximately ± 7%; consistent with the results of similar independent validation exercises carried out in the ZED-2 experimental reactor at Atomic Energy of Canada Ltd (AECL) [2]. The results of this work therefore support the scalability of ZED-2 measurements to CANDU® reactors and the feasibility of using station warm-up data in code suite validation exercises.

Key Words: *Validation, Feasibility, Scalability*

1. Introduction

Significant efforts have been made in the past to validate the Reactor Physics Industry Standard Toolset (RP-IST) WIMS/DRAGON/RFSP [3,4,5] that is used to calculate the neutron distribution in CANDU® reactors for safety analyses and licensing studies. These efforts include validation against measured data in experimental reactors, limited validation using station data, benchmarking against Monte-Carlo based simulations and review of issues by an independent expert panel [2,6,7]. Despite these efforts, regulatory concerns remain with respect to scaling effects; lack of adequate scaling assessment between a CANDU® reactor and an experimental facility, as well as direct application of experimental uncertainty results for full core power reactor applications.

One vital calculation required for safety analyses and licensing studies is the positive reactivity change in a CANDU® core that results from the decrease in coolant density experienced during a Loss of Coolant Accident (LOCA). Regulatory concerns regarding the adequacy of allowance of Coolant Void Reactivity (CVR) uncertainties resulted in the opening of Regulatory Generic Action Item GAI95G04 – PHT Positive Void Reactivity.

In order to help address the closure criteria of this GAI, a validation exercise of the RP-IST code suite against reactor start-up data under equilibrium conditions is desirable. This exercise could potentially lead to an improvement in code validation status and support the industry request for closure of the GAI on coolant void reactivity. The main objective of this work was to assess the feasibility of using station start-up data to validate RP-IST predictions of the combined coolant temperature and density, and fuel temperature induced reactivity changes.

2. Previous validation efforts

Controlled experiments to remove the coolant from an operating CANDU® reactor are not practical, therefore measurements must be carried out in a suitable experimental facility and the results extended to a full scale CANDU® lattice. Comparisons between the calculations carried out by the RP-IST code suite and the measurements made in the experimental facility, following appropriate scaling, provide a measure of how well the physics tools are able to predict the void reactivity. In addition to an estimate of the reactivity worth, a quantitative estimate of the uncertainty and possible systematic bias are also required.

The experimental program to predict the coolant void reactivity in a CANDU® lattice and to validate the RP-IST code suite was carried out in ZED-2, a zero power heavy water reactor at AECL's Chalk River Laboratories [2]. Due to the extremely low power/temperature of ZED-2 it is possible to remove the coolant from some or all of the channels, which enables the phenomenon of void reactivity to be investigated.

The results of these experiments, in combination with the results of numerous code studies/comparisons, have shown an over-prediction bias of 1.6 mk and a random uncertainty of ±1.1 mk in the prediction of the void reactivity for Darlington-type fuel (37-element natural uranium, NU), under normal operating conditions (at all burn-ups)[2]. This value includes model approximations, experimental error and nuclear data uncertainties.

Further IST validation efforts have focused on the prediction of the HTS temperature reactivity effect. This effect encompasses three physical phenomena; (1) the effect of increased coolant temperature, (2) the effect of decreased coolant density and (3) the effect of increased fuel temperature. In this validation exercise, the seven hot (central) channels in ZED-2 were uniformly heated from 25°C to 300°C, with either heavy water or CO_2 in the coolant space. The substitution method was used to determine the bare full-core bucklings for several test fuels, including 37-element NU and 37-element mixed-oxide (MOX, simulated mid-burn). The measured bucklings were input into the code suite, to determine how well criticality can be predicted at various points throughout the warm-up. The results indicated no systematic bias and a random uncertainty of approximately ± 8% in the calculation of HTS temperature reactivity effects for simulated mid-burn 37-element fuel, over the range of temperatures examined [2].

The purpose of this work was to assess the feasibility of reproducing the ZED-2 validation efforts, with regards to HTS temperature reactivity effects, in a CANDU® reactor using station measurements as inputs.

3. Methodology

Under start-up conditions, the reactor is made critical through the removal of poison from the moderator via ion-exchange columns. Once the reactor is declared critical, the shutdown cooling system is valved out and HTS pumps are brought into service to circulate the primary coolant through the circuit. Energy is transferred to the coolant due to friction with the pump impellers and increased circuit ΔP losses, resulting in an increase in coolant temperature, and a corresponding decrease in coolant density. Throughout the transition from the cold to hot equilibrium states, the RRS maintains a constant reactor power by adjusting the Average Zone Level (AZL) to compensate for the reactivity introduced as a result of changes in the following parameters:

1. Coolant temperature (and therefore density), T_c
2. Moderator temperature, T_m
3. Fuel temperature, T_f
4. Fuel burn-up, B
5. Moderator and coolant isotopics, I_m, I_c
6. Poison concentration in the moderator, x
7. Concentration of relevant saturating fission products, X_i

Given that the total change in reactivity is the net result of individual reactivity effects introduced due to changes in the quantities presented above, and that the reactor states under examination are critical states, the following equation can be written for the total reactivity change:

$$\Delta\rho = \frac{d\rho}{dT_c}\Delta T_c + \frac{d\rho}{dT_m}\Delta T_m + \frac{d\rho}{dT_f}\Delta T_f + \frac{d\rho}{dZ}\Delta Z + \frac{d\rho}{dB}\Delta B + \frac{d\rho}{dI_m}\Delta I_m + \frac{d\rho}{dI_c}\Delta I_c + \frac{d\rho}{dx}\Delta x + \sum_i \frac{d\rho}{dX_i}\Delta X_i = 0 \quad (1)$$

If the combined reactivity effect of changes in coolant temperature and fuel temperature is expressed as a single quantity (the HTS temperature reactivity), equation 1 can be re-arranged to give the following:

$$\frac{d\rho}{dT_{HTS}} = -\frac{1}{\Delta T_{HTS}}\left(\frac{d\rho}{dZ}\Delta Z + \frac{d\rho}{dT_m}\Delta T_m + \frac{d\rho}{dB}\Delta B + \frac{d\rho}{dI_m}\Delta I_m + \frac{d\rho}{dI_c}\Delta I_c + \frac{d\rho}{dx}\Delta x + \sum_i \frac{d\rho}{dX_i}\Delta X_i\right) \quad (2)$$

Equation 2 shows that the HTS temperature reactivity coefficient can be expressed in terms of the changes in relevant process parameters (shown above) between two critical states and their respective reactivity coefficients. However, given that the calculation uncertainty increases with each additional reactivity effect that is quantified, one of the primary goals of this study was to identify HTS warm-up events where the number of such effects was minimized. This goal was accomplished by imposing the following set of criteria on the selection of warm-up data from the Plant Information (PI) database:

1. Long shut down; only HTS warm-up events following periods of long shut down were considered to eliminate the need to account for reactivity changes associated with transient concentrations of saturating fission products.
2. Purification out of service; changes in moderator poison concentration, or the removal of contaminants from either the HTS or the moderator, would/could affect core reactivity.
3. No inventory transfers; upgrading or downgrading of either the HTS or the moderator system due to transfer of inventory would affect core reactivity.
4. Stable moderator conditions; no changes in either moderator temperature or level.
5. Low power ($\sim 10^{-3}$ %FP); changes in fuel burn-up over short periods of time can be neglected if the power is sufficiently low.

Given the preceding set of data selection criteria and the assumptions of:

1. Uniform coolant temperature/density distribution throughout the core.
2. Uniform fuel temperature equal to that of the coolant.

equation 2 can be reduced to the following:

$$\Delta T_c \frac{d\rho}{dT_{HTS}} = -\frac{d\rho}{dZ}\Delta Z \qquad (3)$$

Equation 3 states that the HTS temperature change induced reactivity can be inferred from the measured change in primary coolant temperature and the compensatory change in Liquid Zone Control System (LZCS) induced reactivity.

In this study, the RP-IST code suite was used to simulate the coolant/fuel heat up transient during reactor start-up. First, a snapshot reference full-power equilibrium condition was generated using the instantaneous fuel burn-up distribution from the last SORO state prior to the warm-up evolution. The reactor shut down, including the ensuing xenon transient, was then simulated to define a reactor state characteristic of long shut down. The input files required to define both the initial and final critical reactor states for each simulated HTS temperature transition were then constructed based on process measurements acquired during the actual events. The basic cell nuclear cross sections were calculated using the WIMS-IST code. The incremental cross sections of the major reactivity devices that are in core (zone controllers, adjuster rods and their guide tubes) were calculated using DRAGON-IST at the equilibrium fuel conditions. The simulated reactivity bias was then calculated for several temperature transitions.

The change in the measured zone controller level experienced when the HTS was warmed-up was used to calculate the total observed reactivity change for each transition. The observed change in reactivity was then compared with the predicted change in reactivity for each event. The uncertainty in the observed reactivity change was considered along with that of the IST prediction.

4. Results and conclusions

The total observed reactivity change was calculated for five coolant temperature transitions (see Table 1), using the change in measured zone levels and the LZCS reactivity worth. An estimate of the LZCS reactivity worth (-0.0749 mk/%) was obtained from RP-IST code suite simulations of zone level movements under the same conditions. For each simulated temperature transition, the *CERBERUS module was used to calculate the change in core reactivity between the initial and final states, by specifying the individual zone levels at the initial state and holding them constant over the transition to the final state.

Table 1. Summary of DNGS data used in HTS temperature reactivity measurements/code suite predictions

	Nov. 16, 2002 (i)	**Nov. 16, 2002 (ii)**	**May 25, 2005**	**May 10, 2002**	**Nov. 14, 2004**
Unit	1	1	2	3	3
Δt (hh:mm:ss)	1:38:56	1:38:56	0:51:00	0:32:38	0:34:41
ΔT_c (°C)	17.5	12.3	4.3	9.1	14.5
ΔAZL (%)	6.29	4.84	1.59	3.96	4.20

Interpretation of the results required the estimation of the uncertainty in the predictions, for comparison against some benchmark. The results of the ZED-2 validation program were chosen as the appropriate benchmark for comparison. These results show zero bias and a random uncertainty of approximately ± 8% in the prediction of the HTS temperature reactivity effect for mid-burn 37-element fuel [2]. The results encompass the same three measured and predicted reactivity effects as this study; coolant temperature, fuel temperature and coolant density. In addition, the fuel temperature in the ZED-2 experiments was equal to that of the coolant temperature, consistent with the assumption made in this study. Therefore, comparison with the ZED-2 results provides a direct measure of the scalability of such experimental results to full-core conditions.

Figure 1 shows both the predicted reactivity change, as well as that which was inferred from the observed change in AZL, for each of the warm-up events. Estimation of the error associated with the code predictions was complicated by the fact that the inputs to the code at each state were process measurements, each with their own individual uncertainty. These individual uncertainties were therefore propagated in some form into the predictions. Separation of these process uncertainties from that introduced by the code was not straightforward and was considered outside the scope of this work. Nevertheless, the standard error of the estimate was calculated for the five data sets and found to be approximately 0.02 mk, or ~7% of the average predicted reactivity change. The random component of the total prediction uncertainty was therefore consistent with the reported value [2].

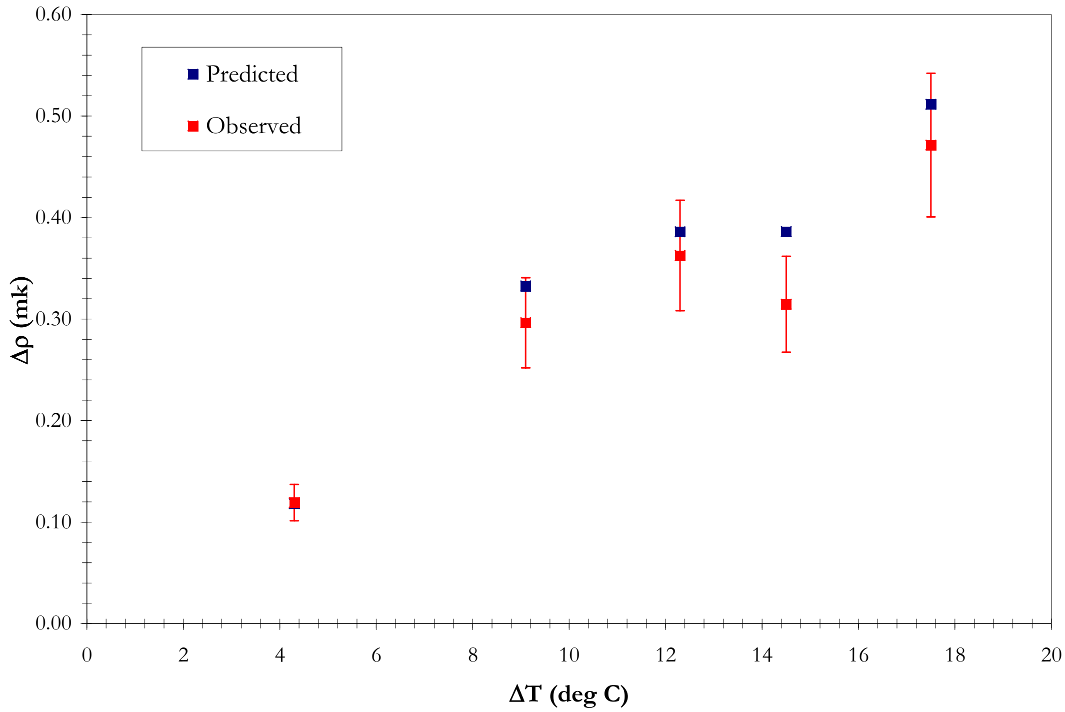

Figure 1. Predicted (RFSP-IST) vs observed change in reactivity due to increased HTS temperature

Additional sources of uncertainty include the use of SORO to predict the bundle burn-up distribution and the random variation in other process conditions that were assumed uniform in the 3D modelling of the core (i.e. coolant thermal hydraulic conditions and fuel temperatures). The assumption of uniform coolant temperature/density distribution in the core was considered acceptable because the reactor power was very low (~10^{-3} %FP) and there was good mixing due to the circulation of the coolant through the HTS via the primary pumps. The assumption of uniform fuel temperature (equal to coolant temperature) was considered acceptable due to the fact that the small internal heat generation in the fuel, in combination with the large convective heat transfer coefficient, would limit the establishment of any significant ΔT between the fuel sheath and the coolant. Effective heat transfer would also limit variation in fuel temperature with bundle location that would otherwise occur due to the distribution in decay powers. Variation in fuel temperature with bundle location due to flux shape would also be negligible given the very low fission power.

The results suggest that it is feasible to use station warm-up data to support ZED-2 validation results. However, current start-up procedures allow for frequent additions of gadolinium to the moderator, to maintain the AZL in the 40-60% range. As a result, current data only supports simulation of small reactivity changes (less than 0.5 mk), such as those seen in Figure 1. Since the analytical uncertainty remains high relative to the magnitude of the reactivity changes being simulated, the use of such analysis to support closure of the CNSC GAI surrounding scalability has been limited.

There is a need to design and carry out further, more carefully controlled warm-up measurements to reduce uncertainty. Once again, all reactivity perturbations other than those under examination should be eliminated. Repeat HTS temperature reactivity measurements, from several units, should be obtained to improve the underlying statistics. Due to the importance of zone controller induced reactivity effects in this type of analysis, a more accurate estimate of the uncertainty in the calculation of zone worth is essential. A formal proposal for the completion of such work as part of future DNGS warm-up evolutions was submitted to station engineering & operations management.

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