Validation of WIMS-IST for CANDU®-Type Lattices

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Abstract

Prior validation studies of 28-element natural uranium (28-NU) CANDU®-type fuel bundles using the WIMS-IST lattice physics code had demonstrated a bias in the calculation of the coolant void reactivity (CVR) of approximately +0.5 to +0.6 mk (1 mk = 100 pcm = 0.001 Δk/k). However, these validation studies were performed using experimental data for 28-element bundles with pressure tubes that were smaller than standard CANDU-type pressure tubes, giving a smaller coolant volume, and a modified neutron energy spectrum. Validation studies performed with 37-element and 43-element fuel bundles with a CANDU-type lattice pitch and pressure tube had shown a CVR bias of ~ 1.7 to 1.9 mk. It was believed that the CVR bias for a 28-element bundle would be closer to this range of values if a standard CANDU pressure tube diameter were used. The objective of this study was to confirm this hypothesis, that using a larger CANDU-standard pressure tube would give a larger CVR bias for a 28-NU fuel bundle, as computed by WIMS-IST in comparison to experimental measurements of critical buckling. Thus, new critical-height and flux-map measurements were performed in substitution experiments in the ZED-2 research reactor to determine the pure critical lattice bucklings for 28-element fuel with standard-size CANDU pressure tubes. The derived bucklings from these experiments were used in WIMS-IST transport calculations to determine the effective multiplication factors for cooled and voided lattices and hence the bias in the CVR. Calculation results demonstrated that the CVR bias for the 28-NU was ~ 1.7 mk ±0.42 mk, which is consistent with the results for 37-element and 43-element CANDU-type lattices.

KEYWORDS: WIMS-IST, WIMS-AECL, CANDU, lattice physics, validation, ZED-2

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1. Introduction

Previous validation studies at AECL with the lattice physics code WIMS-IST using buckling data for a 28-element natural uranium (28-NU) reference fuel lattice with small-diameter aluminum pressure tubes (PT) and calandria tubes (CT) demonstrated a bias in the calculation of the coolant void reactivity (CVR) of approximately 0.53 mk (1 mk = 100 pcm) at standard conditions (22°C and 99.75 wt% D_2O moderator purity). This CVR bias for the 28-element NU channel was smaller than the CVR bias calculated for 37-element and 43-element NU bundles in standard CANDU pressure tubes (a slightly larger diameter, and Zr-2.5%Nb material). For these 37-element and 43-element CANDU lattices, the CVR bias ranged between 1.7 and 1.9 mk. It was hypothesized this difference in the CVR bias was caused by the use of the smaller-diameter aluminum PT in the 28-NU experiments, which reduced the D_2O coolant volume, and caused a shift in the neutron energy spectrum. Hence, if standard-sized CANDU PT's were used in experiments to derive bucklings for 28-NU, the subsequent lattice physics calculations with WIMS-IST should demonstrate a bias in the CVR that is comparable to those for 37-element and 43-element CANDU-type lattices.

The analysis and results reported in this paper meet three main objectives. The first objective was to derive bucklings for air-cooled and D_2O-cooled 28-element natural uranium (UO_2) fuel bundles in CANDU-type channels with a 31-cm hexagonal lattice pitch, based on recent substitution experiments in the Zero Energy Deuterium (ZED-2) research reactor. The second objective was to validate the WIMS-IST lattice physics code using these derived bucklings. The WIMS-IST code was used to compute the effective multiplication factors ($k_{effective}$) and the bias in the CVR (coolant void reactivity) using these derived bucklings, along with the uncertainties in these parameters due to the uncertainties in the bucklings and the BCV (buckling change with voiding). The third objective was to quantify the impact of using CANDU-type pressure and calandria tubes on the WIMS-IST evaluation of the CVR bias.

2. Substitution Experiments and Analysis

2.1 Test and Reference Fuel Channels

Critical experiments were performed in the ZED-2 research reactor at AECL's (Atomic Energy of Canada Limited) Chalk River Laboratories. ZED-2 is a critical facility that uses heavy water moderator, operates for brief periods of time at low power (~100 Watts), and has the flexibility to test a variety of fuel types and lattice arrangements [1].

The design of the test channels in recent substitution experiments in the ZED-2 research reactor closely represented a standard CANDU fuel channel in terms of the lattice pitch, and the size and material of the PT's and CT's. The 31-cm hexagonal pitch is approximately equivalent to a 28.58-cm square pitch lattice in that the moderator-to-fuel ratio is roughly the same. Pressure tubes were made of Zr-2.5%Nb. Calandria tubes were made of Zircaloy-2. Measurements were made with the test fuel substituted into a full-core lattice (55 channels) of reference fuel in the ZED-2 reactor, to cause perturbations in the flux distributions and changes in the critical moderator height. The reference lattice fuel channels were similar to the test fuel channels (both use five 28-element natural UO_2 bundles), but the fundamental differences were that the PT and CT were made of aluminum and were smaller in diameter [1]. The main impact was that the reference fuel channels had a smaller coolant volume than the test fuel.

2.2 Matrix of Experiments

Initially, critical experiments were performed with the 55-channel D_2O and air-cooled reference lattices, and both critical moderator heights and relative flux maps were measured. Critical bucklings for the reference lattices were derived from combined cosine and Bessel function curve fits of the full-core flux maps. These bucklings and the critical moderator heights were then used to obtain the axial and radial extrapolation distances. These were followed by four general sets of substitution experiments. All experiments used the same test fuel and reference fuel channels, but they differed in the choice of coolants. In two sets, the test fuel channels were cooled by either air or D_2O, while the reference fuel was cooled by D_2O. In the other two sets, the test fuel channels were cooled by air or D_2O, while the reference fuel was cooled by air. Substitution experiments were performed in which the central seven channels in the hexagonal reference lattice were progressively replaced with 1, 3, 5, and then finally 7 channels of test fuel.

Critical moderator heights were measured for each substitution experiment, and this was done for both cooled test fuel, and for voided test fuel in both cooled and voided reference lattices. Hence, there were at least 16 different lattice configurations of substitution experiments (2 test fuel coolants × 2 reference fuel coolants × 4 substitutions).

2.3 Substitution Analysis

The critical height measurements for each set of substitution experiments were adjusted to common conditions of lattice temperature and moderator purity (25.1°C and 99.87 wt% D_2O for the D_2O-cooled reference lattice; 24.2°C and 99.84 wt% D_2O for the air-cooled reference lattice). These critical moderator heights, and the measured extrapolation distances, were then used in subsequent core calculations with the CONIFERS code (4-group, diffusion) to determine what the test fuel neutron production correction factor (NPCF), an adjustment factor to ν, should be to make the core just critical (k=1.000). An NPCF was computed for each substitution configuration, and these data were used in a weighted fit to extrapolate what the NPCF would be for a pure lattice of test fuel. This NPCF for a pure critical lattice was then used in a lattice physics calculation (not necessarily WIMS-IST) to infer the critical buckling. A calibration correction was then applied to the bucklings derived from the substitution experiments, using correlated data from previous validation work for the substitution method at Chalk River [2]. The D_2O-cooled test fuel had bucklings that ranged from 4.032 m^{-2} to 4.033 m^{-2}, while the air-cooled test fuel had bucklings that ranged from 4.256 m^{-2} to 4.278 m^{-2}. The uncertainty in the derived bucklings was ~±0.1 m^{-2}, while the uncertainty in the derived buckling change on voiding (BCV) is ~±0.02 m^{-2}. These uncertainties were based on an extensive validation of the substitution method [2]. The uncertainties in the measured temperature, moderator purity and critical heights in the substitution experiments are relatively small, and the impact of these uncertainties on the uncertainty in the derived buckling is negligible. The uncertainty in the derived bucklings is dominated by how realistic and accurate the model of the physical system is.

3. Validation of WIMS-IST

3.1 Computational Method

WIMS-AECL, Version 2-5d code [3] was used for performing the neutron transport analysis of the 28-element natural uranium lattices. WIMS-AECL is a two-dimensional lattice physics code that uses multi-group integral transport theory and collision probability methods to solve for the flux distribution and reaction rates within a given lattice cell design. Because WIMS-AECL Version 2-5d [3] was used in combination with the E6LIB nuclear data library and because specific recommendations for an optimized input model for CANDU-type lattices [3] were followed, the calculation method follows the guidelines for Industrial Standard Toolset, and hence, the analysis will be a validation of WIMS-IST.

3.2 WIMS-IST Validation Results

WIMS-IST calculations were performed for the 28-element fuel in the reference lattice at the common conditions of moderator purity (99.82 wt%) and temperature (23.6 °C), using the bucklings derived from the full-core flux-maps. The bias in $k_{effective}$ was quite low (-0.3 to +0.2 mk), and the CVR bias was ~ 0.43 mk. These results were consistent with what had been found in previous AECL validation studies for the 28-element fuel in smaller-diameter aluminum pressure tubes.

WIMS-IST calculations were then performed for the test fuel channels with both coolants using bucklings derived from the substitution experiments in the two different reference lattices. Calculations were also performed with bucklings that represented the uncertainties for the absolute values of the bucklings (± 0.1 m^{-2}), and for the uncertainty in BCV (± 0.02 m^{-2}). These uncertainties were based on prior validation studies for the substitution method for standard CANDU lattices [2].

It was found that WIMS-IST tended to under-predict $k_{effective}$ for the test fuel in the D_2O-cooled reference lattice, with a bias ranging from –4.4 to –6.4 mk. The uncertainty in the bias due to the uncertainty in the derived bucklings was approximately ±3.4 mk. The bias in the coolant void reactivity (CVR) was 2.01 mk, while the uncertainty in bias in CVR was approximately ± 0.7 mk.

It was also found that WIMS-IST tended to under-predict $k_{effective}$ for the test fuel in the air-cooled reference lattice, with a bias ranging from –6.2 to –7.6 mk. The uncertainty in the bias due to the uncertainty in the derived bucklings was approximately ±3.4 mk, the same as found for the test fuel in the D_2O-cooled reference lattice. The bias in the coolant void reactivity (CVR) was 1.39 mk, while the uncertainty in the bias in CVR was approximately the same, ±0.7 mk.

4. Conclusions

The WIMS-IST code system (WIMS-AECL Version 2-5d, E6LIB nuclear data library, recommended input parameters for CANDU-type lattices) was used to obtain biases and uncertainties for the effective multiplication factor and the coolant void reactivity using buckling data derived from substitution experiments of 28-element natural uranium lattices in the ZED-2 research reactor. The test fuel lattices had pressure tube and calandria tubes that were similar in size and material composition to standard CANDU components. Buckling data were derived for test fuel channels with D_2O and air coolants substituted into D_2O-cooled and air-cooled reference lattices.

Prior validation studies for 28-element NU fuel bundles had determined the bias in the coolant void reactivity to be ~0.53 mk at standardized conditions (22°C, 99.75 wt% moderator purity), and the uncertainty in this bias was shown to be ±0.4 mk. Since these studies were based on fuel bundles with a smaller pressure tube diameter, and hence smaller coolant volumes, it was expected that the WIMS-IST calculation of the CVR bias would be lower than what would be found if a more representative pressure tube size was actually used. For example, previous validation studies for 37-element and 43-element fuel bundles with CANDU-type pressure tubes and lattice pitches had shown a CVR bias ranging from 1.7 to 1.9 mk .

A WIMS-IST calculation for the reference lattice (28-element NU fuel with smaller-diameter aluminum pressure tubes) at common conditions demonstrated a CVR bias of ~0.43 mk, which was within the range of uncertainty of previous validation results (0.53 mk ± 0.4 mk). The results of this validation study with WIMS-IST using more realistic pressure tubes for 28-element natural uranium fuel demonstrated a CVR bias ranging from 1.4 to 2.0 mk, with an uncertainty of ±0.7 mk based on a ±0.02-m^{-2} uncertainty in the BCV. The two values of CVR bias had a mean value of 1.7 mk with a standard deviation of ±0.42 mk. Taking into account this uncertainty, these results confirmed the original hypothesis: 28-NU channels with CANDU PT's and CT's will have approximately the same bias in CVR as 37-element and 43-element channels, as computed by WIMS-IST.

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6. References

[1] K.J. Serdula, "Lattice Measurements with 28-Element Natural UO_2 Fuel Assemblies Part I: Bucklings for a Range of Spacings with Three Coolants", AECL-2606, AECL Chalk River Laboratories, July, (1966).

[2] R.S. Davis, A. Celli, S.R. Douglas, R.T. Jones, D.C. McElroy, and M.B. Zeller, "Validation of the Substitution Method for Measurement of Void Reactivity", 21st Annual CNS Conference, Toronto ON, (2000).

[3] J.D. Irish and S.R. Douglas, "Validation of WIMS-IST", Proceedings of 23rd Annual CNS Conference, Toronto, Canada, June 3-5, (2002).