TECHNICAL NOTE

MONTE CARLO CALCULATIONS APPLIED TO SLOWPOKE FULL-REACTOR ANALYSIS

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Article Info
Keywords: SLOWPOKE, reactor physics, full-reactor analysis, core following, Monte Carlo
Article history: Received 17 October 2012, Accepted 12 December 2012, Available online 17 January 2013
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Abstract

Monte Carlo simulations are applied to the full-reactor analysis of the SLOWPOKE design. The temperature reactivity feedback calculated by using the MCNP code for either the high enriched uranium (HEU) or low enriched uranium (LEU) core is in good agreement with the experimental data, with a k-eff bias of +3.3 mk for a HEU core and +6 mk for a LEU core. Two methods that are based on existing third-party codes have been developed for use in core following: 1) MCNP (for the transport calculation) in conjunction with WIMS-AECL (for fuel burnup advancement), and 2) SERPENT (that combines both transport and burnup capabilities). Both methods show very good agreement with the experimental data for core excess reactivity and detailed power distributions versus burnup and reactivity shim.

1. Introduction

SLOWPOKE (Safe Low Power Kritical Experiment [1]) reactors are AECL-designed research reactors of pool type, loaded with either high enriched uranium (HEU, 93 wt% ^{235}U/U) in UAl metal alloy and Al clad fuel elements, or low enriched uranium (LEU, 20 wt% ^{235}U/U) in UO_2 ceramic oxide and Zr clad fuel elements. The approximate total ^{235}U core loading is 0.82 kg for the HEU fuel and 1.2 kg for the LEU fuel. The core is cooled and moderated by water and has beryllium reflectors (solid metal radially and below the core, and thin metal plates above the core). The SLOWPOKE design has a relatively small excess reactivity (subject to restoration by adding beryllium shim plates to the top reflector) but large negative temperature reactivity feedback – a very special feature assuring its safe operation.

Original reactor physics analysis based on solving the few-group neutron diffusion equation, e.g., HAMMER/EXTERMINATOR [2] (used to analyze the first HEU core) or WIMS-CRNL/CITATION [3] (used to analyze the first LEU core), tended to give rise to large k-eff uncertainty and lack of power and burnup spatial distributions in fuel elements due to core homogenization. Stochastic neutron transport codes (such as MCNP [4] and SERPENT [5]), are able to eliminate these inaccuracies resulting from the diffusion approximation.[1]

The MCNP full-reactor models of SLOWPOKE (Figure 1) with a HEU or LEU core, have been created to study: 1) temperature reactivity feedback, and 2) burnup (or core following) for the SLOWPOKE design. These MCNP models include the main reactor components inside of the reactor container in detail, each of which may be changed with respect to geometry (shim thickness or control rod position), material, or temperature. Due to the simple design of the SLOWPOKE reactor and its small size, very few geometric or material approximations were required; the models are essentially exact. The models used MCNP5 Version 1.40 and an in-house multi-temperature library based on ENDF/B-VII.0 generated with NJOY [6]. When a desired material temperature was between two data sets, a combination of the two sets (interpolation of the square root of temperature) was used. Fuel elements in a hexagonal lattice are modeled to have the burnup-dependent compositions, which may vary not only from element to element but also axially within each element. Where fuel elements are expected to be in similar neutron fluxes due to location they have been grouped together to improve tally uncertainties.

2. Temperature Reactivity Feedback

Using the multi-temperature ENDF/B-VII.0 cross-section library and mixing concentrations at two library temperatures as discussed above, the material temperature in each of the main reactor components (i.e., fuel, coolant/moderator,

[1] The original deterministic codes, and the typical phase space discretization and the nuclear data they used, are all obsolete. Much better results are now possible using modern deterministic codes and data. Comparison of modern stochastic methods to modern deterministic methods is beyond the scope of this paper.

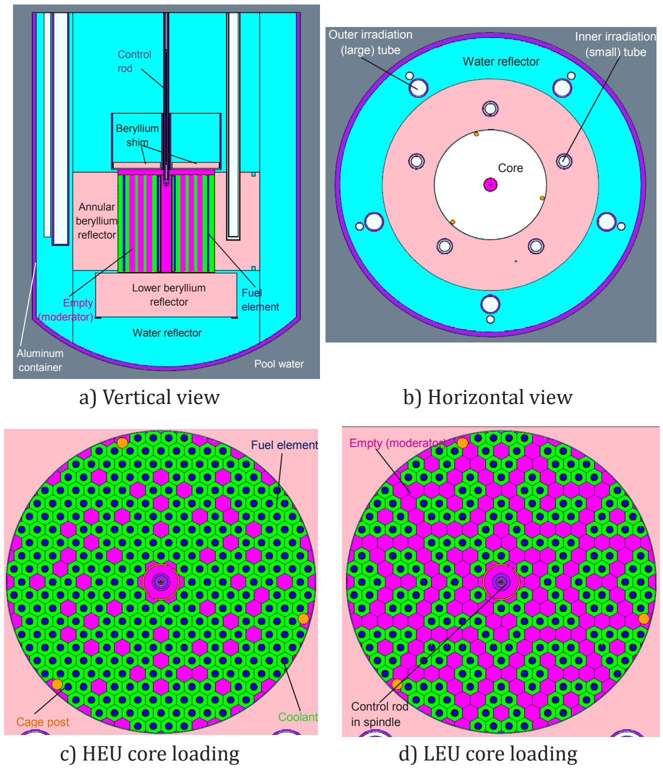


FIGURE 1
Monte Carlo model of SLOWPOKE for both MCNP and SERPENT Codes.

beryllium reflector and water reflector) was set independently to a series of values for the k-eff calculations. The individual reactivity components were combined to obtain the whole core results. The core excess reactivity (i.e., the reactivity with the control rod fully withdrawn) calculated by MCNP is biased relative to the measured values, by +3.3 (±0.2) mk[2] for a HEU core and +6 (±0.2) mk for a LEU core where the uncertainty is one standard deviation. The temperature reactivity feedback for the MCNP models is consistent with the experimental data. In general, the reactivity feedback is slightly positive at low temperatures and turns negative above room temperature. Figure 2 shows the change in core reactivity from a reference state for fresh fuel as the temperature of individual components is changed while holding the others fixed, as well as the combined reactivity of changing all component temperatures together. MCNP predicts the reactivity peak to be in the range of 21–27°C for the HEU core and 32–37°C for the LEU core. The experimental data shows maximum values of excess reactivity at 20°C and 33°C for HEU and LEU, respectively, due to the combination of the individual reactor component temperature reactivity feedbacks which have different signs and values.

The reflector temperature reactivity feedback is mostly small and positive, while the fuel and coolant reactivity feedback is always negative, small for fuel and low-temperature coolant but relatively large for coolant above room temperature (-10 mk and -6 mk over a 50°C change

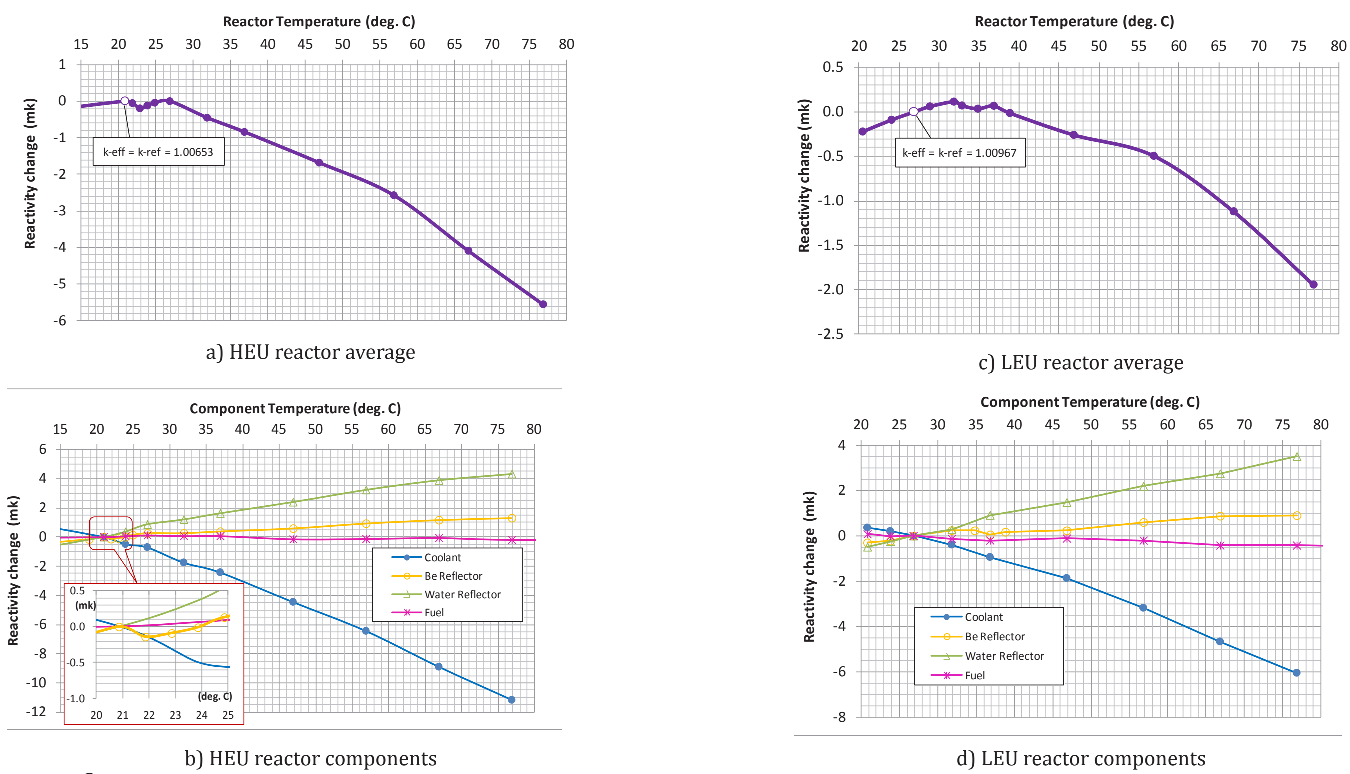
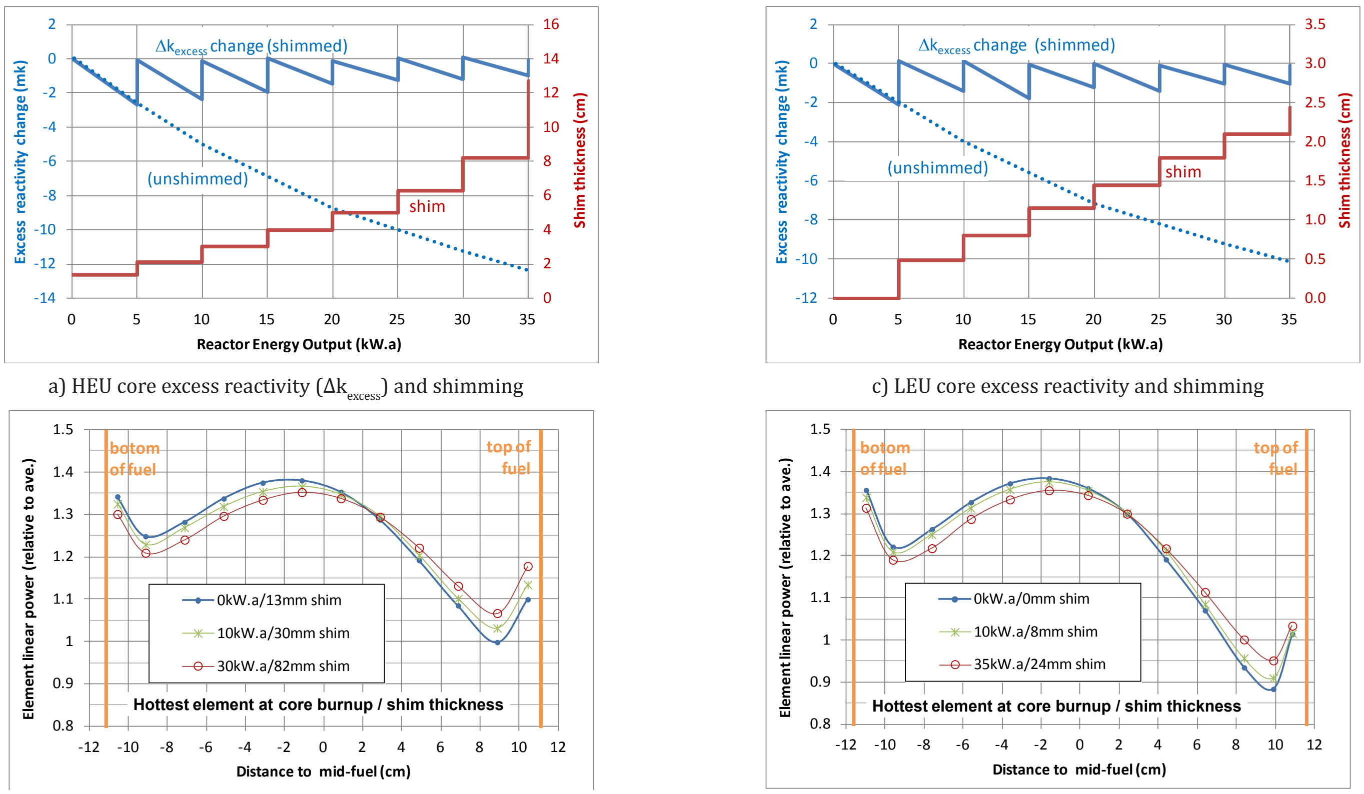


FIGURE 2
SLOWPOKE temperature reactivity feedback.

[2] The unit "mk" is the most common unit of reactivity used in Canada. 1 mk = 100 pcm = 0.001 dk/k.



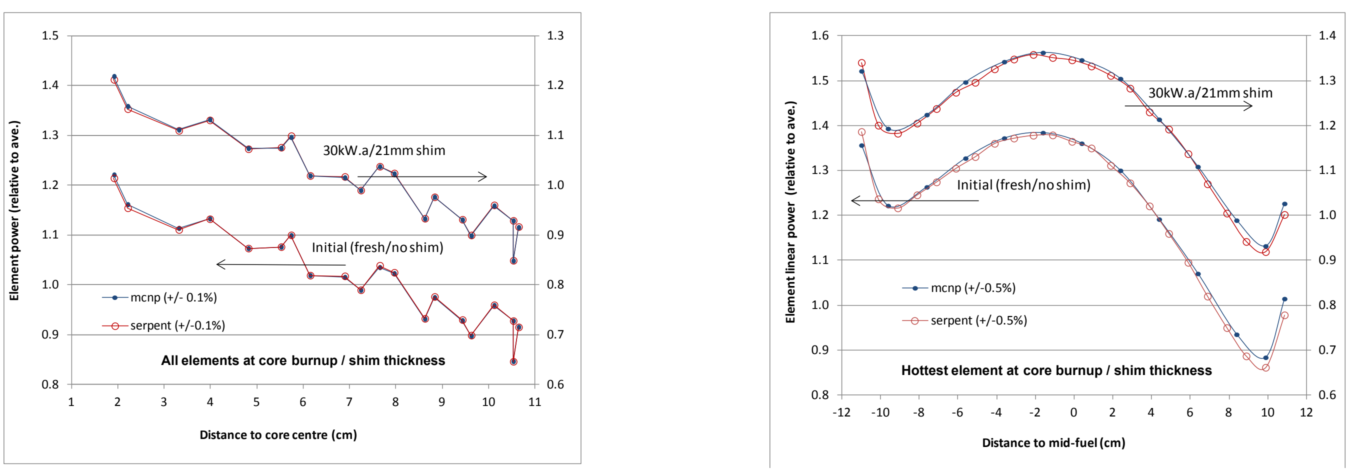
a) HEU core excess reactivity (Δk_{excess}) and shimming

c) LEU core excess reactivity and shimming

b) HEU element power

d) LEU element power

FIGURE 3
SLOWPOKE reactivity and element power distribution versus burnup.



a) Radial distribution (element powers at points)

b) Axial distribution (element linear power)

FIGURE 4
Comparison of MCNP and SERPENT power distribution results.

in the HEU and LEU core, respectively), thus, the coolant dominates the SLOWPOKE reactivity feedback at higher temperatures.

3. Burnup Analysis

For core following, the MCNP full-reactor calculation is performed to provide the three-dimensional power distribution, while a burnup code, such as WIMS-AECL Version 3.1 [7] in this study, is required for fuel burnup advancement. The burnable materials in the MCNP model are updated using the WIMS-AECL pre-computed isotopic composition as a function of burnup. WIMS-AECL is run first from fresh fuel to exit burnup using a two-dimensional model of the whole core with all fuel pins included and using the WIMS-AECL 89-group library (ENDF/B-VII.0, NJOY processed) that is the equivalent of the library that was used with MCNP; then the resulting composition tables are interpolated manually using power distributions from MCNP to advance the composition for each axial segment of fuel in MCNP for the next irradiation step. Since SLOWPOKE fuel depletes only slightly in practice, the element radial power distribution does not change significantly with burnup and top reflector shimming, but the axial power distribution does change with the shim thickness since the shims are added to the top reflector. The power calculations were done holding the control rod position fixed.

For hypothetical operation of SLOWPOKE that restores the excess reactivity by reflector shimming after every 5 kW·a[3], the reactivity loss rate due to burnup decreases with the core burnup, from ~0.4–0.5 mk/kW·a at the beginning of the core life to ~0.2 mk/kW·a at 35 kW·a. Top reflector shim effectiveness, i.e., mk gain per cm beryllium added, also decreases with the core burnup (or more correctly, with the total shim thickness), greater in the HEU core, from 3.4 mk/cm at the beginning to 0.1 mk/cm at 35 kW·a (where the shim-plate tray is full), and less in the LEU core, from ~5 mk/cm at the beginning to ~3 mk/cm at 35 kW·a (where the shim-plate tray is only ~20% full). This indicates that the LEU core can operate much longer than the period simulated (Figure 3).

To verify the MCNP/WIMS-AECL core following method, SERPENT [5] that combines both Monte Carlo transport calculation and burnup capability is used independently. Version 1.1.17 of SERPENT was run using models and cross-section libraries that are identical to those used with MCNP. For any core of a given burnup and top reflector shim thickness, the SERPENT and MCNP power distribution results agree very well, to within the statistical uncertainty of the calculations (<0.5%, see Figure 4). This provides confidence that the transport algorithms in MCNP and SERPENT, and that the WIMS-AECL and SERPENT burnup calculations, are consistent.

4. Conclusions

Monte Carlo methods can be very time-consuming compared to lower-fidelity deterministic methods and so are generally not well suited for real time core following in large reactors like NRU or CANDU that require fuel shuffling and replacement in time frames of the order of days. However, as this paper has demonstrated, Monte Carlo methods *are* practical for tracking burnup and reactivity shimming in small low-power reactors like SLOWPOKE where reactivity adjustments occur in time frames on the order of months or years. The method is also useful for analyzing reactivity coefficients and characterizing experiments. Future work could include an investigation of the calculated beryllium reflector temperature reactivity feedback and the higher burnup sustainable in the LEU core, as well as comparison of these results to recent studies using modern deterministic codes. An investigation of other burnup modelling codes and MCNP coupling techniques will also be considered.

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[3] kW.a is the time-integrated fission energy in kilowatt-years. It is the conventional unit used to express fuel burnup in SLOWPOKE reactors.