Impact of Different Fuel Temperature Models on the Nuclear Core Design Predictions of the NPP Krško

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ABSTRACT

The effect of different fuel temperature models used for the nuclear core simulation calculations is evaluated. Standard CORD-2 temperature model was compared to the several FINIX temperature models, where different pellet – cladding gap conductance approaches were implemented. Evaluated models gave up to 70 K different fuel temperature predictions for the NPP Krško 16×16 fuel assembly over the inspected burnup range. Observed temperature differences result in the fuel assembly reactivity differences in the ± 200 pcm range. To evaluate the fuel temperature effect on the reactor core behavior, calculations of 30 NPP Krško operational cycles have been performed with different temperature models. Comparison with measurement data showed the best results obtained with the temperatures from the FINIX code using FRAPCON-4.0 gap conductance model.

1 INTRODUCTION

The CORD-2 system [1], developed by the Reactor physics department of the “Jožef Stefan” Institute, has been used for the verification of the NPP Krško reload cores since 1990. During the recent validation studies, some indications were found questioning the validity of the used fuel temperature model. The model was built based on the calculations with the thermo-mechanical PIN code [2] some 25 years ago. Since then many new fuel performance codes or versions have become available, reflecting the progress in the field. It was decided to re-evaluate the CORD-2 fuel temperature model using the results obtained from the FINIX code [3]. FINIX is a fuel behavior module that calculates the thermal and mechanical behavior of a nuclear fuel rod during steady-state and transient conditions. It can be used as a standalone code or integrated with the host code on the source level. Since it can be integrated with the Monte Carlo neutron transport code SERPENT2 [4], it is especially attractive for coupled temperature – power analysis.

All fuel performance codes require appropriate knowledge of the fuel pin material properties. These properties are usually proprietary and difficult or even impossible to obtain from fuel vendors. Since material properties dictates processes in the fuel rod, such as cladding creep, pellet swelling, densification etc., which are crucial for the fuel temperature determination, a lack of material data inevitably reflects into fuel temperature uncertainty. Such temperature uncertainties can be ±50 K or even higher [5].

The fuel temperature has a profound impact on the neutron cross sections, influencing neutron transport calculation. For example, an increase in fuel temperature increases the effective resonance absorption cross-section of the fuel and produces a corresponding reduction in reactivity (Doppler broadening).

In this paper, evaluation of different fuel temperature models is assessed. Beside FINIX – CORD-2 (PIN) comparison, a sensitivity study of some FINIX models is performed. The effect of the fuel temperature variations on the neutron transport calculations is analyzed by comparing CORD-2 predictions with measurements of 30 completed fuel cycles of the Krško NPP.

2 BRIEF FINIX DESCRIPTION

The FINIX code was developed to provide a fuel behavior module for other calculation codes in multiphysics simulations. The intended use is to improve fuel behavior description in neutronics, thermal hydraulics and reactor dynamics codes, without having to employ full-scale fuel performance codes. FINIX can be used as standalone code or integrated with the host code on at the source code level, by providing an interface of functions that can be used to access the fuel behavior model from the host code.

FINIX consists of several interconnected models that describe the thermo-mechanical behavior of the fuel rod. The code solves the transient or steady-state heat transfer equation, with couplings to the cladding and pellet mechanical behavior through the gap conductance and pressure. Publicly available experimental correlations are used for the material properties, and simple models for the heat transfer from the cladding to the coolant have been included. FINIX was verified against the FRAPTRAN [6] and FRAPCON [7] fuel performance codes in Reactivity Insertion Accident (RIA) and steady-state scenarios, and compared against experimental Halden reactor data.

The code is still under development. We had some difficulties with the version available from the NEA data bank. Observed deficiencies were eliminated with the newer beta version obtained directly from the VTT.

3 RESULTS AND DISCUSSION

In this paper variations of different fuel temperature predictions are evaluated on the NPP Krško case. The Krško NPP is a 2-loop Westinghouse PWR plant. The core consists of 121 fuel assemblies with some VANTAGE+ features, such as IFBA rods and axial blankets. Each fuel assembly has 235 fuel rods with standard radius of 0.47498 cm arranged in a 16×16 array. The remaining 21 positions contain guide tubes and are intended for control rods and in-core instrumentation. The analysis is performed with the standard CORD-2 sequences using ENDF/B-VII.0 [8] cross sections.

3.1 Fuel temperature predictions

Fuel assembly represented by a simple 2D pin subchannel model with nominal power density and average moderator temperature is considered. Some variations in FINIX input parameters, such as UO_2 grain size, cladding roughness, cladding oxygen concentration etc. were evaluated. Since we do not have actual manufacturing data, it is hard to estimate their impact. However, variations of a few percent from default values have limited impact on the predicted fuel temperature. It was discovered that the gap conductance model has the largest impact on the results. FINIX offers three calculation models:

1. FRAPCON-3.4 model,
2. FRAPTRAN model, which is recommended,
3. FRAPCON-4.0 model.

Fuel temperature predictions are shown in Figure 1. FINIX predictions are labelled with GAP'X' label, while the CORD-2 prediction, originating from the PIN code, is denoted as CORD2. Significant differences in the gap conductance and in the heat transfer are observed, when the pellet and cladding are in the close contact. Differences between the FINIX and CORD-2 predictions are up to 70 K, while the different FINIX models give up to 50 K differences.

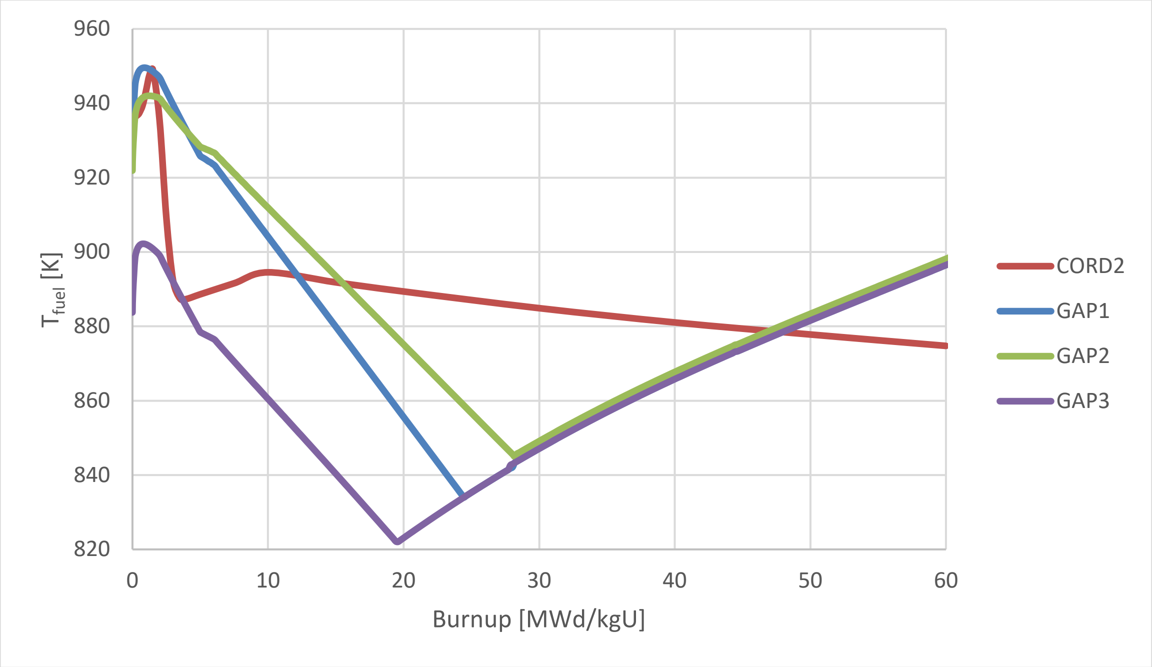

Figure 1: Fuel temperature predictions as a function of burnup for different heat transfer models

3.2 Fuel assembly

It is interesting to evaluate what is the impact of such temperature differences on the neutron transport. A typical fuel assembly with 4.95 % enrichment in an infinite array was chosen as a test case. Parameters of the test case simulates Hot Full Power (HFP) average operational parameters applied in the last NPP Krško cycles.

The impact of FINIX results to the multiplication factor k_{inf} compared to the reference CORD-2 values, as a function of burnup, are shown in Figure 2. Differences between FINIX and CORD-2 are within ± 200 pcm range, while individual FINIX models differ from each other up to 150 pcm. These are significant variations, which could result in the reactor core critical boron differences of few tens of ppm. It should be noted that these differences are directly applicable to the prediction of the reactivity power defect, since the temperature in the reference Hot Zero Power (HZP) state is the same in all cases.

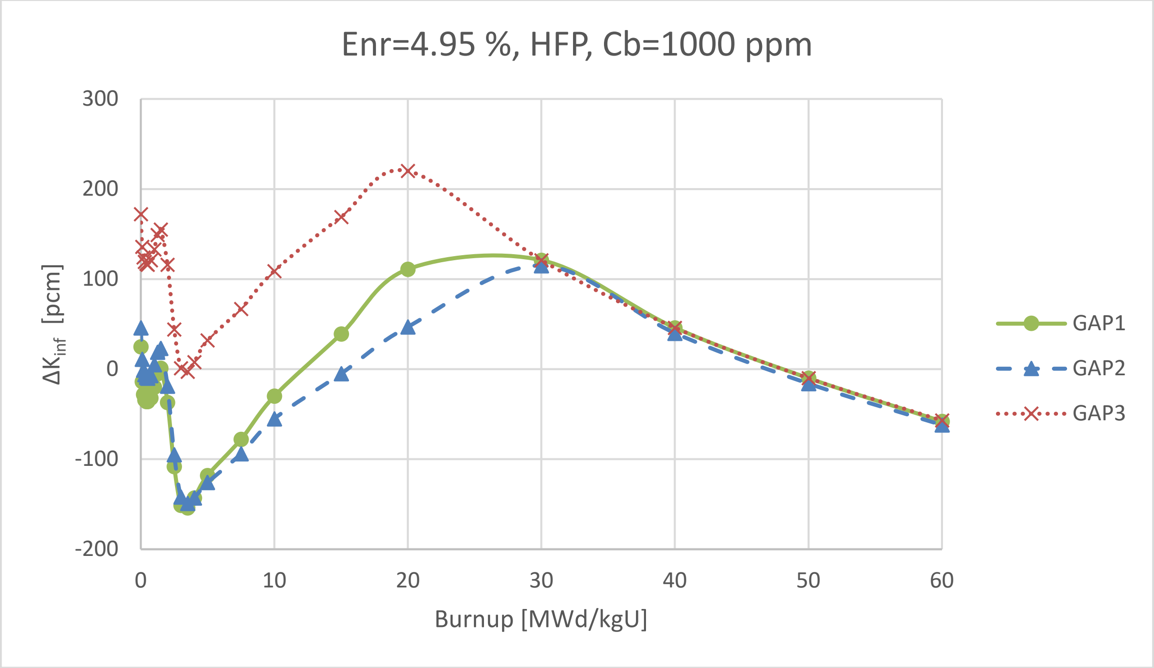

Figure 2: Differences in multiplication factor as a function of burnup from the reference CORD-2 results

3.3 Critical boron concentrations

In order to evaluate the fuel temperature effect on the core behavior, calculations of 30 NPP Krško operational cycles were performed. Differences from the measurements performed periodically at the plant are presented in Figures 3-6.

Differences from the measurements at HZP conditions at the Beginning Of the Cycle (BOC) are almost negligible (Figure 3). This is understandable, since the temperature is the same in all models and we only see differences from slightly different nuclide composition caused by the neutron spectral changes induced by different temperature models in the already burned fuel.

Differences at HFP condition (Figures 4-5) are larger. FINIX results give up to 20 ppm higher boron concentrations compared to CORD-2 with increased deviations from the measurements. The effect is caused by somewhat lower fuel temperature in the fuel already burned in the previous cycle. Differences at the EOC, shown in the Figure 6 are again smaller. Slightly lower temperatures in the FINIX models are compensated through the changes in nuclide composition caused by the neutron spectral changes.

It is instructive to inspect only specific parts of the fuel cycle. A good parameter is the difference in critical boron concentration between HZP and HFP critical boron concentration at 500 MWd/tU. This difference covers reactivity power defect, worth of equilibrium xenon and changes in samarium concentration from initial cycle value (0 in fresh fuel) to equilibrium. The discrepancy of this parameter from measured values for all 30 cycles are plotted in Figure 7. The FINIX GAP3 model seems to give the best results. This is consistent with our previous work [9], which indicated that the CORD-2 fuel temperature model might give too high fuel temperatures.

The second inspected parameter is the difference of the HFP critical boron concentration between 500 MWd/tU and EOC burnup. This difference covers almost the entire fuel burnout during the fuel cycle. Discrepancies of this parameter from measured values are plotted in Figure 8. The FINIX GAP3 model is slightly overpredicting the measured difference.

According to the findings in [9], this is very convenient and allows the introduction of ENDF/B-VIII.0 [10] cross sections, since this library provides smaller parameter values compared to the values obtained by the ENDF/B-VII.0 cross sections used in the present analysis.

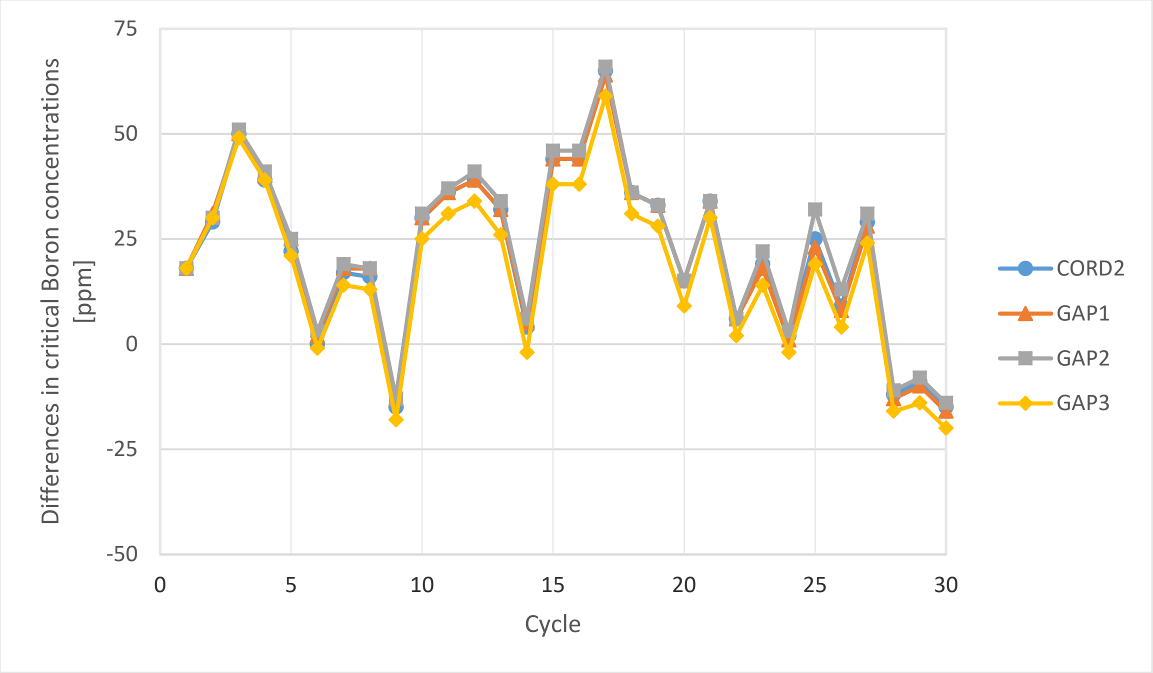

Figure 3: Differences in the critical boron concentration at HZP, BOC for different operating cycles of NPP Krško

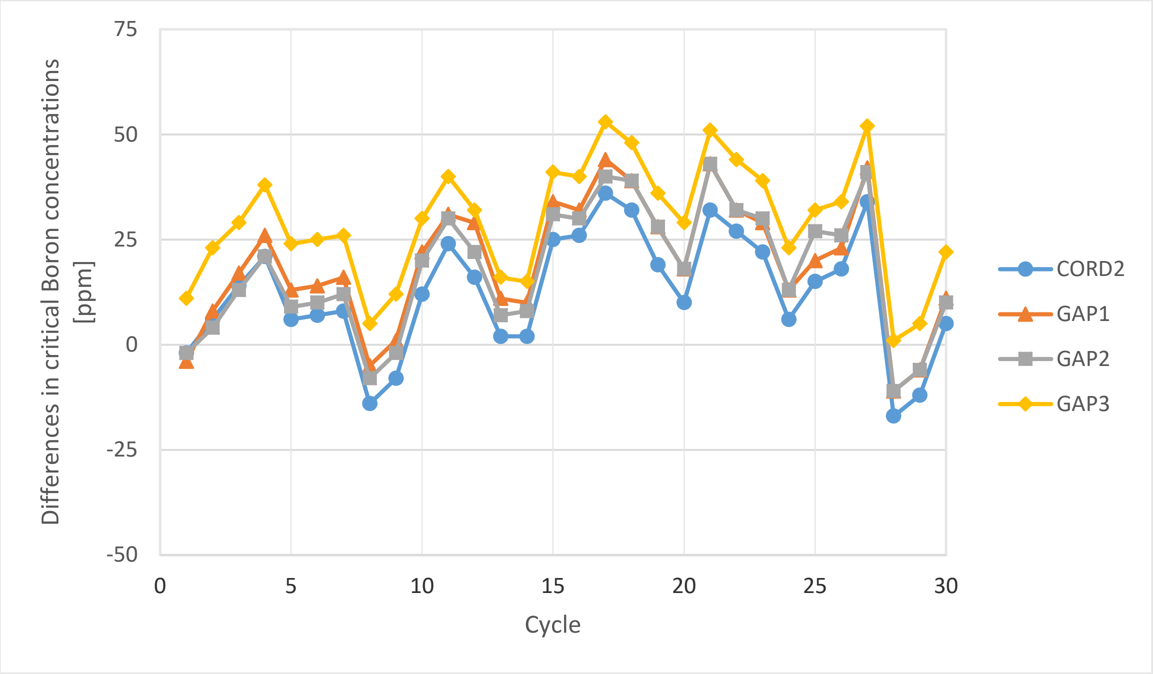

Figure 4: Differences in the critical boron concentration at HFP, 150 MWd/tU for different operating cycles of NPP Krško

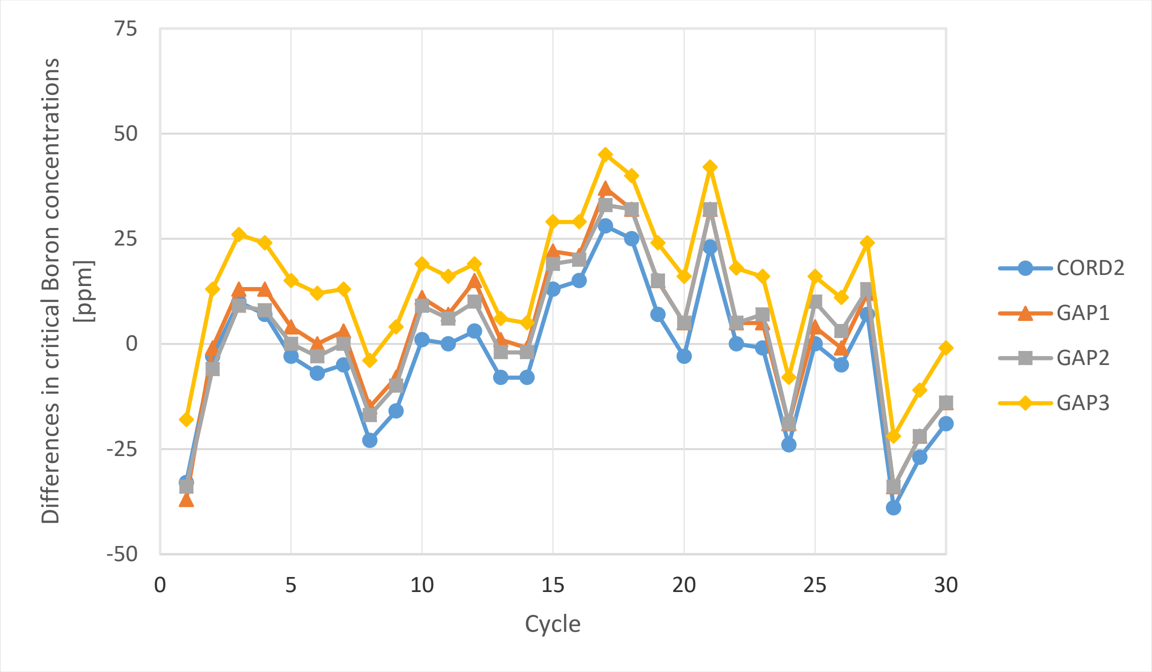

Figure 5: Differences in the critical boron concentration at HFP, 500 MWd/tU for different operating cycles of NPP Krško

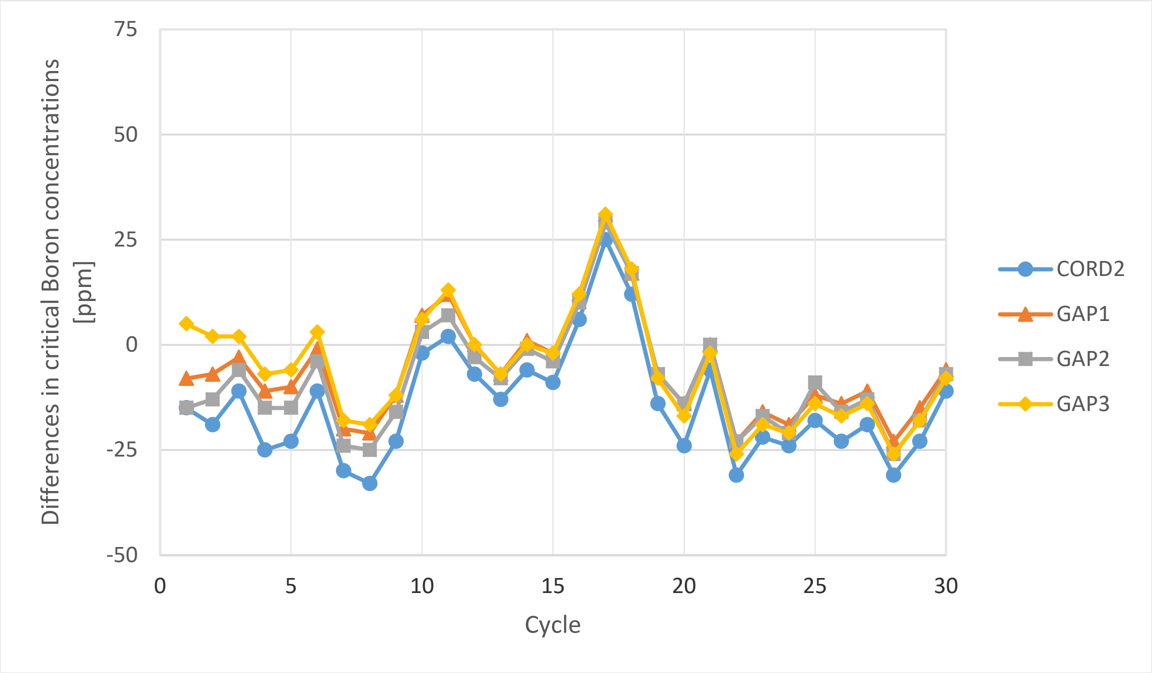

Figure 6: Differences in the critical boron concentration at HFP, EOC for different operating cycles of NPP Krško

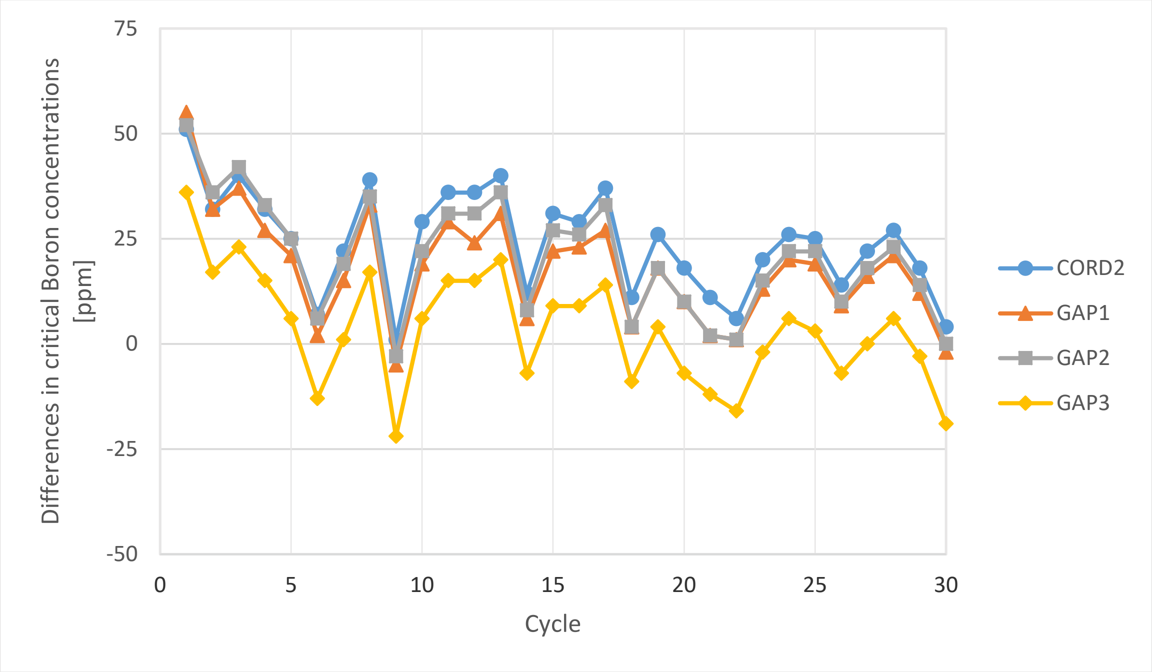

Figure 7: Differences in the critical boron concentrations ($Cb_{HZP,\ 0\ MWd/tU}$ - $Cb_{HFP,\ 500\ MWd/tU})^{x}$ - ($Cb_{HZP,\ 0\ MWd/tU}$ - $Cb_{HFP,\ 500\ MWd/tU})^{measured}$ for different operating cycles of NPP Krško

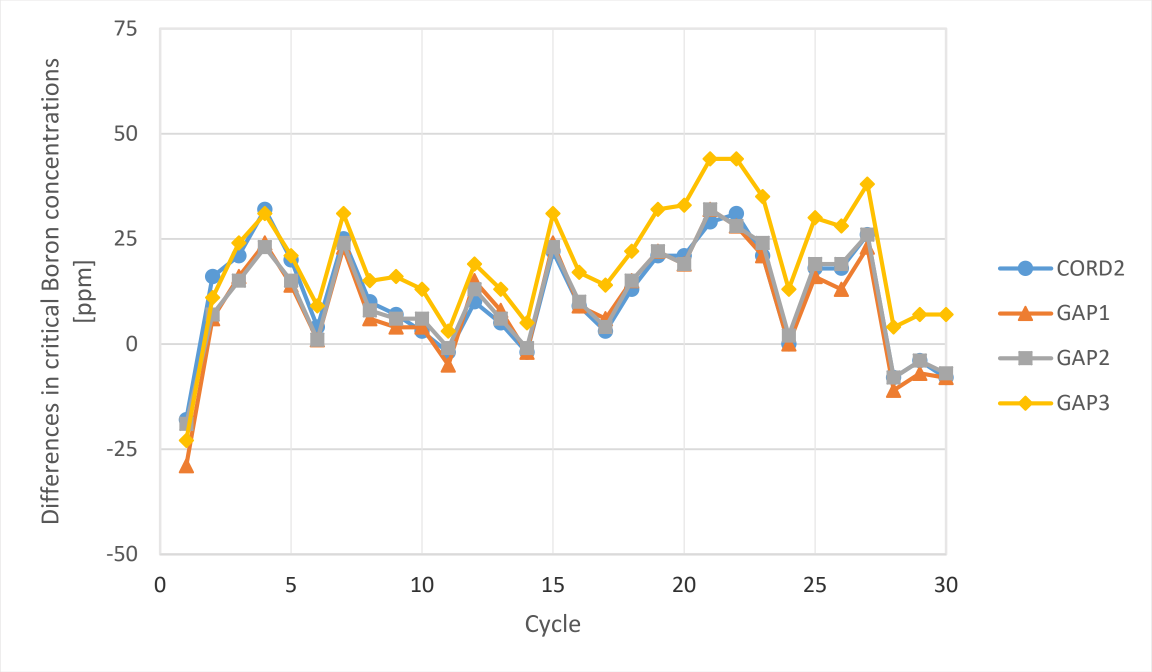

Figure 8: Differences in the critical boron concentrations ($Cb_{500\ MWd/tU}$ – $Cb_{EOC})^{x}$ - ($Cb_{500\ MWd/tU}$ – $Cb_{EOC})^{measured}$ for different operating cycles of NPP Krško

4 CONCLUSION

The objective of this work was to evaluate the effect of different fuel temperature models used for the nuclear core simulation calculations. The standard CORD-2 temperature model obtained from the PIN code calculations was compared to the several FINIX temperature models.

Differences between the FINIX and CORD-2 predictions are up to 70 K, while the different FINIX models give up to 50 K differences in the fuel temperature predictions over the evaluated fuel burnout range. These differences affect the fuel assembly reactivity estimations. Differences between the FINIX and CORD-2 values are in the range ± 200 pcm, while individual FINIX models differ among themselves by up to 150 pcm at the fuel assembly level. In order to evaluate the effects of fuel temperature on the reactor core behavior, calculations of 30 NPP Krško operational cycles were performed using different temperature models. Comparison with measurement data showed that the best results were obtained with the temperatures from the FINIX code using the FRAPCON-4.0 gap conductance model. Results have confirmed our previous indications and will allow the introduction of the newer neutron cross section library in the CORD-2 system.

ACKNOWLEDGMENTS

This work has been founded from the ARRS project “Stability of nuclear reactors in load follow mode of operation”.

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