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Three-Batch Reloading Scheme for IRIS Reactor Extended Cycles

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ABSTRACT

To fully exploit the IRIS reactor optimized maintenance, and at the same time improve fuel utilization, a core design enabling a 4-year operating cycle together with a three-batch reloading scheme is desirable. However, this requires not only the increased allowed burnup but also use of fuel with uranium oxide enriched beyond 5%. This paper considers three-batch reloading scheme for a 4-year operating cycle with the assumptions of increased discharge burnup and fuel enrichment beyond 5%. Calculational model of IRIS reactor core has been developed based on FER FA2D code for group constants generation and NRC's PARCS nodal code for global core analysis. Studies have been performed resulting in a preliminary design of a three-batch core configuration for the first cycle. It must be emphasized that this study is outside the current IRIS licensing efforts, which rely on the present fuel technology (enrichment below 5%), but it is of long-term interest for potential future IRIS design upgrades.

1 INTRODUCTION

The International Reactor Innovative and Secure (IRIS), an integral, modular, medium size (335 MWe) PWR, has been under development since the turn of the century by an international consortium led by Westinghouse and including over 20 organizations from ten countries [1]. Maintenance of IRIS reactor has been optimized to enable extended operating cycles up to four years [2]. Different IRIS reactor fuel management options have been examined with the assumption of current enrichment licensing limitation (less than 5% enriched uranium oxide) [3], leading to a two-batch reloading scheme. To fully exploit the IRIS optimized maintenance, and at the same time to improve fuel utilization, a core design enabling a 4-year operating cycle together with a three-batch reloading scheme is desirable. However, this requires not only the increased allowed burnup but also use of fuel with uranium oxide enriched beyond 5%.

This paper considers three-batch reloading scheme for 4-year operating cycle with the assumptions of increased discharge burnup and fuel enrichment beyond 5%. Studies have been performed resulting in development of a preliminary three-batch core design. It must be emphasized that this study is outside the current licensing efforts, but it is of long-term interest for potential future IRIS design upgrades. Development of a three-batch reloading scheme for IRIS reactor extended cycles is described in Section 2. Calculational model of the IRIS reactor core is given in Section 3. A preliminary three-batch core configuration for the first cycle of IRIS reactor is presented in Section 4. Conclusions are given in Section 5.

2 DEVELOPMENT OF THREE-BATCH RELOADING SCHEME

For a three-batch reloading scheme it is assumed that about one third of all fuel assemblies are replaced each cycle. Due to the requirement of quarter core symmetry and discharge burnup limit we assumed replacing 32 out of 89 fuel assemblies at the end of each cycle. Additionally, we consider use of erbium as burnable absorber (BA), in the form of erbia (Er_2O_3), directly mixed with the uranium oxide fuel. We also assumed that the axial fuel stack is composed of the main central part with erbia and the top and bottom axial blankets containing reduced U^{235} enrichment. In the development of a three-batch reloading scheme we employed a checkerboard pattern of fresh fuel, once burnt fuel, and twice burnt fuel. Our goal is to determine enrichment of fresh fuel as well as concentrations of erbia, which will enable 4-year operating cycle length and acceptable loading pattern for the first and equilibrium cycles.

In cycle 1 all fuel is fresh; therefore, once-burnt fuel and twice-burnt fuel are replaced by fresh fuel of reduced enrichments. These enrichments (including axial blankets enrichments) as well as the loading pattern for the first cycle have to be determined.

In order to perform loading pattern design calculations a new calculational model of the IRIS reactor core, based on FA2D code for group constants generation and PARCS nodal code for global core calculation, has been developed. The new calculational model is described in the next section.

3 CALCULATIONAL MODEL

Homogenized two-group cross section data at fuel assembly level were calculated using FA2D, 2D collision probability transport code developed at FER. One eighth of IRIS fuel assembly is modeled. Two equal-volume rings are used in UO_2 pellets and 4 angular sectors per cell. The total number of flat flux regions in the model is 735. Fuel rod gaps and inter-assembly gaps are explicitly modeled. Cold dimensions were used in calculations. Spacer material is mixed with moderator to form a homogenous mixture. Moderator density is calculated from the input temperature and system pressure using IF97 [4] water and steam properties. Numerical integration parameters used in collision probability solver determine accuracy of the procedure. The distance between parallel lines used in discretization is 0.05 cm with the number of equally spaced angles being 16. The normalized calculated volume was used in calculation. Tracking distance used in ray tracing algorithm is 6 mean free paths. Reflective boundary conditions were used at outside boundaries.

The neutron data library used in calculation is based on ENDF/B-VI.5 library with additional Er isotopes taken from JENDL 3.3 library. The number of micro groups in library is 97. In order to speedup depletion calculation at some burnup steps, 2D transport calculation was done using only 21 groups. Group collapsing is based on less frequently calculated 97-group spectrum. The influence of that assumption is checked against full group depletion at average fuel assembly parameters showing small difference if recalculation interval is of reasonable length and if burnups where full treatment is used are judiciously chosen. The fundamental mode B1 leakage spectrum was used for depletion and for calculation of 2-group cross section data. Integration is of the predictor corrector type. Burnup calculation was performed at fuel assembly level up to 72 GWd/tU. Depletion is at the nominal power density, boron concentration of 500 ppm and average thermal-hydraulic conditions (fuel average temperature is 773.15 K, clad temperature is 613.15 K, moderator temperature/density is 584.15 K/0.7025 g/cm^3). The procedure was performed for each material composition used in the core. The material composition is determined by fuel enrichment and burnable absorber weight fraction. Seven compositions were used in the proposed core loading pattern. Branch points calculations were performed at 14 burnup points using isotopic compositions calculated during depletion under average conditions. As a result of branch point calculations, cross section (XS) tables were generated. Presently the history effects are not included. In order to keep the number of calculations at a reasonable level only three branch points were used to describe local variations in each variable (moderator temperature/density, fuel temperature, boron concentration), leading to the number of branch points calculation per burnup point equal to 27. The post-processing program saves XS 2-group data for each material composition in a format similar to the cross section library format used in the MSLB benchmark [5]. In addition to usual macroscopic cross sections, discontinuity factors were saved, microscopic cross sections, yield fractions and decay constants for Xenon (Iodine) and Samarium (Promethium), average neutron fluxes, power factors to be used in pin power reconstruction, delayed neutron data needed only for transient calculation and multiplication factors for each of the branch points. The library is organised in a way that for each burnup point all relevant data are stored in the form of a 3D array (data from branch point calculation), and then block is repeated for each burnup point. Each composition can have its own number and values of thermal hydraulics variables and burnup points. The library is in ASCII format so it can be viewed or modified from outside. Presently FA2D has no capability to calculate reflector constants, so reflector data are entered manually based on separate calculation using required data format. In the case of IRIS steel radial reflector the cross sections are provided by Westinghouse. In order to keep and use cross section data within nodal code, a separate data structure is developed using Fortran 90 user derived types and module properties. The coding is so organized that it can be plugged into almost any nodal code for 3D depletion or transient calculation. A trilinear interpolation procedure (similar to the one used in 3D linear FEM) is part of the implementation.

A modified version of the NRC's 3D nodal code PARCS v2.3 [6] was used for depletion at core level. The modification was done in order to provide internal depletion capability and to make possible usage of cross section tables prepared by FA2D code. Something similar was done by Purdue University using external PVM coupling and data from HELIOS and NEWT codes. Beside a couple of new switches and new XS table input, the only changes required in PARCS input are burnup steps (in terms of cycle burnups) to be used in depletion calculation, initial 3D burnup distribution and data needed to calculate heavy metal mass in the initial core loading. These data include number of pins per FA, effective UO_2 and Er_2O_3 density and for each type of fuel, nominal pellet diameter, pellet dishing, and fuel enrichments with corresponding burnable absorber fractions. Based on the described data the initial heavy metal mass in each PARCS calculation cell was calculated as well as the initial heavy metal mass per FA and the total heavy metal mass initial core loading. The data are required in calculation of the core burnup distribution. Based on the initial data, critical boron concentration and power distribution for the core are calculated. Using input cycle burnup increments, nominal core power and initial core loading, duration of each step in EFPDs is calculated, and using these times and calculated cell powers and heavy metal mass loadings burnup increments for each cell are calculated. Based on the new burnup distribution the step is repeated and initial burnup distribution for the next step is calculated as arithmetic average of burnups obtained in predictor and corrector step. Xenon correction of XS data is implemented as part of calculation of cross sections for local thermal-hydraulic conditions. Cross section data were calculated using trilinear interpolation for two burnup points of the interval containing the wanted local burnup. Final values are again obtained through linear interpolation from the values for two bounding burnups. Order of interpolation within the trilinear procedure can be chosen from outside. Two presently used schemes are: (1) moderator density – boron concentration – fuel temperature; and, (2) fuel temperature –

moderator density – boron concentration. Fuel temperature interpolation is in terms of square root of Doppler fuel temperature.

PARCS model used in depletion assumes 2×2 nodes per fuel assembly and 28 equidistant nodes in axial direction. Thickness of axial reflector is 30.48 cm and radial reflector is modeled with fictitious calculation cells of the same size as fuel elements. The thermal-hydraulic model of PARCS code is a simple one, suitable for single-phase flow. In present calculation one TH channel per FA was used with 6 nodes per pellet, 2 nodes in cladding and a constant value of gap heat transfer coefficient. Nodal kernel of HYBRID type was used in calculation with a nonlinear update frequency of 2 (preliminary loading pattern with high enrichments and Erbium weight fractions causing significant changes in material compositions and rather high peaking factors) and T/H calculation at each nonlinear update. Criterion for eigenvalue convergence check was 1.0E-06. Maximum number of outer iteration was 500 with Wielandt shift acceleration applied. Pin power reconstruction was not used in this preliminary phase.

4 THREE-BATCH CORE CONFIGURATION FOR FIRST CYCLE

The calculational model described in the previous section has been used to develop the three-batch core configuration for the first cycle of IRIS reactor. The configuration is shown in Figure 1. The nominal enrichments (enrichments of the fuel assembly central part) are 6.93 w/o, 3.1 w/o, and 2.1 w/o. The enrichments of the fuel assembly axial blanket are 3.1 w/o, 2.6 w/o, and 1.6 w/o. The erbia concentrations used in the central part of fuel assemblies with the highest enrichment are 2.5 w/o, 2.0 w/o, and 1.5 w/o. Core depletion calculation showed that the fuel inventory given above enables 4-year operating cycle length. The critical boron concentration as a function of burnup is shown in Figure 2. The radial peaking factor as a function of burnup, the axial peaking factor as a function of burnup, and the total peaking factor as a function of burnup are depicted in Figures 3 to 5, respectively. The axial relative power profiles for selected burnups of the first cycle are given in Figure 6. The three-dimensional relative power distribution up to axial layer 25 for cycle burnup of 30 GWd/tU is shown in Figure 7.

It must be emphasized that this loading pattern is not fully optimized because the primary goal was to determine the fuel inventory (fuel enrichment, burnable absorber concentrations), which enables 4-year operating cycle. In present calculation Xe correction was not enabled within the PARCS code and thus all cross section data are based on the equilibrium Xe concentration at nominal core average power density. That assumption caused an overestimation in the calculated peaking factors.

This core configuration for the first cycle will be used as a starting point to generate the loading pattern for a 4-year three-batch equilibrium cycle.

5 CONCLUSIONS

To fully exploit the IRIS reactor optimized maintenance, and at the same time improve fuel utilization, a core design enabling a 4-year operating cycle together with a three-batch reloading scheme is desirable. However, this requires not only the increased allowed burnup but also use of fuel with uranium oxide enriched beyond 5%. Calculational model of the IRIS reactor core based on FA2D code for group constants generation and PARCS nodal code for global core calculation has been developed to enable core configuration design. The three-batch fuel inventory and loading pattern for the first core of 4-year operating cycle has been determined. This core configuration for the first cycle will be used to generate loading patterns for the equilibrium cycle. It must be emphasized that this study is outside the current IRIS licensing efforts, but it is of long-term interest for potential future IRIS design upgrades.

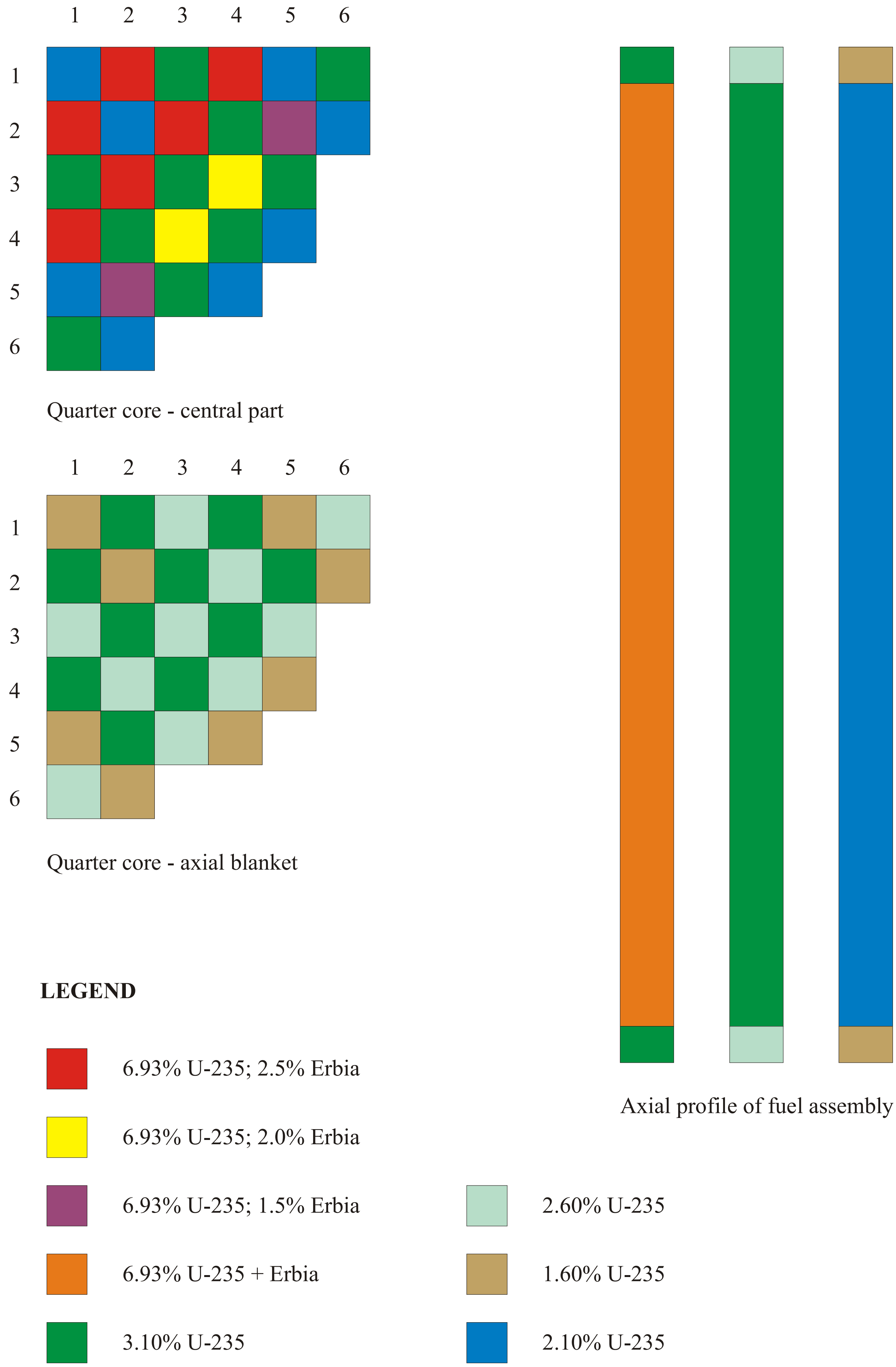

Figure 1**:** Three-batch core configuration for the first cycle

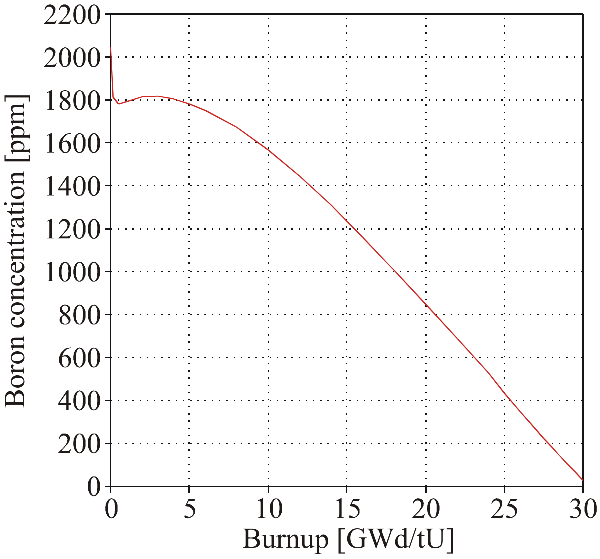

Figure 2: Critical boron concentration as a function of burnup for the first cycle

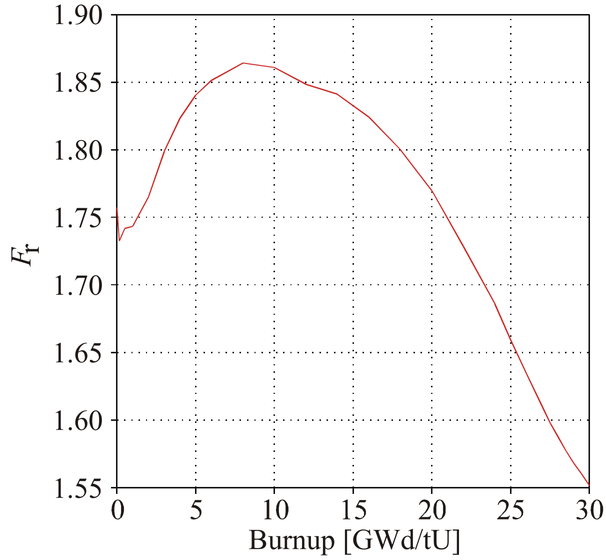

Figure 3: Radial peaking factor as a function of burnup for the first cycle

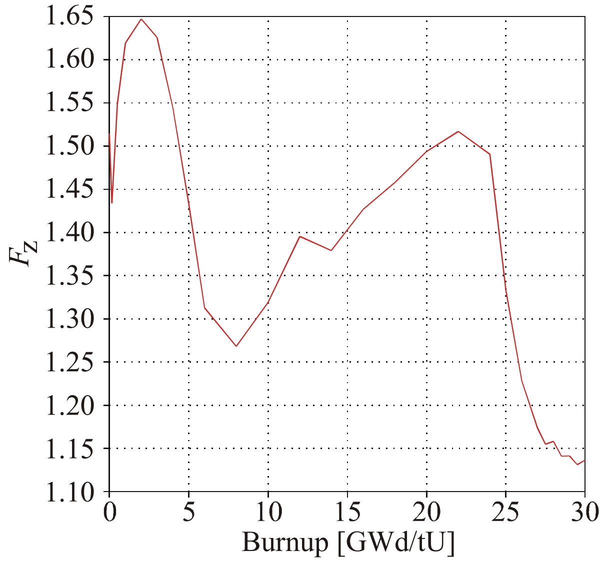

Figure 4: Axial peaking factor as a function of burnup for the first cycle

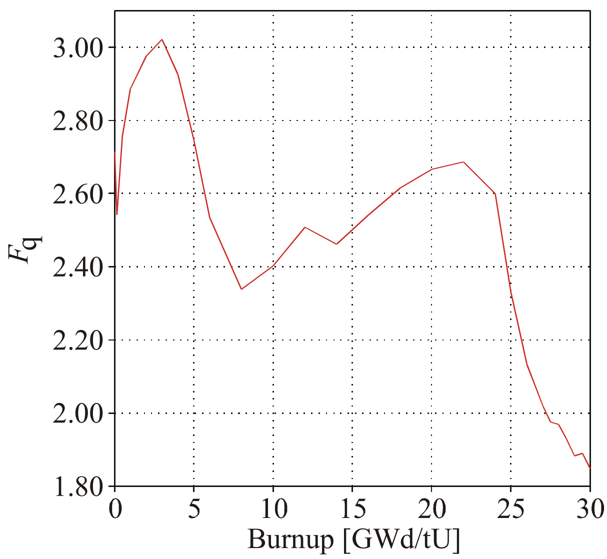

Figure 5: Total peaking factor as a function of burnup for the first cycle

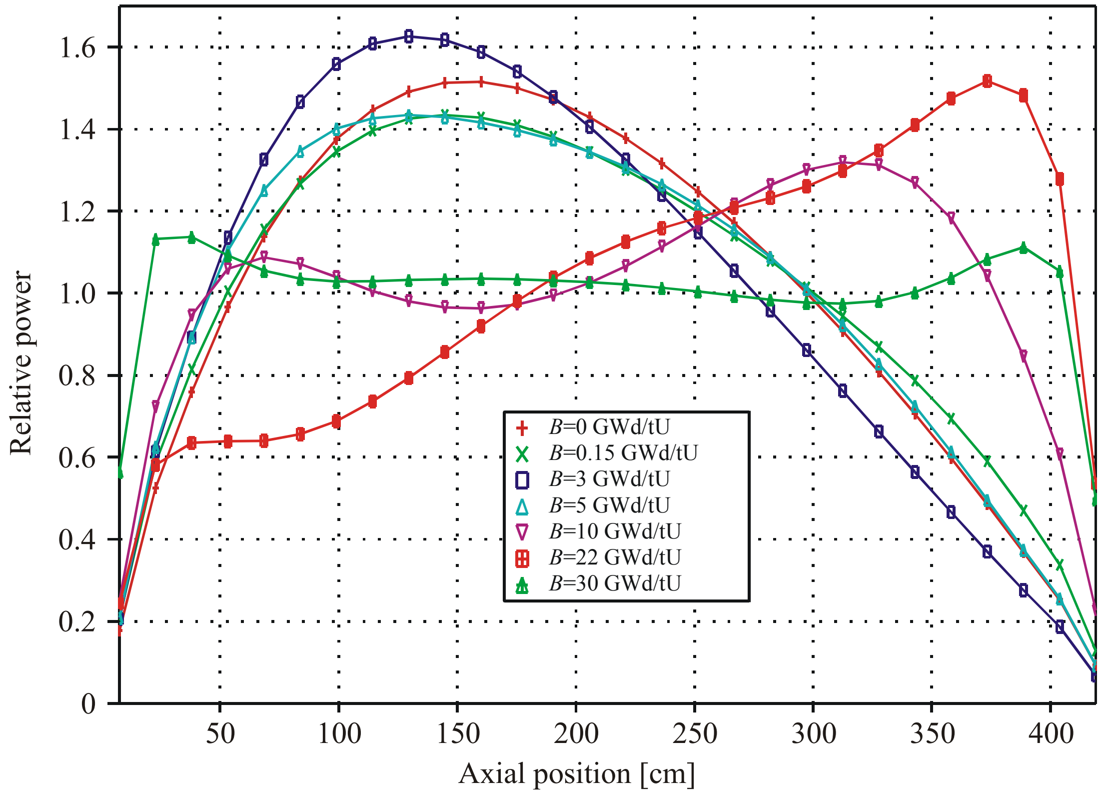

Figure 6: Axial relative power profile for selected burnup steps of the first cycle

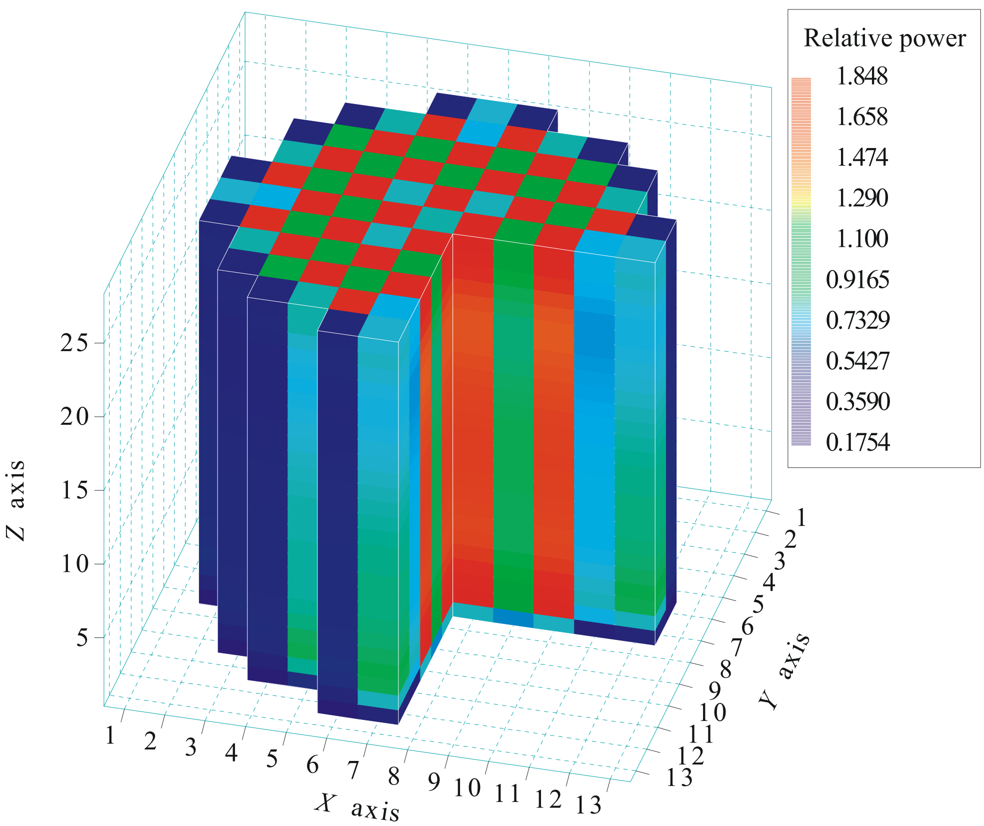

Figure 7: 3D relative power distribution up to layer 25 for first cycle burnup 30 GWd/tU

REFERENCES

[1] M.D. Carelli, L.E. Conway, L. Oriani, B. Petrović, et al., "The Design and Safety Features of the IRIS Reactor", *Nuclear Engineering and Design*, **230**, 151-167, 2004.

[2] M. Galvin, N.E. Todreas, L.E. Conway, "Maintenance Cycle Extension in the IRIS Advanced Light Water Reactor Plant Design", *Nuclear Technology*, **143**, 270-280, 2003.

[3] B. Petrović and F. Franceschini, "Fuel Management Options to Extend the IRIS Reactor Cycle", Proceedings of the 5th International Conference "Nuclear Option in Countries with Small and Medium Electricity Grids", Dubrovnik, Croatia, May 16-20, 2004. p. S-4.14.1-10.

[4] W.Wagner and A. Kruse, "Properties of Water and Steam, Springer-Verlag, Berlin, 1998.

[5] K.N. Ivanov, T.M. Beam, A.J. Baratta, A. Irani, N. Trikouros, "Pressurised Water Reactor Main Steam Line Break (MSLB) Benchmark", Volume I: Final Specifications: OECD NEA/NSC/DOC(99)8, April 1999.

[6] H. Joo, D. Barber, G. Jiang and T. Downar; "PARCS: A Multi-Dimensional Two-Group Reactor Kinetics Code Based on the Nonlinear Analytic Nodal Method", PU/NE-98-26, Purdue University, 1998.