BURNUP CALCULATIONS OF THE TRIGA RESEARCH REACTOR USING DETERMINISTIC AND STOCHASTIC CODES

ANŽE PUNGERČIČ, DUŠAN ĆALIĆ, LUKA SNOJ
Reactor Physics Department, Jožef Stefan Institute
Jamova cesta 39, 1000 Ljubljana – Slovenia

ABSTRACT

The TRIGA Mark II research reactor at the Jožef Stefan Institute started operating more than 50 years ago and has been playing an important role in developing nuclear technology and safety culture in Slovenia. Recently we initiated activities to thoroughly document and analyse complete operation history. From this a detailed TRIGA model in 3D Monte Carlo Serpent code was made together with a complete history simulation using deterministic in-house developed 2D TRIGLAV code. The latter was compared with the measurements of excess reactivity, where clear correspondence is observed. With Serpent, preliminary tests of TRIGA burnup calculations were performed to optimise the time and CPU usage for future simulations. From this, isotopic composition distribution in all four types of TRIGA fuel elements was obtained. The results show great promise in fuel management optimisation as well as the determination of final isotopic composition of each fuel element ever used in the reactor.

1. Introduction

The TRIGA Mark II research reactor at the Jožef Stefan Institute in Slovenia achieved first criticality on May 31st 1966. Its maximum steady-state power is 250 kW. In 1991 it was reconstructed for pulse mode operation, where the peak power reaches up to 1 GW. The reactor is mainly used for training and education of university students, future operators at the Slovenian Nuclear power plant Krško, neutron activation analysis, radiography and validation of computer codes and nuclear data [1]. Before the reconstruction, the reactor was also used for isotope production, therefore high amount of burnup was achieved in older fuel elements.

In the 50-year operation period more than 300 different fuel elements were used, arranged in 220 reactor core configurations (cycles). As more than 200 irradiated fuel elements were shipped back to USA in 1999, amount of fresh fuel is limited and therefore optimization of fuel management is required. Determination of individual fuel element burnup and its isotopic composition is vital to optimise fuel management strategy together with accessing the reactor life-time and later the decommissioning of the research reactor. In addition fuel burnup data is one of the key information, when shipping irradiated fuel to another site or to the final depository. The first step in fuel burnup determination is knowing the research reactor operation.

The complete operational history of diverse reactor operation since the first criticality is thoroughly described in the operator logbooks. This information is very valuable as it allows us to use the data for experimental validation of reactor simulation codes, such as neutron transport and fuel burnup codes. A need for experimental benchmark experiments for the purpose of validation of computer codes has already been identified by the OEXD NEA [2]. However publicly available data about operational history of reactors that could be used for burnup calculation validation are very scarce. Some experiments at the JSI TRIGA research reactor already serve as international benchmark experiments for criticality and reactor physics calculations [2][3][4]. Hence it was decided to analyse the complete operational history and use the data for burnup calculations performed by the in-house developed deterministic TRIGLAV [5] and stochastic Serpent [6] neutron transport and burnup code.

2. Operational History Analysis

The source of the JSI TRIGA research reactor operational data are the reactor logbooks in which TRIGA operators note every change made with the reactor. In total around 200.000 pages were analysed in 50 reactor logbooks. An example of logbook entry is shown in Fig. 1. Data for every single operation made with the reactor was obtained and put into a computer readable format, where information regarding the reactor power changes, fuel element positions and movements in the core and excess reactivity measurements are stored.

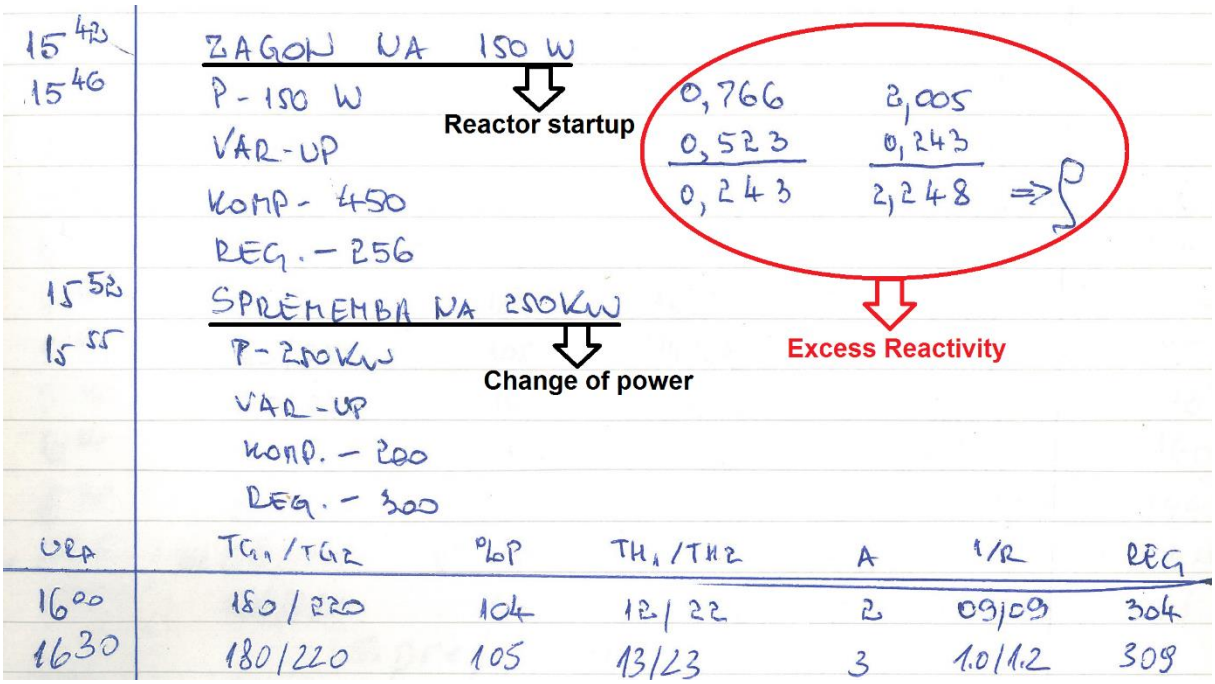

Fig 1. Reactor operation log entry example in which reactor started operating at 15:42 on power 150 W, where excess reactivity measurement was performed. After that the reactor power was changed to its steady-state full power 250 kW.

From reactor operation data, we are able to calculate the energy generated from each operation and analyse the changes in excess reactivity. The sum of energy generated from 1966 to 2017 is 24.1(1 ± 0.1) GWh in total. The quoted uncertainty is due to the uncertainty in the steady-state reactor power, which can contribute up to 10 % [7]. Measured excess reactivity for one year period is presented on Fig. 2, where the changes due to fuel shuffling and fuel element burnup are visible.

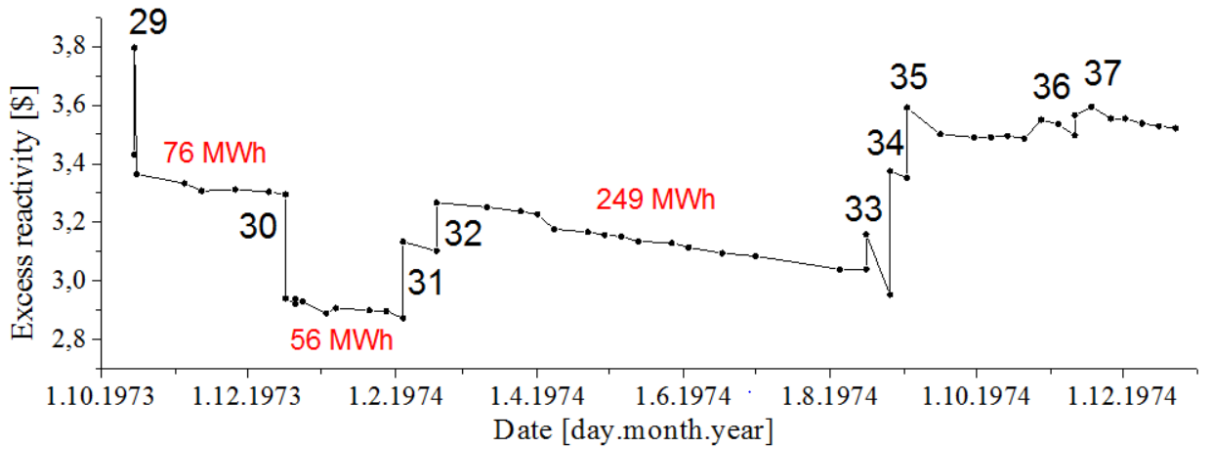

Fig 2. Example of excess reactivity measurements for a period from 15.10.1973 to 23.12.1974. Energy generated for longer operations on core No. 29, 30 and 32 are denoted.

Other uncertainties related to measurements of excess reactivity are the uncertainty in control rod calibration and uncertainty in core reactivity changes due to inserted samples and xenon build-up. Reactor operators measure excess reactivity after the reactor was not operating for at least two days to minimize the uncertainty due to xenon build-up. Both other contributions could be estimated with the analysis of the history of control rod calibrations and sample irradiations.

2.1 TRIGA core configurations

In the reactor operation history four different fuel element types were used, with characteristics given in Tab. 1. Fuel elements are cylindrical rods with Type 304 stainless steel (SS) or aluminium (Al) cladding. Fresh fuel is a homogeneous mixture of uranium (U), zirconium hydride (ZrH) and burnable poison erbium (Er), which is only present in HEU fuel elements. In the centre of the fuel rod is a region filled by a zirconium rod with the exception of the LEU Al fuel element. Fuel element illustration is presented in next section where the Serpent TRIGA model is analysed and used to calculate isotope distribution in all four types of fuel elements.

Tab 1. Generic data on TRIGA fuel elements properties [8].

	Aluminium 8.5 %	Standard 8.5 %	Standard 12 %	FLIP 8.5 %
Type → Composition*	LEU	LEU	LEU	HEU
Fuel	U-ZrH	U-ZrH	U-ZrH	U-ZrH-Er
Cladding	Al	SS 304	SS 304	SS 304
U content [wt%]	8.5	8.5	12	8.5
Mass(U) [g]	185	190	277	192
Enrichment [%]	20	20	20	70
Mass(^{235}U) [g]	37	38	55	134
Burnable poison	-	-	-	Er (1.5 wt %)
Years of usage	1966-1983	1970-1996	1991-	1973-1991

*Typical fuel element composition data. Some fuel element data can differ from values in this table.

In order to get accurate data for a particular fuel element, delivery documentation for every element had to be analysed and compiled in a table for later use in calculations. During the analysis we found that 105 out of 123 Standard 8.5 % Stainless Steel fuel elements were already used in a TRIGA Mark I research reactor at Goethe University in Munich, Germany. These elements were later sent to our TRIGA reactor and were even used after the reconstruction in 1991. Therefore burnup calculations cannot be split into two parts (before and after the reconstruction) and additional uncertainty arises from unknown burnup of these fuel elements.

The next step of the analysis was to determine the position of the fuel elements in the reactor core over time. Fuel element movements were tracked throughout complete history, together with energy released on each core configuration (cycle). In total 218 cycles were analysed to create the complete TRIGA operation history model, which can be used for detailed burnup calculations.

3 Description of burnup calculations

In the past criticality calculations were performed with MCNP on TRIGA core benchmark with burned fuel [9] [10], in which fuel element burnup was determined with deterministic TRIGLAV code [5]. Our goal is to calculate the burnup of each fuel element in every step of the JSI TRIGA Mark II operation. This was already performed using TRIGLAV code, due to its simplicity and short calculation time for each cycle ($\approx$ 2 min). Main goal is to eliminate the use of deterministic code and use stochastic Monte Carlo codes for both criticality and burnup calculations. With the fast development of computing power this was made possible in the recent years. For this purpose we chose the Serpent 2 [6] neutron transport and burnup code and performed preliminary calculations on several cycles (calculation time $<$ 1 hour).

3.1 Deterministic TRIGLAV code

Neutron transport and burnup deterministic code TRIGLAV was developed at the Jožef Stefan Institute at the Reactor Physics Department. A more detailed description of the code can be found in [5], as only a brief description relevant for understanding burnup calculations and the presented results is described in this paper. The code was developed for TRIGA reactor geometry with annular fuel element rings. The calculations are performed in two-dimensional (r,ϕ) geometry. It is based on the four-group diffusion equation, where effective cross-sections together with isotopic composition are calculated in the unit-cell approximation using WIMS-D/5 [11]. The geometry employed in the model encompasses the TRIGA cylindrical core in its entirety with a maximum of seven rings, subdivided into unit cells. Each fuel and non-fuel element position in the core is treated as a unit cell, which is represented with position coordinate and surrounded by water. Tracking position coordinates of inserted fuel elements enables the option to analyse fuel element shuffling. Schematic diagram of TRIGLAV burnup calculations is presented in Fig. 2, where fuel element burnup is characterized with the mass of ^{235}U and total burnup given in % of initial ^{235}U burned.

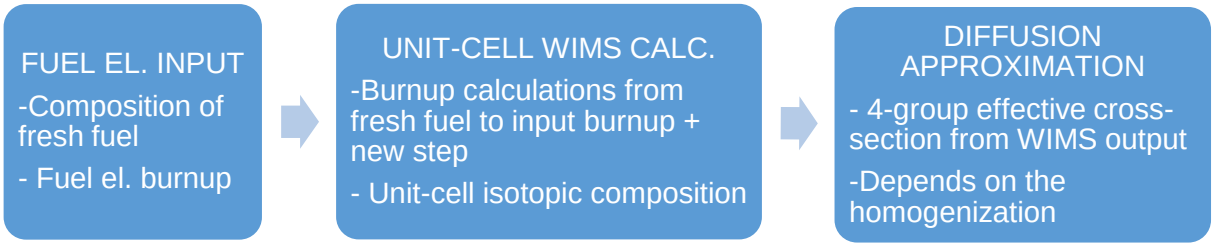

Fig 3. A simplified schematic diagram of TRIGLAV burnup calculations, which starts from 0 % burnup of a given fuel element in the unit-cell.

3.2 Stochastic Serpent code

Serpent 2 is a multi-purpose three-dimensional continuous-energy Monte Carlo particle transport code, that is still under development at VTT Technical Research Centre of Finland. The code has been publicly distributed by the OECD/NEA Data Bank and RSICC since 2009. Serpent burnup calculation capability was established early on, and is entirely based on built in calculation routines, without coupling to any external solvers. Irradiation history can be divided into multiple intervals with different normalizations, defined by power, power density, total flux, fission or source rate. Depletion steps are given in units of burnup or time. With the increased multi-core CPU's capabilities, full 3-D burnup calculations of research reactors are possible in acceptable time [3].

Similar to other Monte Carlo codes the basic geometry description in Serpent relies on a universe-based constructive solid geometry (CSG) model, which allows the description of practically any two- or three-dimensional fuel or reactor configuration. A geometrically detailed 3-D Serpent TRIGA model was developed and criticality calculations were compared to MCNP model and validated on benchmark core configurations [12] [13]. Geometry model of three new elements was added to the existing Serpent TRIGA Mark II. One of each type of TRIGA fuel elements was divided into 100 axial depletion zones in order to obtain axial isotope and burnup distribution. It is important to note that aluminium fuel elements contain absorbers in the form of samarium on top and on the bottom of the fuel meat, with comparison to stainless steel and FLIP elements, which have molybdenum absorber only on the bottom. With comparison to Serpent, TRIGLAV only has fuel meat included into the model.

The time integration method in Serpent burnup calculations was set to LELI, which uses linear extrapolation for the predictor method and linear interpolation for corrector method. The burnup optimization mode was set to maximum performance at the cost of memory usage, which resulted in calculation time to be less than half an hour for each burnup step.

4 Results

In this section, results of TRIGLAV and Serpent simulations are presented and analysed. Excess reactivity calculated with TRIGLAV for cycles with burned fuel is compared to weekly measurements. Isotopic distribution inside burned fuel elements was calculated with Serpent 2 code. In the last part, comparison of TRIGLAV and Serpent burnup calculation for benchmark core configuration [13] is presented and the discrepancies investigated.

For the analysis of excess reactivity reduction, two cycles were chosen based on high energy generated and higher number of measurements performed. At the start of both cycles burned fuel was used, therefore independent Serpent calculations were not possible as complete history was not yet simulated and isotopic composition for each cycle not determined. The measured excess reactivity for cycle No. 69 and 218 is compared to excess reactivity calculated with deterministic TRIGLAV code and presented on Fig. 4. Due to low burnup of both cycles, linear reduction of excess reactivity was approximated. The comparison of measured and calculated excess reactivity reduction coefficient is presented in Tab. 2. The relative difference between measured and calculated reactivity is 15 % for cycle No. 69 and 30 % for cycle No. 218. FLIP type fuel elements were used in cycle No.69, therefore the difference in excess reactivity reduction coefficient is expected.

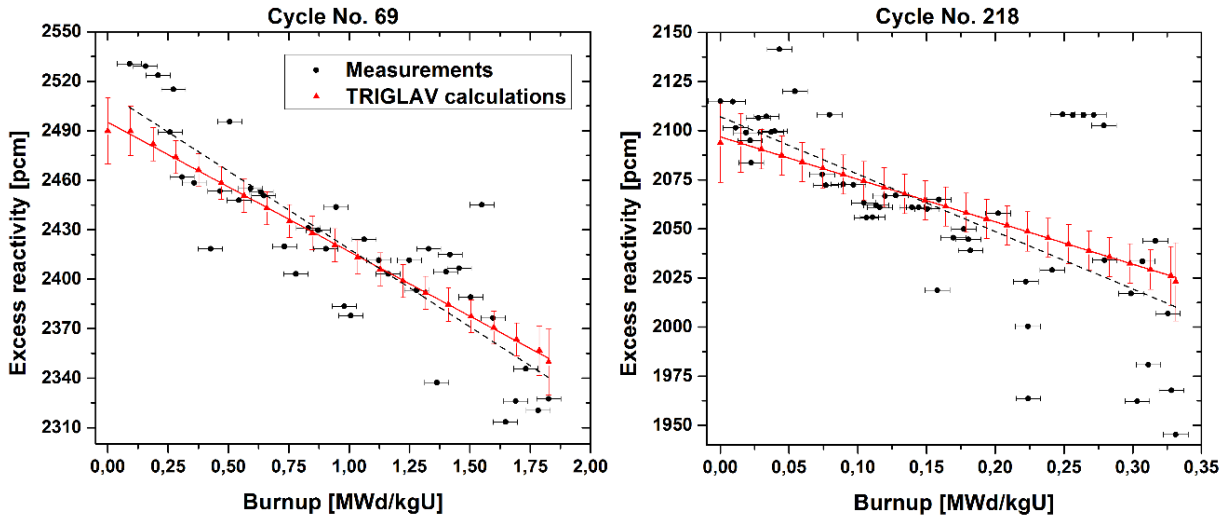

Fig 4. Reduction of excess reactivity due to burnup increase for cycle No. 69 and 218, calculated with TRIGLAV and measurements obtained from operational history analysis.

Tab 2. Comparison of measured and calculated excess reactivity reduction coefficient for TRIGA core with (cycle No. 69) and without burnable poison erbium (cycle No. 218).

Excess reactivity reduction coefficient	Cycle No. 69	Cycle No. 218
Measured $\left[\frac{pcm\ kgU}{MWd}\right]$	-94.4 ± 12.8	-292.4 ± 67.3
Calculated with TRIGLAV $\left[\frac{pcm\ kgU}{MWd}\right]$	-78.4 ± 3.9	-216.0 ±10.8

Hypothetical cycle with large was analysed with Serpent 2 code. All four types of fuel elements were represented in the outermost ring F. Fuel part of each fuel element was divided into 100 regions in order to obtain axial distribution of important isotopes. Distribution of ^{235}U and ^{135}Xe in all four types of fuel elements are presented in Fig. 5 together with thermal neutron flux distribution inside fuel and graphite part.

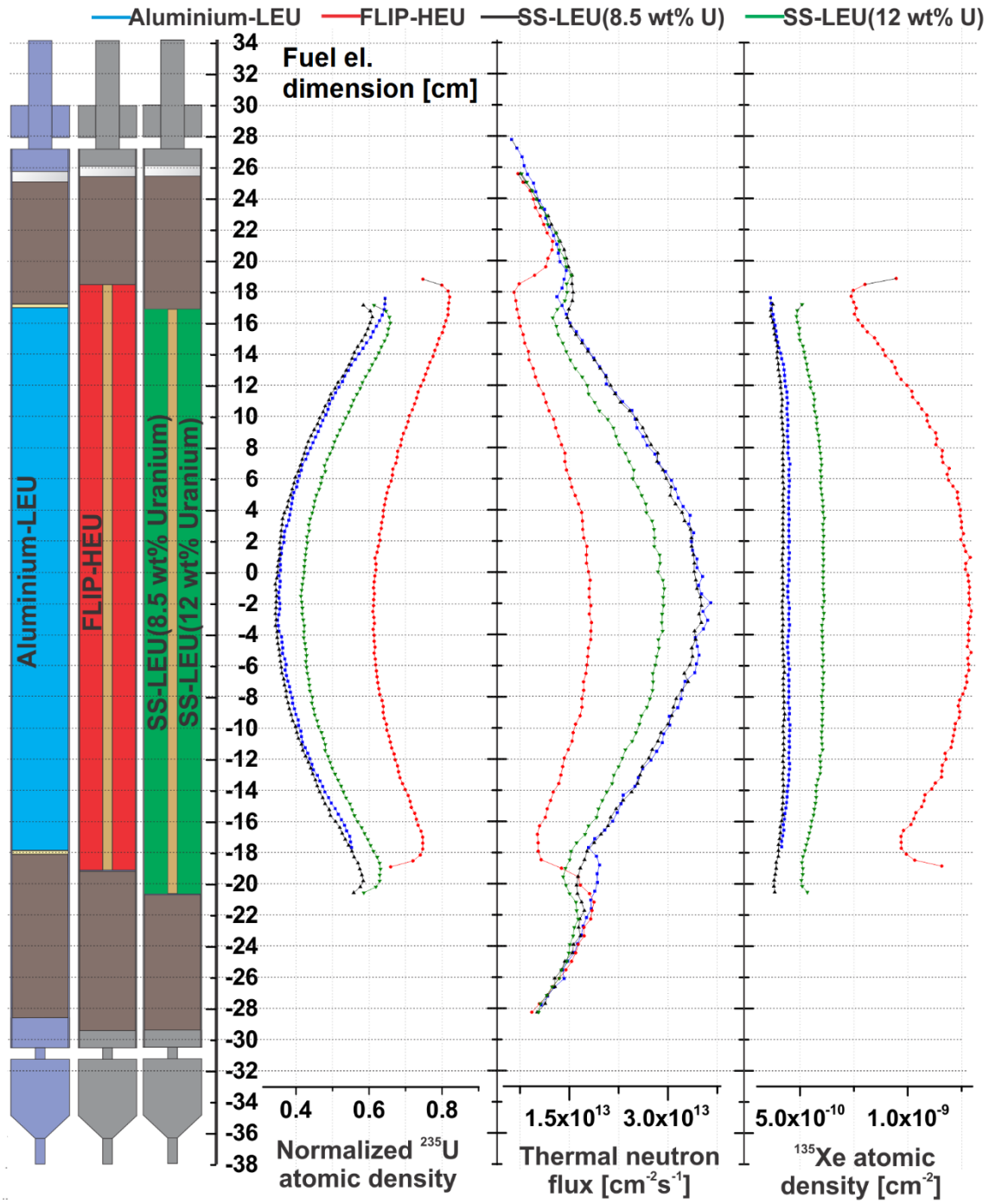

Fig 5. Isotopic distribution of ^{235}U and ^{135}Xe in highly burned fuel element. Thermal neutron flux distribution inside fuel and graphite is presented. Calculations were performed for all four types of fuel elements of which models are depicted on the left. Atomic density of ^{235}U was normalized to its initial value therefore % of initial ^{235}U burned is depicted on the first graph.

The absolute value of thermal neutron flux varies from previously calculated and measured values by one order, which could be explained with large final burnup of 100 $\frac{MWd}{kgU}$ and calculated k_{eff} of 0.82 in the last step. The difference in isotope distributions between HEU and LEU fuel elements was expected and ranges from 10 % to more than 50 % in thermal flux distribution. It is evident from the analysis that each type of fuel element should be taking into consideration separately with the exception of aluminium LEU and stainless steel LEU,

because both have same fuel composition of 8.5 wt% of 20% enriched uranium and the only difference is the cladding, which has no visible effect in study of isotope distribution.

For the comparison of deterministic TRIGLAV and stochastic Serpent codes, fresh fuel cycle was chosen and both programs had equal initial material composition. This cycle was chosen, because the measurements performed serve as a benchmark [13] for validation of neutron transport simulations. The fuel element burnup of the selected cycle was too low and therefore inadequate to show long-term expected decrease in reactivity. Substantial hypothetical burnup was used in the calculations to show the differences in calculated excess reactivity, as presented on Fig. 6. TRIGLAV's free parameter B (buckling) was determined so the calculated excess reactivity of the benchmark core matched the measured one. From this, we can also conclude that TRIGLAV code is viable for the analysis of relative changes due to burnup and fuel shuffling.

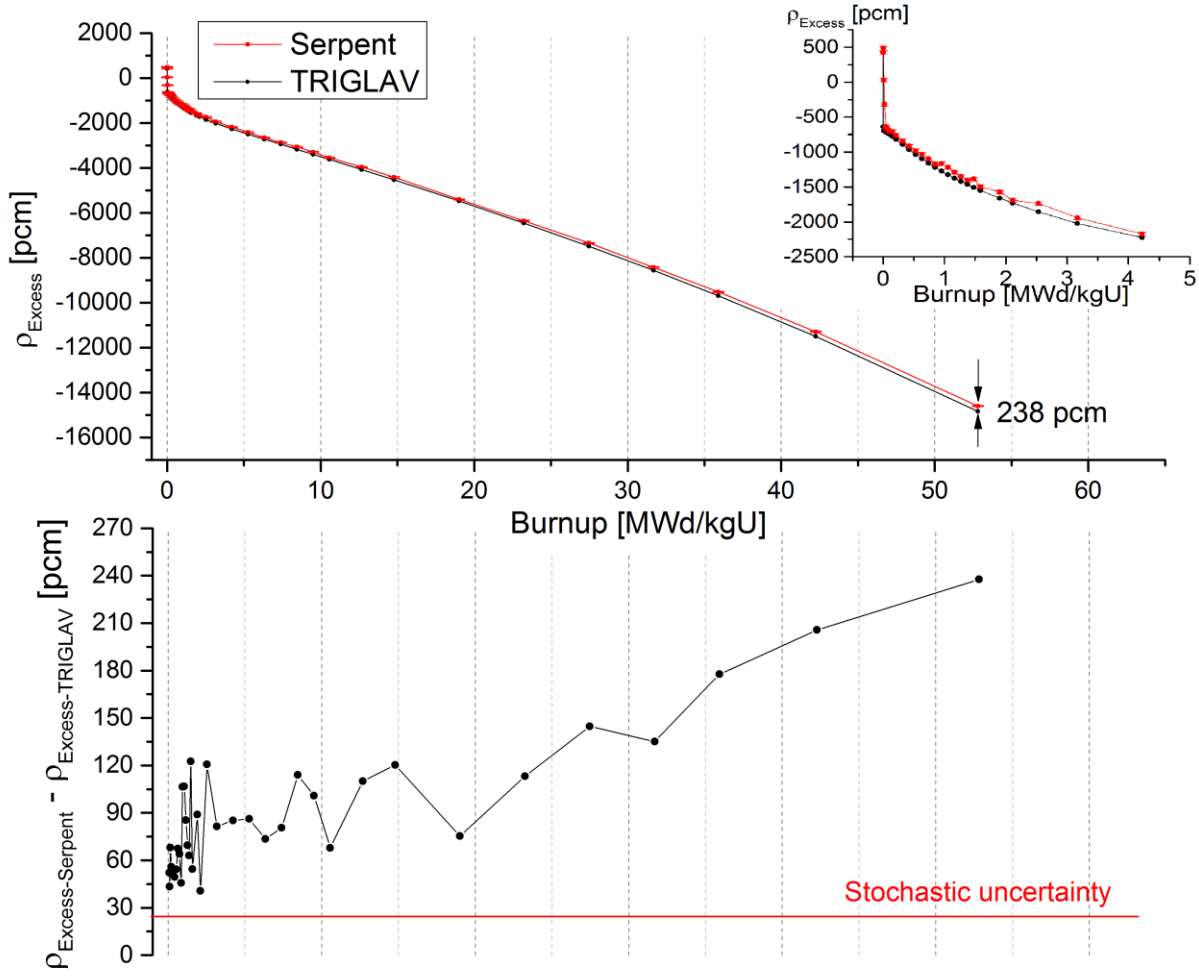

Fig 6. Excess reactivity ρ_{Excess} calculated with deterministic TRIGLAV and stochastic Serpent for benchmark cycle No. 132, with initial material condition of fresh fuel. Substantial hypothetical burnup was chosen in order to maximize the differences between used programs.

The difference between deterministic and stochastic codes is surprisingly low, even after burnup that represent complete burnup JSI TRIGA reached in 50 years of operation. It should be noted that difference between first four steps are substantial and were taken out of absolute difference analysis. This can be explained with TRIGLAV's approach to xenon concentration calculation, because if the burnup of fuel element is more than 0, the xenon is saturated. For burnups higher than 0.2 MWd/kgU this uncertainty is negligible.

5 Conclusion

The deterministic TRIGLAV code was compared to stochastic Serpent code in a TRIGA burnup calculation. The difference between the two codes was less than 250 pcm for larger burnup of 55 MWd/kgU. TRIGLAV code was compared to measurements of excess reactivity for two cycles with burned fuel. The isotopic distribution analysis provides the differences between all four types of fuel elements in form of distribution of burnup, fission products and the thermal neutron flux. Based on these first exploratory results great promise is shown in determination of burnup effects and final isotopic composition in a TRIGA reactor acquired with two independent neutron transport and burnup codes.

5 References

[1] L. Snoj, B. Smodiš, “45 Years of TRIGA Mark II in Slovenia”, Proc. Int. Conf. Nuclear Energy for New Europe 2011, Bovec, Slovenia, September 12-15, Nuclear Society of Slovenia, 2011.

[2] R. Jeraj, M. Ravnik, “TRIGA Mark II Reactor: U(20)-Zirconium Hydride Fuel Rods in Water with Graphite Reactor, IEU-COMP-THERM-003”, International Handbook of Evaluated Criticality Safety Benchmark Experiments. NEA/NSC/DOC(95)03, OECD NEA, Paris, France, 2010.

[3] Ž. Štancar, L. Snoj, L. Barbot, “Reaction Rate Distribution Experiments at the Slovenian JSI TRIGA Mark II Research Reactor, TRIGA-FUND-RESR-002”, International Handbook of Evaluated Reactor Physics Benchmark Experiments. NEA/NSC/DOC(2006)1, OECD NEA, Paris, France, 2016.

[4] T. Kaiba, G. Žerovnik, A. Jazbec, Ž. Štancar, L. Barbot, D. Fourmentel, L. Snoj, “Validation of neutron flux redistribution factors in JSI TRIGA reactor due to control rod movements”, Applied Radiation and Isotopes, 104, 2015, pp. 34-42.

[5] A. Peršič, T. Žagar, et all, “TRIGLAV: A program package for TRIGA reactor calculations”, IJS-DP-7862, Nuclear Engineering and Design, Volume 318, July 2017, Pages 24-34.

[6] J. Leppänen, et all, “The Serpent Monte Carlo code: Status, development and applications in 2013.” Ann. Nucl. Energy, 82 (2015) 142-150.

[7] Ž. Štancar, L. Snoj, L. Barbot, “Evaluation Of The Effect Of Burn-Up On Neutron Flux And Reaction Rate Distributions In The Triga Mark II Reactor”, Proceedings of the PHYSOR 2016 – Unifying Theory and Experiments in the 21st Century, American Nuclear Socitey, Sun Valley, Idaho, USA, May 1-5, 2016.

[8] T. Žagar, M. Ravnik, “Fuel Element Burnup Determination in HUE - LEU Mixed TRIGA Research Reactor Core”, 2000 International Meeting on Reduced Enrichment for Research and Test Reactors, Las Vegas, Nevada, October 1-6, 2000.

[9] R. Jeraj, T. Žagar, M. Ravnik, “Monte Carlo Simulation of the TRIGA Mark II Benchmark Experiment with Burned Fuel”, Nucl. Technol., 137, 2002, pp. 169-180.

[10] I. Mele, M. Ravnik, A. Trkov, “TRIGA Mark II Benchmark Experiment, Part I: Steady- State Operation”, Nucl. Technol., 105, 1994, pp. 37-51.

[11] “WIMS-D/4 Program Manual”, NEA-0329, Organization for Economic Cooperation and Development Nuclear Energy Agency Data Bank, 1983.

[12] D. Ćalić, G. Žerovnik, A. Trkov, L. Snoj “Validation of the Serpent 2 code on TRIGA Mark II benchmark experiments” Applied Radiation and Isotopes, 107 (2016) 165-170.

[13] R. Jeraj, M. Ravnik, “TRIGA Mark II Reactor: U(20)-Zirconium Hydride Fuel Rods in Water with Graphite Reactor, IEU-COMP-THERM-003”, International Handbook of Evaluated Criticality Safety Benchmark Experiments. NEA/NSC/DOC(95)03, OECD NEA, Paris, France, 2010.