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Criticality Calculations of Various Spent Fuel Casks – Possibilities for Burnup Credit Implementation

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Abstract

A methodology for criticality safety analysis of spent fuel casks with possibilities for burnup credit implementation is presented. This methodology includes the world well-known and applied program systems: NESSEL-NUKO for depletion and SCALE-4.4 for criticality calculations.

The possibilities of this methodology to analyse storage and transportation casks with different type of spent fuel is demonstrated on the base of various tests. The depletion calculations have been carried out for the power reactors (WWER-440 and WWER-1000) and research reactor IRT-2000 (C-36) fuel assemblies. The criticality calculation models have been developed on the basis of real fuel casks, designed by the leading international companies (for WWER-440 and WWER-1000 spent fuel assemblies), as well as for real WWER-440 storage cask, applied at NPP"Kozloduy". The results obtained show that the criticality safety criterion K_{eff} less than 0.95 is satisfied for both: fresh and spent fuel. Besides the implementation of burnup credit allow to account for the reduced reactivity of spent fuel and to evaluate the conservatism of the fresh fuel assumption.

1. INTRODUCTION

The criticality safety analysis of spent fuel systems has traditionally assumed that the fuel is fresh. The “fresh fuel” assumption is very conservative since the potential reactivity of the nuclear fuel is substantially reduced after fuel irradiation in reactor core. The concept of taking credit for this reduction in the reactivity due to fuel burnup, opposed to using the fresh fuel assumption in the criticality safety analysis, is referred to as “burnup credit” [1].

The motivation for using burnup credit involves both: economic benefits and enhanced safety. In the area of spent fuel storage, burnup credit and its resultant capacity improvements can avoid or minimize the environmental impacts, associated with expanding or building new storage facilities. For dry cask storage and transportation, higher capacity casks result in fewer shipments, less worker and public exposure, and lower risk both, radiological and non-radiological. Burnup credit is already standard practice in many countries [1,2]. Some results of burnup credit criticality calculations are presented in Ref.[3,4].

In this paper a methodology for criticality safety analysis of spent fuel casks with burnup credit implementation is presented. This methodology gives a possibility for criticality evaluation of various storage and transportation facilities with different type of spent fuel. It includes the world well-known and applied program systems: NESSEL-NUKO for depletion and SCALE-4.4 for criticality calculations. The possibilities of this methodology to analyse criticality safety of storage and transportation casks with different type of spent fuel (from power and research reactors) is demonstrated on the base of several test models. The methodology allows also accumulation of detailed information for the spent fuel characteristics, needed for the computerised system for management of nuclear materials in Bulgaria, according to the international requirements and regulations.

2. COMPUTER CODES AND NUCLEAR DATA

The application of burnup credit requires detailed knowledge of the irradiated fuel isotopic concentrations. The isotopic inventory and post decay power of the irradiated fuel has to be calculated by a depletion code, depending on the initial state and irradiation history of the fuel. The results of the depletion analysis are a necessary input to the criticality analysis of the system for which the burnup credit is taken.

The methodology is based on the two world well known and used code systems for depletion and criticality calculations, respectively:

- NESSEL-NUKO - for depletion calculations.
- SCALE-4.4 - for criticality calculations.

2.1. NESSEL-NUKO

NESSEL-NUKO is a complex code system intended especially to WWER depletion analysis. The NESSEL-4 code [5] calculates the local neutron physics characteristics and depletion of different nuclear fuel assemblies in the core. The NUKO code [6] calculates the isotopic inventory and post decay power of spent fuel assemblies – the concentrations of actinides and fission products with medium decay period important for practice.

2.2. SCALE- 4.4 CODE SYSTEM

The SCALE-4.4 modular code system [7] is verified and world-widely used for criticality safety analyses of PWR spent fuel storage facilities. The system has been recently in process of international testing for WWER applications. It is also under verification at the INRNE, BAS for analyses of WWER spent fuel storage and transportation facilities [8]. The analytical sequence CSAS6 has been applied for the criticality calculations. It includes the modules BONAMI, NITAWL-II and XSDRNPM for neutron data preparation, as well as the 3D multigroup Monte Carlo criticality code KENO-VI. The 44-group neutron data library 44GROUPNDFB5 based on evaluated data file ENDF/B-V has been used [7].

3. RESULTS

3.1. DEPLETION CALCULATIONS

In order to prepare nuclear inventory data for implementation of burnup credit in the criticality calculations of spent fuel storage casks, the nuclear densities of the basic fuel isotopes from the Uranium - Plutonium chain, the actinides and the fission products under consideration have been determined by the NESSEL-NUKO code system for three different fuel assembly types, given in Table 1.

Table 1. Fuel assemblies, calculated by the NESSEL-NUKO code system

Type of reactor under consideration	Assembly type (enrichment)	Burnup reached [MWd/kg]	Cooling time[d] after discharge
IRT-2000	C36	23.6	4876.9
WWER-440	3.6%	30.0	2575.0
WWER-1000	3.3%	27.53	3220.0

These fuel assemblies are shown on Fig.1÷3 respectively. The real geometry data and material content of each assembly have been modeled corresponding to the homogenization procedure of the NESSEL code, generating binary data files with the isotopes number densities, the fission and capture microscopic cross sections and the 34-group neutron spectrum in dependence on fuel burnup. The real operational power history and the outages for reloading of the given assembly has been taken as follows: for the IRT-2000 assembly - from the Energoproject Report [9]; for the WWER-440 assembly – from the benchmark task [10] and for the WWER-1000 assembly - from the operational benchmark for the Unit 6, Kozloduy NPP [11]

3.2. CRITICALITY CALCULATIONS

3.2.1. WWER SPENT FUEL CASK MODELS

The first configuration is referred to a cask for interim storage of spent fuel from the research reactor IRT-2000, Sofia. The technical possibility for using the WWER-440 spent fuel transport cask including basket with 19 tight panels for interim storage of all spent fuel assemblies C-36 from IRT-2000 Sofia at the Away-from-reactor (AFR) basin of the NPP Kozloduy has been analysed in Ref.[12]. The C-36 fuel assembly with maximal number of fuel rods 16 (Fig. 1) is used for calculations. The model presents a basket with 19 tight penals [12], arranged in lattice with minimal pitch of 22.5 cm. Each penal involves 4 fuel assemblies C-36 in axial direction. The x-y cross section of a penal is given on Fig.4. A model of basket with 19 penals is shown on Fig.5.

The second model (Fig.6) is developed on the basis of a real WWER-440 spent fuel cask for storing 84 fuel assemblies, designed by the SKODA Nuclear Machinery [13]. The WWER-440 fuel assembly model is given on Fig.2. The geometry and material data needed for modeling the fuel assemblies are taken from Ref. [10,14]. The internal rack for loading the fuel is manufactured from hexagonal aluminum tubes shielded by stainless steel (containing 1.0% of natural boron), each of 0.3 cm thickness. Correspondingly, the stainless steel plate is 7.5 cm and the aluminum plate is 7.9 cm away from the center. The fuel assemblies are located in a triangular lattice with pitch 17 cm, in the stainless steel cask with 90 cm inner radius and 28 cm thick wall.

The third model (Fig.7) is based on a real cask, designed by the Izorskie zavody (Russia) [15]. The inner radius of the cask is 77 cm, the cask wall is 20 cm thick. It contains 54 WWER-440 fuel assemblies, located in a triangular lattice with pitch 16.5 cm, in compact rack made of stainless steel containing 1.1% of natural boron, with 0.3 cm thickness and at distance 7.5 cm from the center of the assembly.

The forth model (Fig.8) is developed on the basis of a real WWER-1000 spent fuel cask for storing 18 fuel assemblies, designed by the Izorskie zavody (Russia) [15]. The WWER-1000 fuel assembly, described in Ref. [14] is shown on Fig.3.

The calculations have been carried out for both fresh and spent fuel assemblies in casks filled with distilled water. Actinides and fission products credit has been also taken into account. The number of neutrons in every generation is 600 and the number of generations is 300.

3.2.2. RESULTS

The calculated values of multiplication factors K_{eff} and their statistical errors 1σ for both fresh and spent fuel at different cooling times for various spent fuel assemblies and cask models are presented in Table 2. They show that the reduction of the K_{eff} value due to the burnup credit implementation especially for higher cooling times is of about 23 %.

The calculated values of average K_{eff} for fresh and spent fuel of several types at different cooling times are presented graphically on Fig.9÷12. The K_{eff} values for both fresh and spent fuel are less then the criticality safety limit $K_{eff} = 0.95$. The conservatism of the “fresh fuel assumption” compared to the real criticality state of the spent fuel cask can be clearly seen from these figures. The reduction of K_{eff} value due to the burnup credit implementation varies from 16% to 23% for the presented models with WWER fuel assemblies. For the WWER-440 transport cask with IRT-2000 spent fuel the reduction of K_{eff} is very small probably due to the deep subcriticality of the chosen configuration. This effect needs further investigations.

Table 2 Effective multiplication factor K_{eff}^{av} for various spent fuel cask models and for different cooling times, calculated by the SCALE- 4.4 code system

Configuration	Fresh fuel	Spent Fuel			
		At discharge	T_{cool} 1 year	T_{cool} 3 years	T_{cool} n*) years
Model of basket for 19 penals with 76 fuel assemblies C-36	0.3126± 0.0016				0.3051± 0.0017
Model of SKODA WWER-440 cask for 84 fuel assemblies	0.8316± 0.0018	0.6850± 0.0015	0.6829± 0.0014	0.6779± 0.0015	0.6768± 0.0015
Model of Izorskie zavody WWER-440 cask for 54 fuel assemblies	0.7858± 0.0021	0.6454± 0.0015	0.6447± 0.0015	0.6401± 0.0015	0.6340± 0.0015
Model of Izorskie zavody WWER-1000 cask for 18 fuel assemblies	0.8205± 0.0019	0.6868± 0.0015	0.6750± 0.0015	0.6717± 0.0016	0.6684± 0.0018

*) n=13 for the first configuration, n=6 for the second and third configurations and n=5 for the forth configurations.

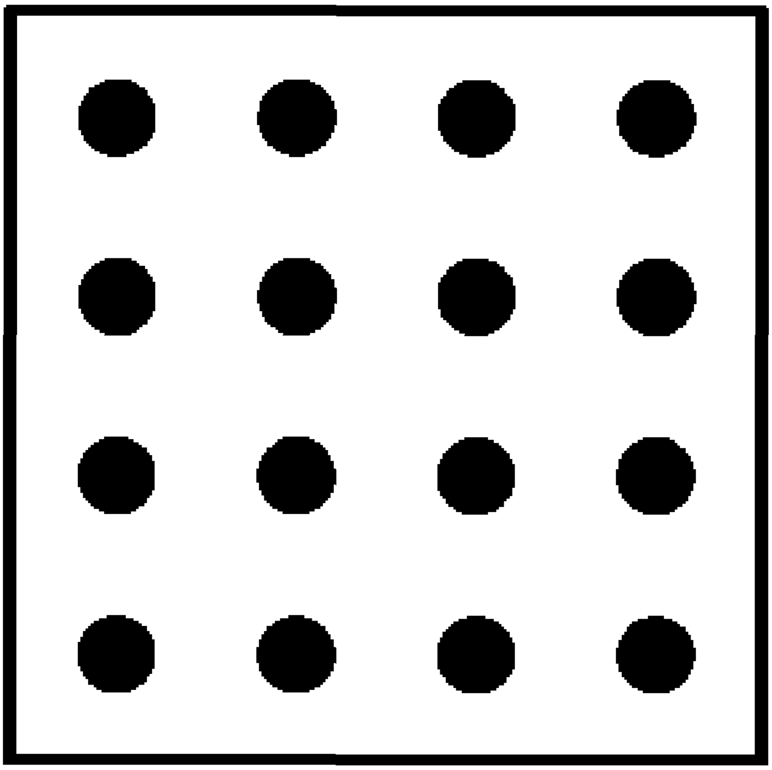

Fig. 1 C-36 fuel assembly (IRT-2000-Sofia research reactor) (x-y plane). Visualisation by the KENO-VI

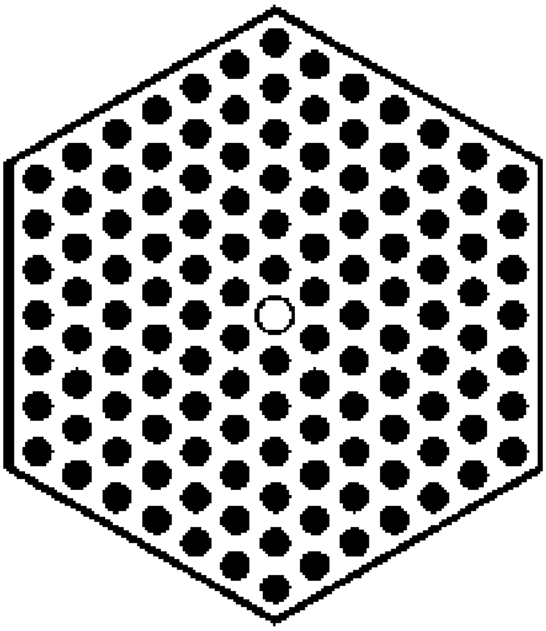

Fig. 2 WWER-440 fuel assembly.Visualisation by the KENO-VI

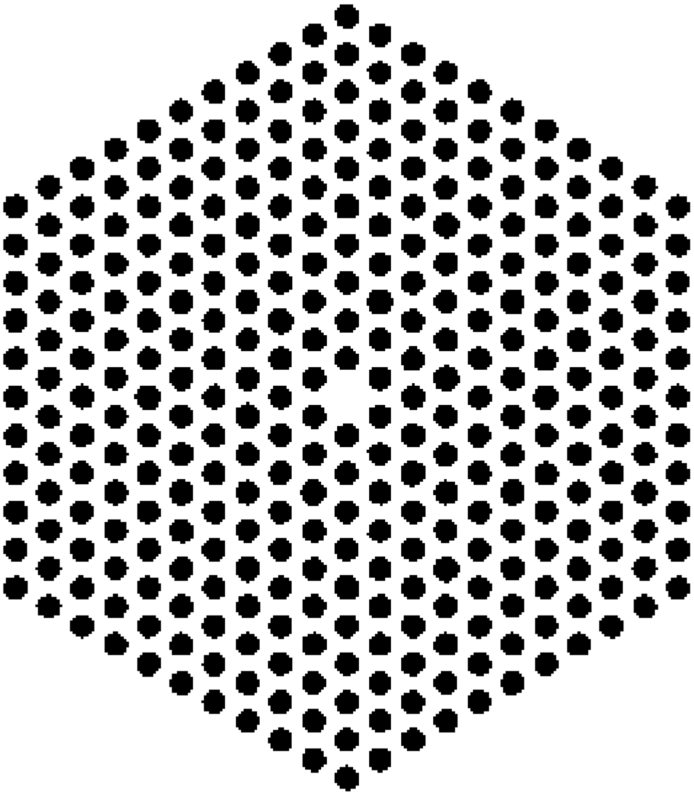

Fig. 3 WWER-1000 fuel assembly.Visualisation by the KENO-VI

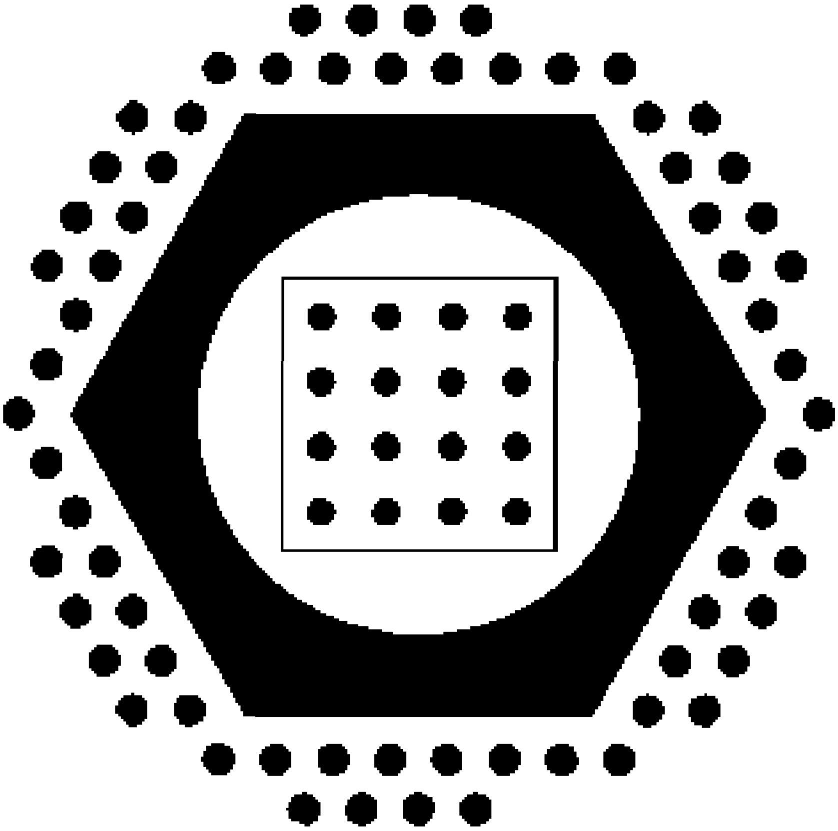

Fig. 4 Penal with C-36 fuel assembly (x-y plane).
Visualisation by the KENO-VI

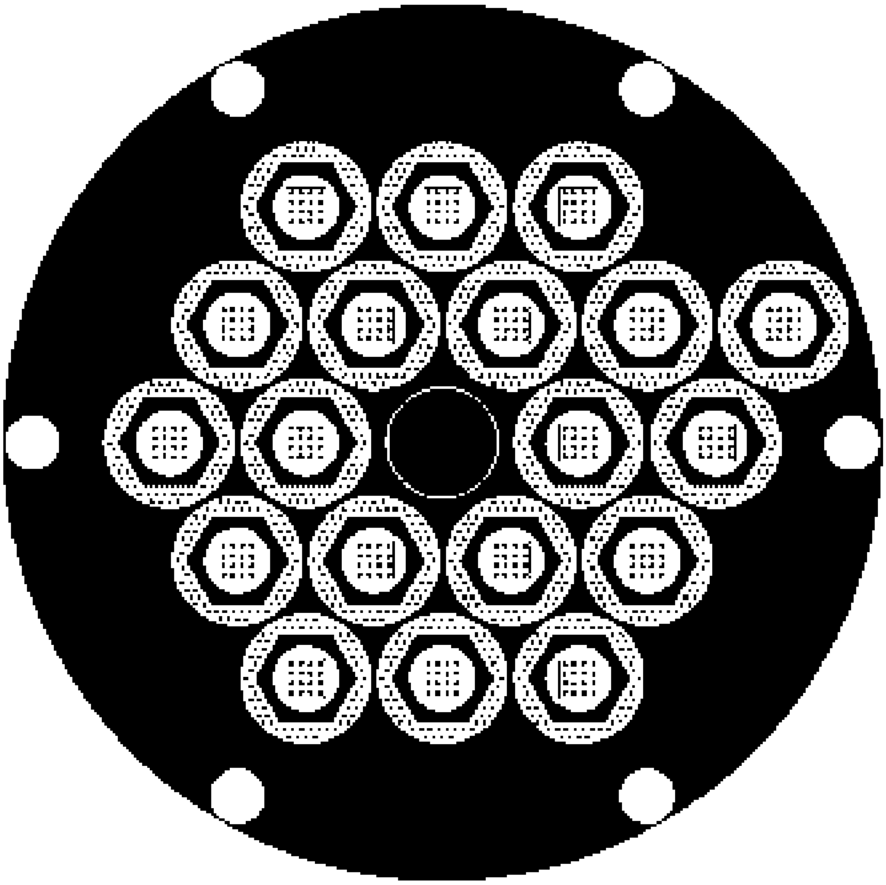

Fig. 5 Basket with 19 tight penals (x-y plane)
Visualisation by the KENO-VI

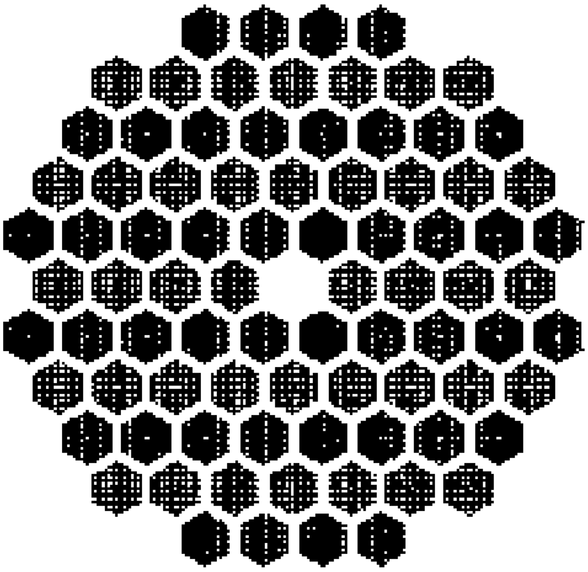

Fig. 6 SKODA spent fuel cask model (84 WWER-440 fuel assemblies)
Visualisation by the KENO-VI

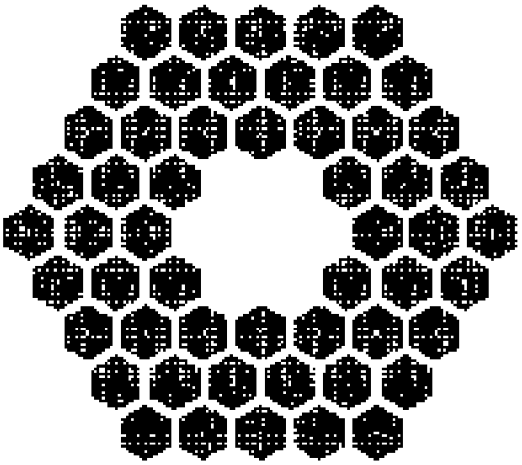

Fig. 7 Izorskie Zavody cask model (54 WWER-440 fuel assemblies)
Visualisation by the KENO-VI

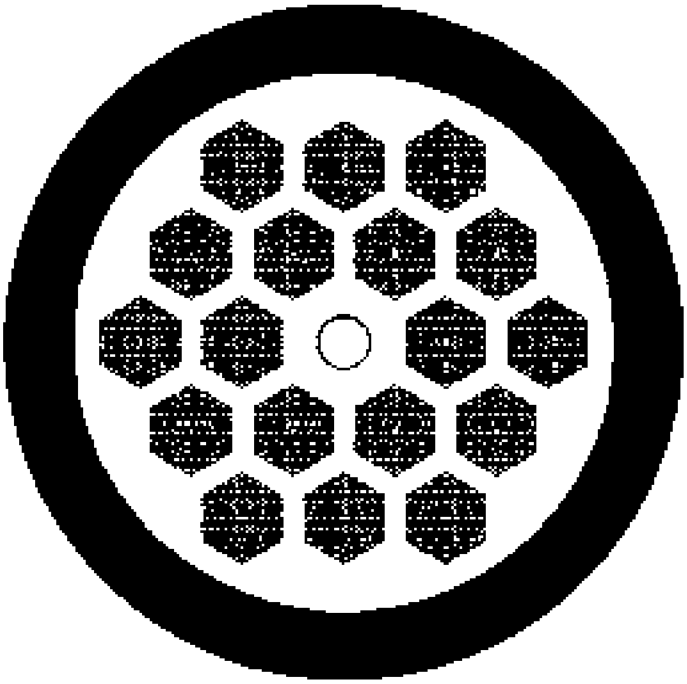

Fig. 8 Izorskie Zavody cask model (18 WWER-1000 fuel assemblies) (x-y plane).Visualisation by the KENO-VI

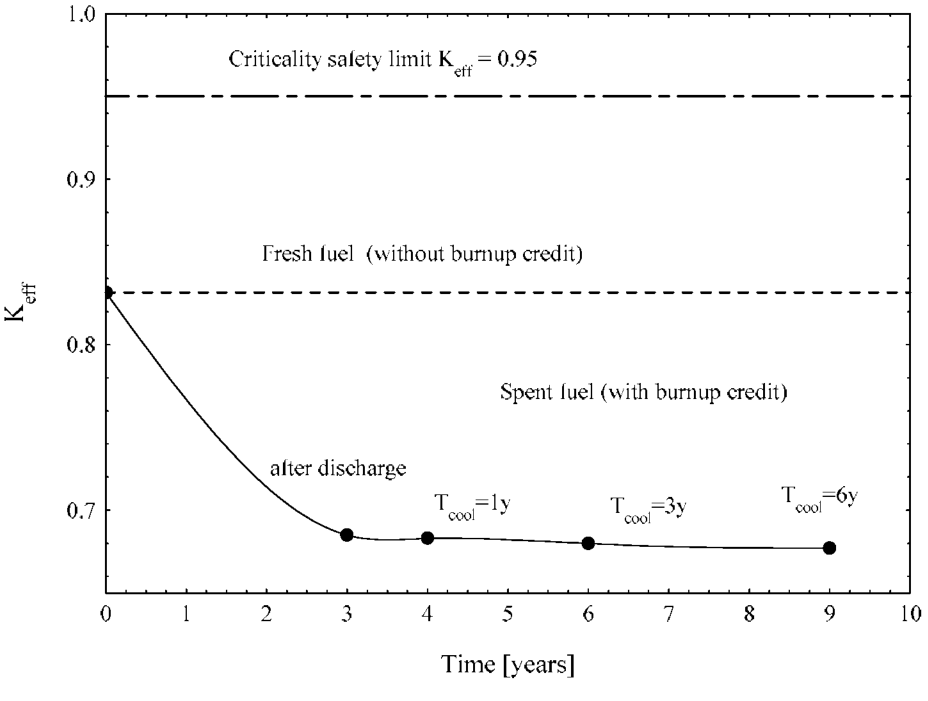

Fig.9. Time dependent criticality of the CASTOR WWER-440 fuel cask

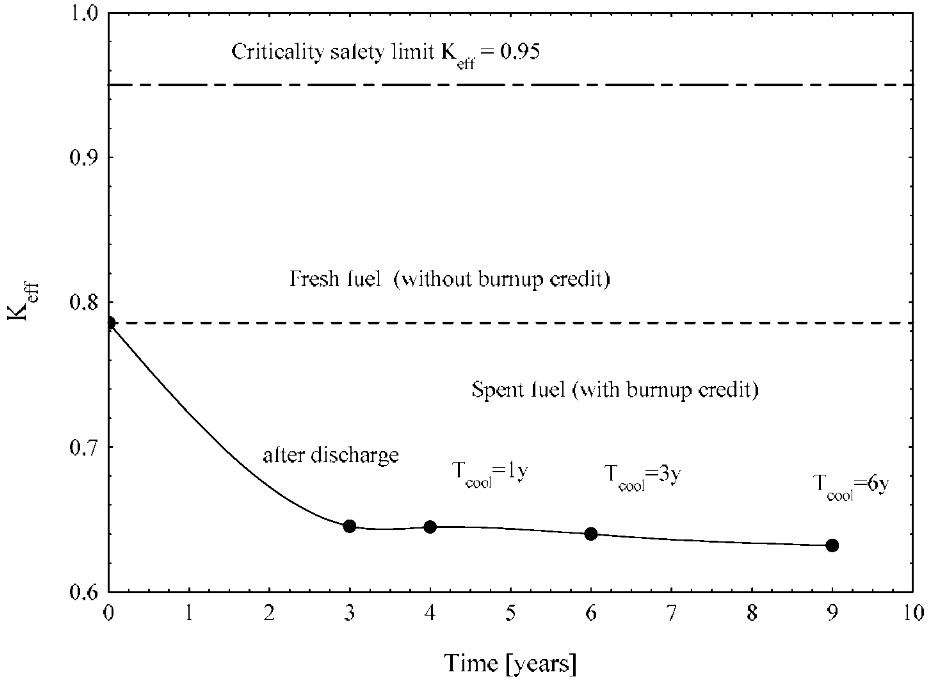

Fig.10. Time dependent criticality of the Izorskie zavody WWER-440 fuel cask

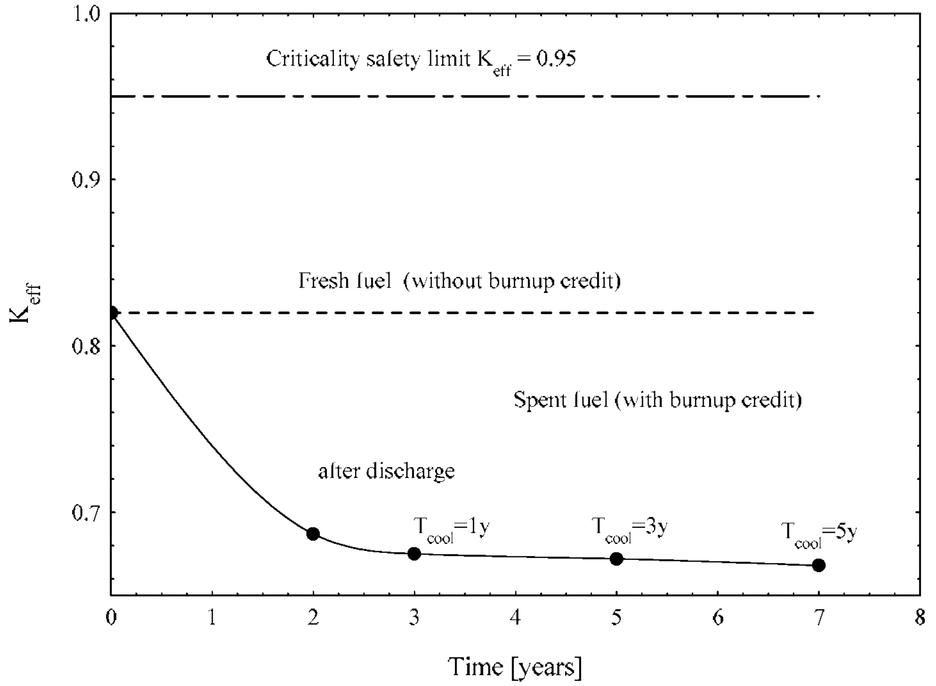

Fig.11. Time dependent criticality of the Izorskie zavody WWER-1000 fuel cask

4. CONCLUSIONS

On the basis of the obtained results the following conclusions could be drown:

- The ability of the presented methodology for burnup credit criticality safety analysis for spent fuel cask of several designs and different fuel types is demonstrated.

- The results for K_{eff} obtained by the SCALE-4.4 code system (CSAS6 analytical sequence) for the WWER-440 and WWER-1000 cask models confirm that the modelled real casks with Russian and Czech design satisfies the criticality safety requirements $K_{eff} < 0.95$ for both fresh and spent fuel. The implementation of burnup credit accounts for the reduced reactivity of spent fuel and allows decreasing the conservatism of criticality evaluation in comparison with the fresh fuel assumption.

- The NESSEL-NUKO and SCALE-4.4 code systems can be used for both: the WWER and IRT-2000 spent fuel casks safety analyses (criticality and dose), including thermal analysis (by SCALE) and implementing burnup credit. The SCALE code system should be beforehand verified for WWER on the basis of both WWER benchmark problems and WWER experimental data. This verification has already been undertaken by a contract with the Bulgarian Regulatory Body.

- The results obtained for the basic characteristics of the spent fuel assemblies of WWER and IRT-2000 research reactor could be applied for the computerised system for management of nuclear materials. As a country, ratified the Treaty for nonproliferation of nuclear weapons and Treaty for safeguards INFCIRC/178 Bulgaria is obliged to build up such a system and put it into operation.

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REFERENCES

1. Implementation of Burnup Credit in Spent Fuel Management Systems. Proc. of an Advisory Group Meeting, IAEA-TECDOC-1013 (IAEA,Vienna, 1998)
2. Topical Report on Actinide-Only Burnup Credit for PWR Spent Nuclear Fuel Packages. DOE/RW-0472 Rev.2 (DOE, USA,1998)
3. T. Apostolov, M. Manolova, R. Prodanova. Criticality Safety Assessment of WWER-1000 Spent Fuel Cask, 9th Annual Conference of the BgNS, Sofia, October 2000. BgNS Transactions (in print).
4. M. Manolova. Criticality Calculations Of WWER-440 Spent Fuel Casks with Burnup Credit Implementation. BgNS Transactions, Vol.5, No2, September 2000, ISSN 1310-8727, pp.36-38
5. G. Schulz, NESSEL-4 Version 6, K.A.B. AG, 1994C
6. W. Moller, Kernenergie 34 (1991) 89

7. SCALE: A Modular Code System for Performing Standartized Computer Analyses for Licensing Evaluation", NUREG/CR-0200 Rev.6 (ORNL/ NUREG/CSD-2/V1/R6), Vols. I, II and III (September 1998), Version 4.4.
8. Verification of the SCALE Modular Code System for Criticality Safety Analysis of WWER Spent Fuel Storage Facilities. Contract №266-00/09.10.2000, CUAEPP
9. Energoproekt plc, Final Report on Project No.24/23.03.2000.
10. L. Markova. Results of CB1 Burnup Credit Criticality Benchmark Calculations and Calculational Burn-up Credit Benchmark №2 (CB2) Proc.of the seventh Symposium of AER, 23-26 Sept. 1997,Germany, Vol.II, p.871.
11. T. Apostolov, B. Petrov. Operational Benchmark for VVER-1000, Unit 6, Kozloduy NPP. Proc.of the Ninth Symposium of AER, Slovakia, 4-8 October 1999, Budapest, 1999, ISBN 963-372-616-6, pp.131-151.
12. T. Apostolov, V. Kirilov, M. Manolova, S. Beloussov.Criticality safety Assessment of a cask for IRT-2000 Spent Fuel Interrim Storage at NPP Kozloduy AFR Basin. 9th Annual Conference of the BgNS, Sofia, October 2000. BgNS Transactions (in print) (in Bulgarian).
13. V. Lelek, K. Wagner. End of Fuel Cycle and Related Problems. Proc.of the Fourth Symposium of AER, 10-15 Oct. 1994, Bulgaria (Budapest, 1994) 31-42.
14. In-core Fuel Management Code Package Validation for WWERs". IAEA-TECDOC-847, Vienna, November 1995.
15. Dry Cask Storage of NPP Kozloduy Spent Fuel. Izhorskiye Zavody. Saint Peterburg, 1995 (in Russian).