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Neutron Absorber for VVER-1000 Storage, Transport and Final Disposal Facilities

Martin Lovecký
University of West Bohemia
Univerzitní 8
30614 Plzeň, Czech Republic
lovecky@fel.zcu.cz

Jiří Závorka, Kristýna Klímek Gincelová, Jana Jiřičková, Radek Škoda
University of West Bohemia
Univerzitní 8
30614 Plzeň, Czech Republic

ABSTRACT

The recent increasing demand for better nuclear fuel utilization requires higher enriched uranium fuels which is a challenge for spent fuel handling facilities in all countries with nuclear power plants. The operation with higher enriched fuels leads to reduced reserves to legislative and safety limits of spent fuel transport, storage and final disposal facilities. In some cases, the required boron amount in the absorber plates or tubes can be higher than current metallurgy processes allows. This study addresses the neutron absorber solution with significantly increased nuclear safety and improved economics where a concept of inseparable neutron absorber is introduced to achieve fuel reactivity decrease.

Storage, transport and disposal facilities for VVER-1000 nuclear fuel can be modified with the neutron absorber for better nuclear safety and better economics. For selected fuel handling facilities (spent fuel pool, storage and transport spent fuel cask, final disposal cask), both approaches are used independently. In the first part of criticality safety analysis, neutron absorber is used without facility changes to show maximum increase of nuclear safety in reactivity decrease. In the second part, neutron absorber is used with facility changes for improved economics while achieving the same level of nuclear safety, i.e. the same neutron multiplication factor. Improved economics include boron amount reductions, steel thickness reduction and increased facility capacity.

1 INTRODUCTION

Criticality safety in spent fuel cask systems is commonly achieved by placing neutron absorbers in the cask basket design. Aluminum or stainless steel tubes spatially separate fuel assemblies in the cask basket. Currently, boron is exclusively used as the absorber material. The reason is the chemical and mechanical properties of light boron nuclei that can be added directly to basket tubes material, or placed in extra sheets between the tubes. Increasing fuel enrichment and limitations of boron content in the steels or alloys [1] can be solved by using burnup credit methodology in the criticality safety analysis.

The improved neutron absorber concept is based on placing neutron absorbers directly into the fuel assembly. This solution is more efficient than absorber tubes even with neutron flux trap and allows significant basket design changes. The main changes are lowering boron content in absorber tubes and decreasing fuel assembly pitch in the basket resulting in lower cask wall diameter and total cask mass. Absorber is placed in steel cladding and fixed inside guide tubes. Because the temperature, radiation, chemical compatibility and pressure parameters are not limiting since the absorber would not be exposed to reactor core operation environment, material selection analysis is performed to optimize improved neutron absorber concept. This concept was studied recently [2], [3], [4].

2 CALCULATION MODELS

Generic VVER-1000 spent fuel storage pool for V-320 specification was modelled with 5.0 wt% U-235 uniform nuclear fuel. 3-D model with infinite array of 12 fuel assemblies. Neutron absorber is placed in 9 fuel assemblies, i.e. 75 % of the storage capacity is equipped with the neutron absorber in order to reasonably decrease the required number of loaded absorbers below 100 %. Criticality safety is designed for fresh fuel, steel tube is borated to 1.0 wt% B-nat at lattice with 288 mm assembly pitch.

CASTOR-1000/19 is a dual-purpose storage and transport spent fuel cask used in Czech fuel cycle back-end. 2-D model was implemented based on data from [5]. Neutron absorber is placed in 13 out of 19 fuel assemblies, i.e. 68 % of the storage capacity is equipped with the neutron absorber and it is lower than in the spent fuel storage pool. Criticality safety is designed for fresh fuel, steel tube is borated to 1.0 wt% B-nat at adopted regular lattice with 297 mm assembly pitch.

SKODA-1000/3 is a final disposal cask for Czech deep geological repository. Current design is based on placing three VVER-1000 fuel assemblies inside the cask. For neutron absorber concept, a 3-D model of the cask was analyzed. Since the disposal cask is not licenced yet, legislative limit 0.95 on neutron multiplication factor (system k-eff) was replaced by calculation limit 0.88 that takes into account uncertainties in fuel composition (conservatively 0.05 according to [6]), fuel assembly manufacturing uncertainties and nuclear data bias (conservatively 0.02). Neutron absorber is placed in 2 out of 3 fuel assemblies, i.e. 67 % of the storage capacity is equipped with the neutron absorber and it is lower than in the spent fuel storage pool.

Fuel composition was determined by depletion calculations performed with Serpent (version 2.1.32) transport code [7] and ENDF/B-VIII.0 continuous energy nuclear data library. Fuel assembly depletion model is depicted in Figure 1, uniform material was assumed since other parameters (fuel enrichment, fuel burnup, cooling time) have a significantly larger effect on the reactivity, especially for feasibility study. Actinide and fission product burnup credit level with NRC approved set of 28 nuclides was used. Nuclide set is very similar to French selection of 27 nuclides [8]; Eu-151 fission product makes the only difference. Isotopic correction factors were not applied since the absorber reactivity worth is around 10 times larger, however, the analysis conservatively accounts for isotopic correction factors in decreased k-eff limit.

Criticality calculations were performed with Serpent (version 2.1.32) transport code [7] and ENDF/B-VIII.0 continuous energy nuclear data library, see Figure 2 to Figure 4.

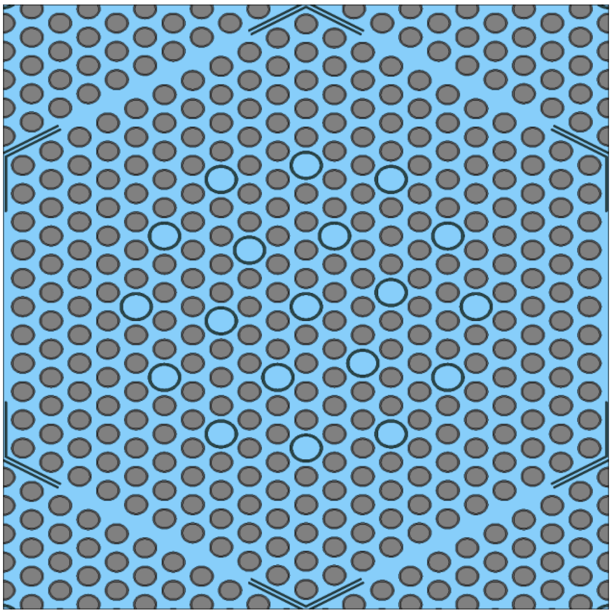

Figure 1: Fuel assembly depletion in Serpent 2.

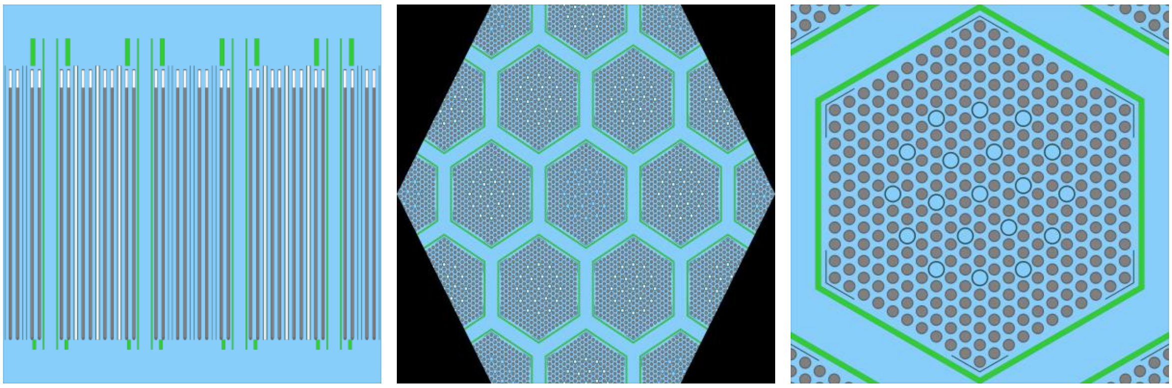

Figure 2: Spent fuel storage pool criticality model in Serpent 2.

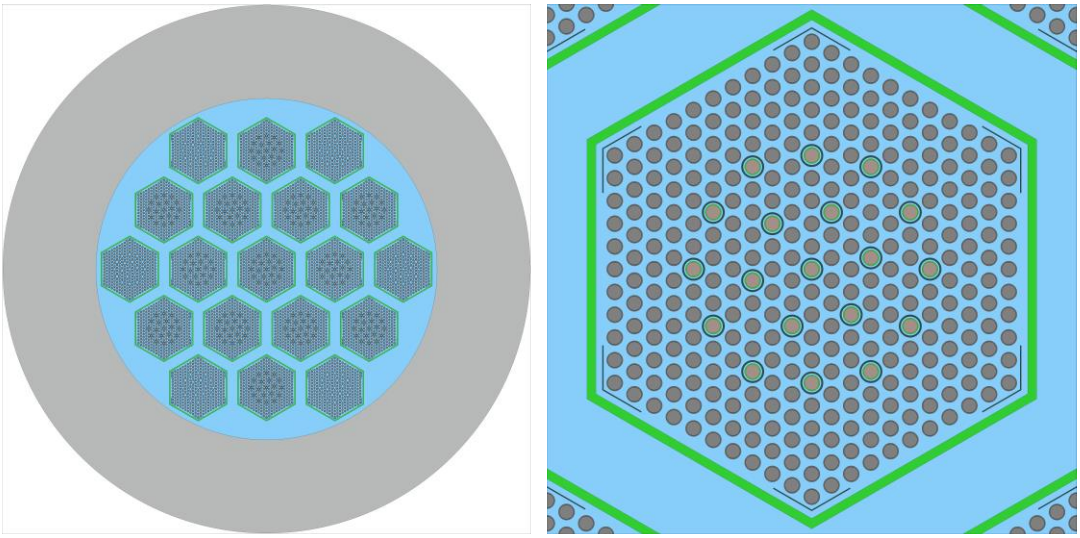

Figure 3: Spent fuel cask criticality model in Serpent 2.

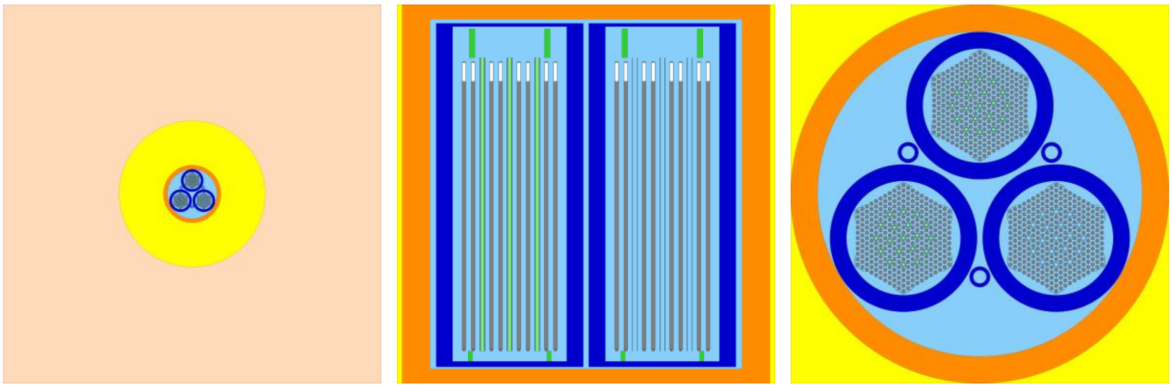

Figure 4: Final disposal cask criticality model in Serpent 2.

3 CALCULATION RESULTS

Absorber materials were selected by the most common chemical composition, one carbide, 4 oxides and 3 metals: B_4C (2.52 g/cm^3), Sm_2O_3 (8.347 g/cm^3), Eu_2O_3 (7.42 g/cm^3), Gd_2O_3 (7.07 g/cm^3), Dy_2O_3 (7.80 g/cm^3), Hf (13.31 g/cm^3), Re (21.02 g/cm^3), Ir (22.56 g/cm^3). Neutron absorber materials have the same diameter as the fuel pellet and it is placed inside its own steel cylinder tube in all 18 guide tube positions.

Spent fuel pool criticality is achieved with neutron multiplication factor 0.916 without assuming uncertainties, see Figure 5. This subcriticality level can be achieved with neutron absorbers and decreased assembly pitch according to Figure 6, volume of one regular cell decreases to 82 % for the strongest absorber (boron) and to 85 % for the least effective chosen absorber (gadolinium). Associated fuel pitch varies from 260 mm to 264 mm from reference value of 288 mm.

CASTOR-1000/19 spent fuel cask has similar design of borated steel tubes with 1.0 wt% B-nat. Reference assembly pitch 297 mm have 0.910 neutron multiplication factor (Figure 7) that can be maintained with neutron absorbers and decreased pitch from 259 mm to 265 mm. Regular assembly cell volume decreases to between 81 % and 84 % and allows for smaller cask wall while still maintaining 405 mm of shielding wall thickness. Summarized in Figure 8, cask wall volume decreases to between 90 % and 91 %. Because cask wall mass is the main contributor to cask economics, neutron absorbers can save around 10 % of cask price.

SKODA-1000/3 final disposal cask criticality for current design specifications is achieved with stainless steel tubes around each fuel assembly. It should be noted that the design of the tubes is the result of required cask lifetime and strength properties from structural analysis rather than criticality design. However, with burnup credit, it can be easily shown that the cask is safely subcritical. Minimal fuel burnup is 12745 MWd/MTU that is achieved by all fuel assemblies in their first fuel cycle in the nuclear reactor operation, see Figure 9.

Stainless steel tubes around fuel assemblies in SKODA-1000/3 final disposal cask are replaced by cask inner cylinder and fuel assemblies are placed adjacent to each other. Cask wall thickness remains unchanged (orange color in Serpent model), however, cask wall inner diameter decreases from 784 mm to 554 mm and resulting cask wall volume (and mass and price) in decreased by 57 %, see Figure 10. Minimal fuel burnup of 49996 MWd/MTU is required if no neutron absorbers are used; that cannot be achieved by all fuel assemblies. If neutron absorbers are used, minimal burnup decreases to around 30000 MWd/MTU for 2 fuel assemblies loaded with absorbers; this burnup is acceptable for the fuel with assumed enrichment.

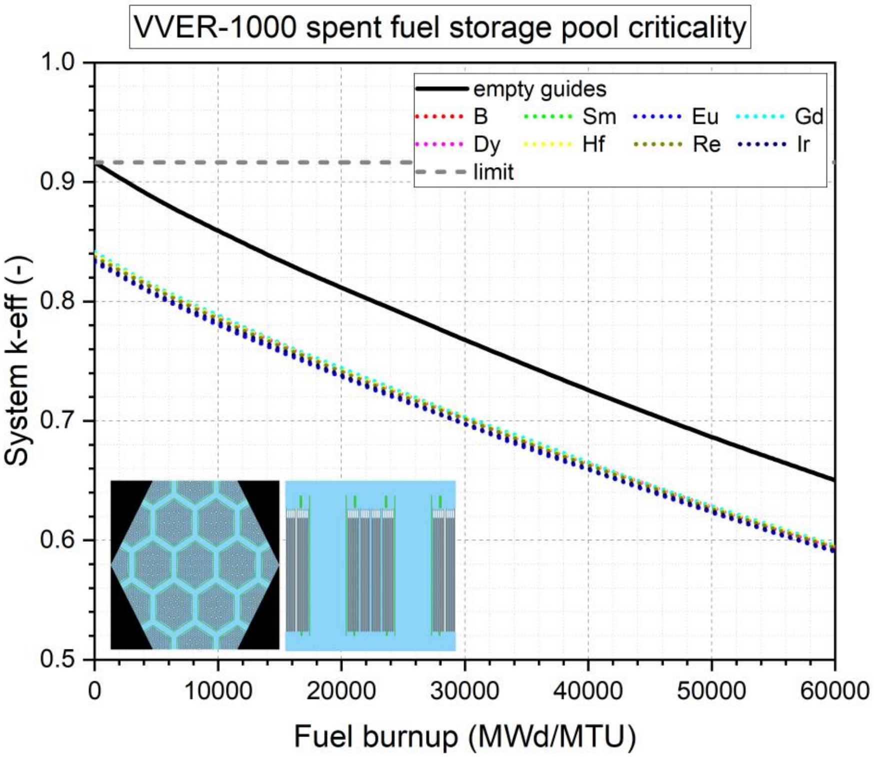

Figure 5: Facility 1 (spent fuel storage pool) criticality with reference pitch.

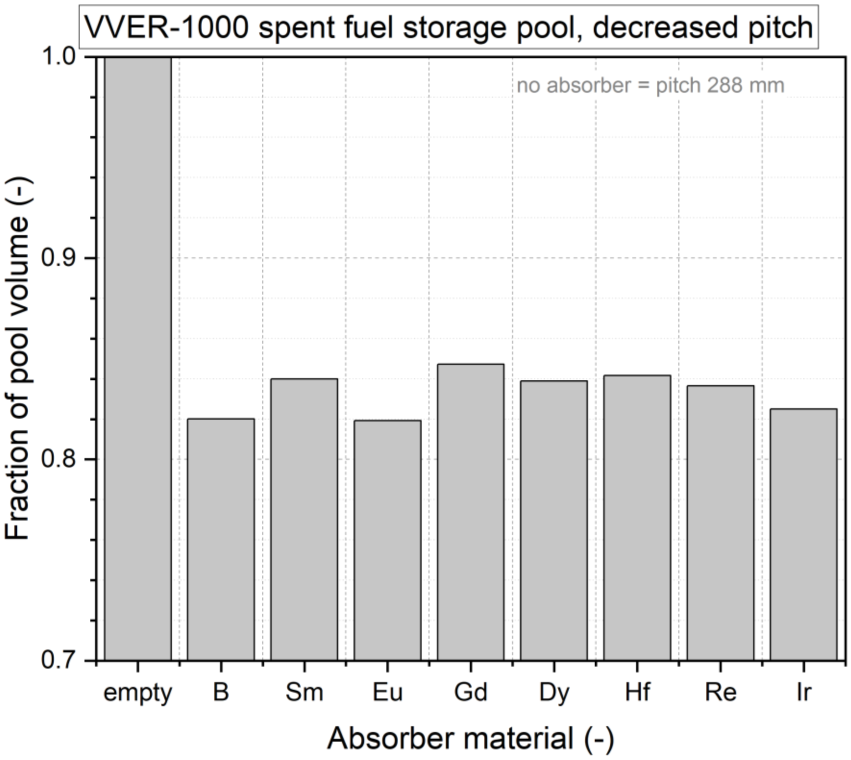

Figure 6: Facility 1 (spent fuel storage pool) criticality with decreased pitch.

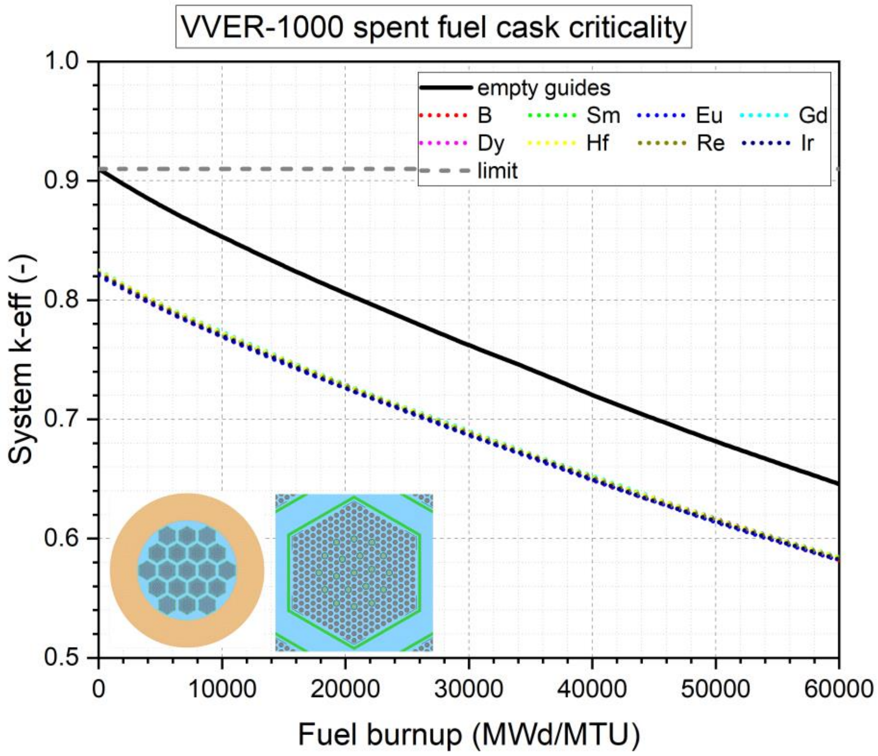

Figure 7: Facility 2 (spent fuel cask) criticality with reference pitch.

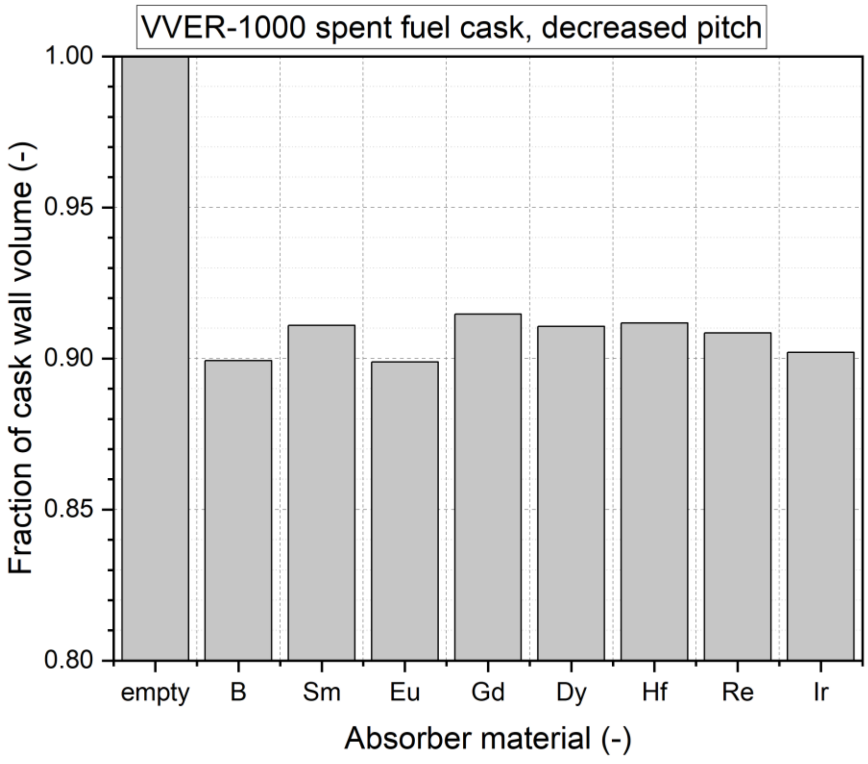

Figure 8: Facility 2 (spent fuel cask) criticality with decreased pitch.

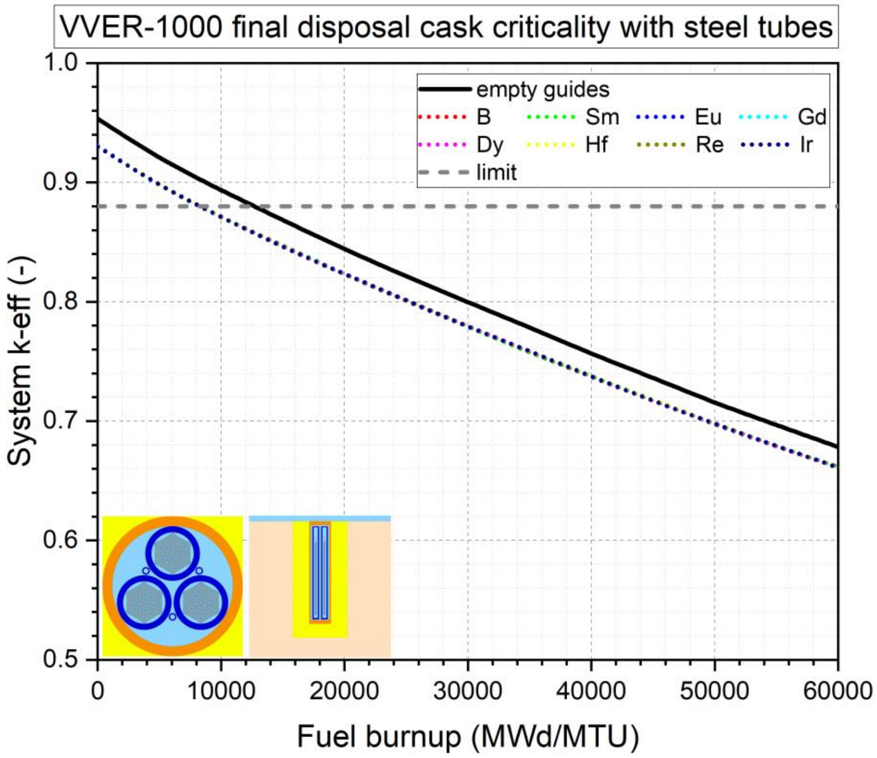

Figure 9: Facility 3 (final disposal cask) criticality with reference pitch.

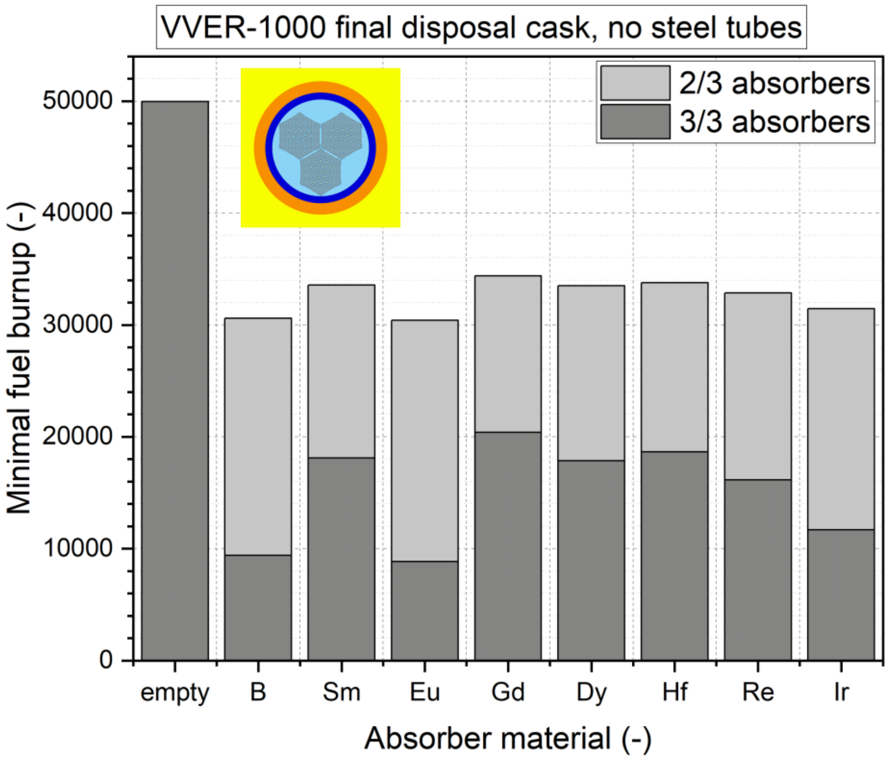

Figure 10: Facility 3 (final disposal cask) criticality with decreased pitch.

CONCLUSIONS

An improved concept of neutron absorber for VVER-1000 storage, transport and disposal facilities is analysed from criticality safety point of view. The absorber placed directly within fuel assembly guide tubes significantly decrease reactivity in fuel handling facilities. 8 various absorber materials (B, Sm, Eu, Gd, Dy, Hf, Re, Ir) were analyzed and all of them allows facilities design changes. It is recommended to place the absorber into fuel assembly in the early storage stage in the spent fuel pool, thus allowing its usage in subsequent facilities and reducing back end cost.

Neutron absorber is used with facility changes for improved economics while achieving the same level of nuclear safety. Loading the absorber into 75 % of fuel assemblies, spent fuel pool can increase its capacity by 18% to 22 % because of decreased fuel assembly pitch. Similarly, spent fuel cask can decrease fuel assembly pitch that result in 10 % decrease of cask wall volume while maintaining its shielding thickness. Lastly, loading the absorbers in final disposal cask can justify cask changes involving cask wall volume decrease by 57 %.

ACKNOWLEDGMENTS

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