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Original Article

Fixed neutron absorbers for improved nuclear safety and better economics in nuclear fuel storage, transport and disposal

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ABSTRACT

Current designs of both large reactor units and small modular reactors utilize a nuclear fuel with increasing enrichment. This increasing demand for better nuclear fuel utilization is a challenge for nuclear fuel handling facilities. The operation with higher enriched fuels leads to reduced reserves to legislative and safety criticality limits of spent fuel transport, storage and final disposal facilities. Design changes in these facilities are restricted due to a boron content in steel and aluminum alloys that are limited by rolling, extrusion, welding and other manufacturing processes. One possible solution for spent fuel pools and casks is the burnup credit method that allows decreasing very high safety margins associated with the fresh fuel assumption in spent fuel facilities. This solution can be supplemented or replaced by an alternative solution based on placing the neutron absorber material directly into the fuel assembly, where its efficiency is higher than between fuel assemblies. A neutron absorber permanently fixed in guide tubes decreases system reactivity more efficiently than absorber sheets between the fuel assemblies. The paper summarizes possibilities of fixed neutron absorbers for various nuclear fuel and fuel handling facilities. Moreover, an absorber material was optimized to propose alternative options to boron. Multiple effective absorbers that do not require steel or aluminum alloy compatibility are discussed because fixed absorbers are placed inside zirconium or steel cladding.

1. Introduction

Spent fuel handling in nuclear fuel back-end includes spent fuel pool near the reactor, transport and storage cask for long term storage and final disposal cask for deep geological repository. Criticality safety is achieved by placing boron in steel or aluminum alloy in tubes around fuel assemblies or sheets fixed by non-absorbing tubes or plates between the fuel assemblies. Currently, only boron is exclusively used as the absorber material. The reason is the chemical and the mechanical properties of light boron nuclei that can be added directly to the absorber material. However, with increasing fuel enrichment and limit on boron content as the additive material [1], criticality safety criteria are hard to met. Moreover, each fuel assembly requires multiple absorbers, one for each facility.

Placing neutron absorbers directly into the fuel assembly where the absorber efficiency is much higher was proposed in [2]. Guide tubes represents an ideal position where the neutron absorbers for spent fuel handling can be placed. The absorber is required to be inseparably fixed to the fuel assembly guide tubes to be accepted by a regulatory body. 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 was performed to optimize neutron absorber material and facility design. The only material that can be a chemical additive in the steel and aluminum alloys is boron because of its light nuclei. Achieving meaningful density of the boron absorber nuclei as the additive element is possible even with mass content of the boron that is low for manufacturing processes. That is impossible for absorbers with stronger absorbing nuclei, i.e. gadolinium. Materials other than boron [3] can be

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introduced due to higher absorber efficiency and the elimination of steel or aluminum alloy chemical compatibility requirement.

Fixed neutron absorbers can be used to improve nuclear safety and back-end economics. Placing fixed neutron absorbers in current spent fuel handling facilities would decrease system reactivity and increase criticality safety even with higher enriched fuel. Improved nuclear safety can be accompanied or replaced by better back-end economics while achieving the same level of nuclear safety. From overall point of view, placing fixed absorber inseparably into the fuel assembly after reactor discharge and using the same absorber in all subsequent fuel handling facilities until the final disposal in deep geological repository represents significant material savings.

The main economic benefit of fixed absorbers is decreasing a neutron flux trap volume that is linked to fuel assembly pitch. Space between two adjacent assemblies, separated by absorber material in sheets or tubes on each side, creates a neutron flux trap. Neutron particles leaving the fuel assemblies are moderated in the trap. After the moderation, the neutron returning to the fuel assembly have higher absorption probability in the absorber material. The space between the fuel assemblies is not optimized for the fuel amount capacity, but for the minimum neutron flux trap volume for the specified fuel and fuel handling facility.

Using fixed absorbers allows design changes of the neutron flux trap volume. Fuel assembly pitch is decreased in spent fuel pool as well as in various casks where a more compact design is favorable for heat transfer and structural integrity analyzes. Decreased fuel assembly pitch can be used to increase the facility capacity (spent fuel pools) or decrease material consumption (spent fuel cask), both improving back-end economics. Spent fuel cask price is driven by cask wall cast iron or steel material cost. Fixed absorbers with decreased fuel assembly pitch result in a decreased cask wall inner diameter. Maintaining the cask wall thickness for shielding purposes with decreased cask diameter require comparatively less shielding material mass that directly influence the cask price due to lower material consumption.

2. Calculation analysis of GBC-32 benchmark cask

The efficiency of fixed neutron absorbers was demonstrated on criticality safety analysis of the GBC-32 spent fuel cask. It is a benchmark cask, simplified for burnup credit benchmark purposes and described in [4], main parameters are summarized in Table 1. For fixed neutron absorber concept feasibility, a 2-D model of the pressurized water reactor (PWR) cask was analyzed by Serpent 2 Monte Carlo code [5] and ENDF/B-VIII.0 continuous nuclear data library [6]. Fuel was assumed uniform in all fuel rods as one material. Uncertainties were not taken into account and it was assumed that they are at the same level as 2-D simplification, therefore, 0.95 limit used in the analysis. The criticality limit is recommended by International Atomic Energy Agency (IAEA) and subsequently restricted by national regulatory decrees (e.g. 10 CFR 50.68 in the US). Initial analysis with boron and gadolinium was studied in [7], detailed analysis of absorber design was performed in [8] and [9].

Table 1
GBC-32 spent fuel cask physical dimensions.

Parameter	cm
Cell inside dimension	22.0
Cell outside dimension	23.5
Cell wall thickness	0.75
BORAL panel thickness	0.2565
BORAL center thickness	0.2057
BORAL Al plate thickness	0.0254
Cell pitch	23.7565
Boral panel width	19.05
Cask inside diameter	175
Cask outside diameter	215

Spent fuel composition for burnup credit was calculated with actinide and fission product level with Nuclear Regulatory Commission (NRC) approved set of 28 nuclides [10] by Serpent 2 Monte Carlo code [5] and ENDF/B-VIII.0 continuous nuclear data library [6] on 2-D fuel assembly model with uniform fuel enrichment. Nuclide set is very similar to French selection of 27 nuclides [11]; Eu-151 fission product makes the only difference. Isotopic correction factors were not applied since the absorber reactivity worth is around ten times larger. Criticality and depletion calculations were performed with 20 million active neutrons divided into 1000 generations that resulted in 0.00020 neutron multiplication factor Monte Carlo uncertainty.

The GBC-32 geometry model, shown in Fig. 1, is comprised of 32 fuel assemblies of Westinghouse OFA 17 $\times$ 17 design. Fixed neutron absorbers were placed in all 25 guide tubes in the fuel assembly of selected fuel assemblies. Filling only a fraction of guide tubes in the fuel assembly while inserting the absorbers to all assemblies can be slightly more effective with the same amount of absorbers as in the previous case. However, filling all guide tube positions in lower number of fuel assemblies result in cost savings during reactor outage when fixed absorbers are being installed because the time required to transport the absorbers inside containment building with fresh fuel and subsequently move the absorbers into the spent fuel can prolong the outage if these manipulations cross the critical path of the outage. Manipulation with fixed absorbers represent additional tasks during outage and in order to minimize them, filling higher number of absorbers in lower number of fuel assemblies minimize the required time. Fuel assemblies are placed in aluminum tubes with absorbing BORAL (borated aluminum) panel inserted between adjacent tubes. The BORAL panel is 0.2057 cm thick with boron density of 0.0225 g B-10/cm^2. The cask is flooded with unborated water.

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/cm3), 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). The material selection was studied in detail for final disposal cask and subsequently used in all other fuel handling facilities.

Absorber material with 0.45 cm radius was placed inside 0.5 cm steel cladding tube. The possibility to save absorber material by using it with inner hole was analyzed, however, only 1/6 of absorber mass can be saved and the added manufacturing cost are not justified. The results favor full absorber design.

Fuel burnup influence reactivity distinctly, as shown in Fig. 2. The initial enrichment of the fuel is 5.0 wt% U-235. Because cooling time plays a minor role, the analysis investigated spent fuel with zero cooling time. For the cask with no fixed neutron absorbers, the criticality safety limit of 0.95 is only achieved if the assembly has achieved burnup higher than 35418 MWd/MTU. All of 8 selected absorber materials significantly decrease system reactivity and 0.95 criticality limit is achieved with significant margin even for fresh fuel.

Criticality safety of GBC-32 cask is achieved by two measures, using BORAL absorber sheets and burnup credit. Each of the criticality measures can be modified or even replaced by using fixed absorbers.

In the first case, criticality is achieved by using BORAL absorber sheets and fixed absorbers. In this case, BORAL content can be lowered up to 2.2 % of the original BORAL content for the most effective absorber (europium). The least effective absorber from the analyzed batch (gadolinium) can lower BORAL content to 17 % of the original BORAL content.

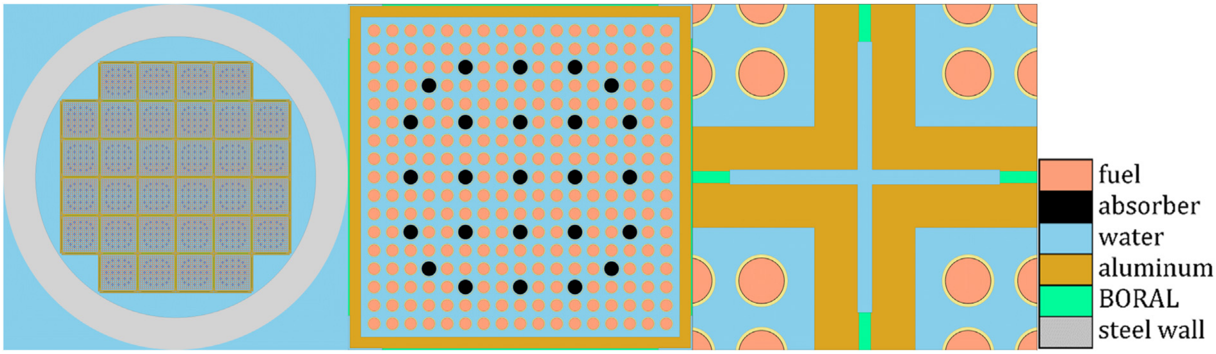


Fig. 1. GBC-32 spent fuel cask criticality model in Serpent 2.

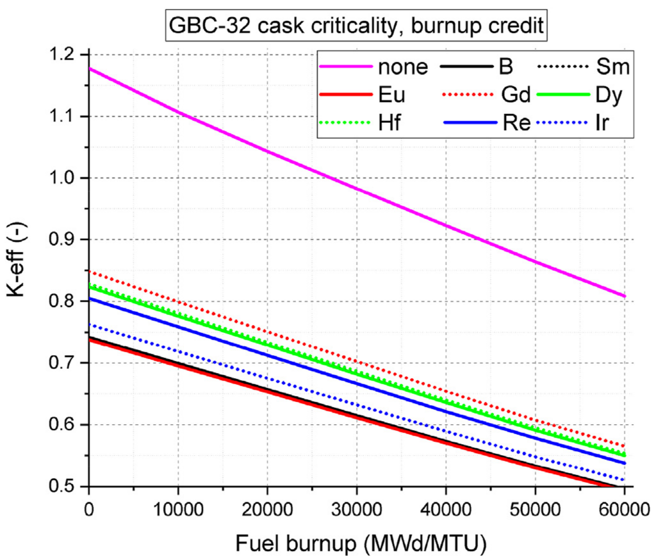


Fig. 2. GBC-32 cask criticality with fixed neutron absorbers.

In the second case, criticality is achieved by using fixed absorbers and burnup credit without changes in minimum burnup. BORAL sheets are removed and fuel assembly pitch is decreased even by removing aluminum tubes. However, in order to securely place fuel assemblies, 2 mm aluminum plate between assemblies were assumed to remain in the cask. Inner cask wall radius decreased by almost 7.5 cm and consequently, cask wall mass decreased by 8 %. Moreover, system reactivity still has margins. Neutron multiplication factor varies between 0.80 and 0.89 for various absorber materials.

The least effective absorber was analyzed for lowering the number of fuel assemblies loaded with fixed absorbers. Various absorber loading schemes summarized in Fig. 3 were analyzed. Both number of absorber-loaded fuel assemblies as well as their positions in the cask influence cask criticality, see Fig. 4. Higher number of fuel assemblies loaded with the absorber generally improves safety margins. Recommended absorber loading scheme is shown in Fig. 5.

3. Calculation analysis of VVER-1000 spent fuel pool

The efficiency of fixed neutron absorbers in used spent fuel handling facilities was analyzed in [14]. VVER-1000 (Water-Water Energetic Reactor) was nuclear fuel chosen for the analysis. The first spent fuel facility where the spent fuel is stored is spent fuel pool. Generic VVER-1000 spent fuel storage pool for V-320 reactor specification was modelled in Serpent 2 code with ENDF/B-VIII.0 nuclear data library [5]. The pool was modeled as a 3-D infinite array with the unit cell consisting of 12 fuel assemblies, as shown in Fig. 6. All assemblies in the unit cell have the same burnup and initial enrichment of 5.0 wt% U-235. Nine of the 12 assemblies in the unit cell are loaded with fixed absorbers. Therefore, the pool capacity is equipped by fixed absorbers by 75 % that defines the loading limit for subsequent fuel handling facilities. Loading of 2/3 for final disposal cask (67% of the capacity) in the last facility is the minimum loading for the previously operated facility (spent fuel cask, 13/19 fuel assemblies, 68% of the capacity), that is the subsequently the minimum for the first facility, the spent fuel pool where 9/12 fuel assemblies in regular cell were loaded with fixed neutron absorbers. Criticality safety is maintained by placing fuel assemblies in absorbing steel tubes in 288 mm pitch and 1.0 wt% boron content in the steel.

Fuel depletion and burnup credit methodology for VVER-1000 model was consistent with the initial GBC-32 analysis. 2-D fuel assembly model was used in fuel depletion calculation to calculate isotopic composition of 28 selected burnup credit actinides and fission products by Serpent 2 code. All 18 guide tube positions were loaded with fixed absorbers. Results are summarized in Fig. 7. Burnup credit is not required since neutron multiplication factor without assuming uncertainties is slightly below 0.92. It is observed that differences between various absorbers are negligible for VVER-1000 spent fuel (see Fig. 7) pool when compared to GBC-32 spent fuel cask (see Fig. 2). Large volume of neutron flux trap in the pool design is the cause of the different behavior.

This subcriticality level can be maintained by simultaneously introducing fixed neutron absorbers and decreased assembly pitch. The first measure decrease system criticality while the latter increases it. More compact rack consequently reduce regular cell volume that can be used to enlarge pool capacity. For the strongest absorber (boron), the regular cell volume reduction is 82 %, while for the least effective absorber (gadolinium), the reduction stands at 85 %, see Table 2 for comparison of pool capacity. Associated fuel pitch varies from 260 mm to 264 mm from reference value of 288 mm.

4. Calculation analysis of VVER-1000 spent fuel cask

Nuclear fuel is being cooled in the spent fuel pool near reactor for up to 10 years and then transported for long-term storage. There are two common solutions, wet and dry storage. Wet storage pool is very similar to spent fuel pool, only with capacity typically for the whole country. Using fixed neutron absorbers for wet storage is therefore very similarly efficient as in the spent fuel pools. Dry

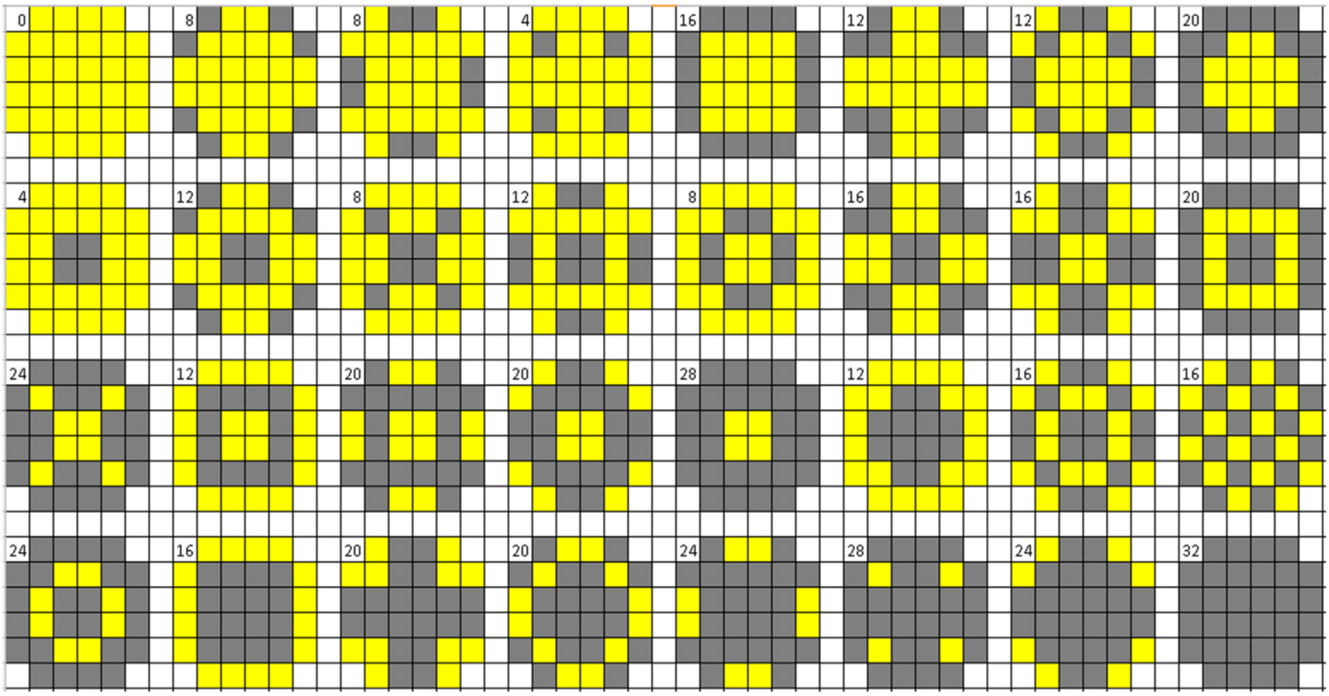


Fig. 3. GBC-32 absorber loading scheme (grey = absorber FA, yellow = no absorber FA). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

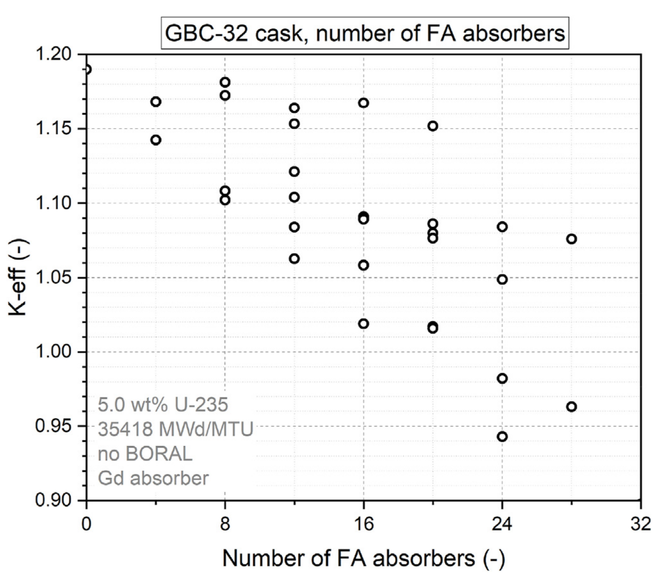


Fig. 4. GBC-32 criticality with partially loaded fixed absorbers.

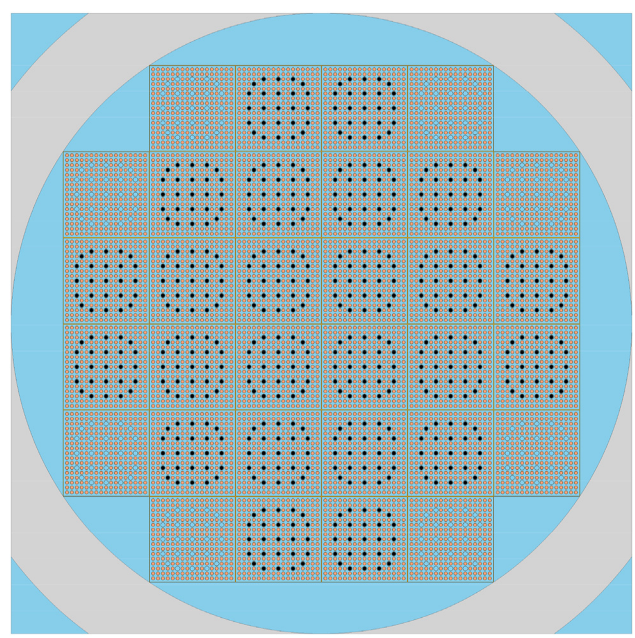


Fig. 5. GBC-32 cask design with fixed absorbers.

storage is based on spent fuel casks that can be constructed and licensed as both for transport and storage. CASTOR-1000/19 cask is a typical dual-purpose cask licensed for transport and storage of spent nuclear fuel.

Two-dimensional model of CASTOR cask was implemented based on data from [15]. Loading factor of fixed neutron absorbers is 68 %, intentionally slightly less than in the spent fuel pool, see Fig. 8. Absorbers are loaded in 13 central assemblies out of 19 assemblies in the cask. Criticality safety is secured by fresh fuel assumption and steel tube borated to 1.0 wt%. Regular lattice with 297 mm assembly pitch was adopted for the calculations.

Cask criticality with fixed neutron absorbers is summarized in Fig. 9, uniform 5.0 wt% U-235 fuel enrichment was used in the analysis. Burnup credit is not required since neutron multiplication factor is around 0.92 without uncertainties. Similarly to spent fuel pool, fixed neutron absorbers can be combined with design changes. In the case of spent fuel cask the benefit of using fixed neutron absorbers is cask wall mass reduction rather than capacity increase. Smaller cask size is achieved by decreased pitch from 259 mm to 265 mm from original 297 mm. Regular assembly cell volume decreases to between 81 % and 84 % and related cask wall

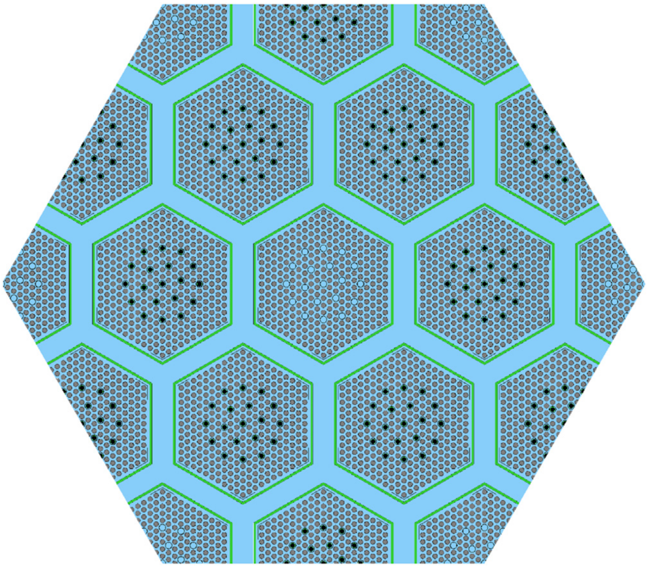


Fig. 6. VVER-1000 spent fuel pool criticality model in Serpent 2.

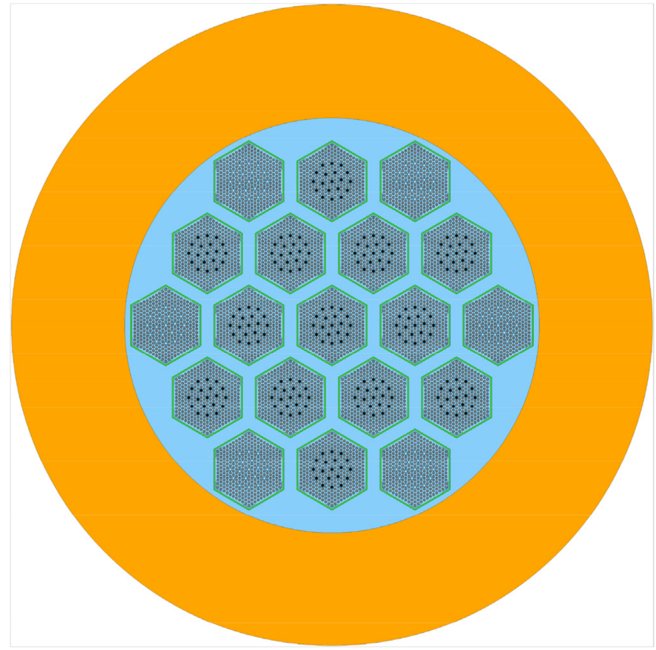


Fig. 8. CASTOR spent fuel cask criticality model in Serpent 2.

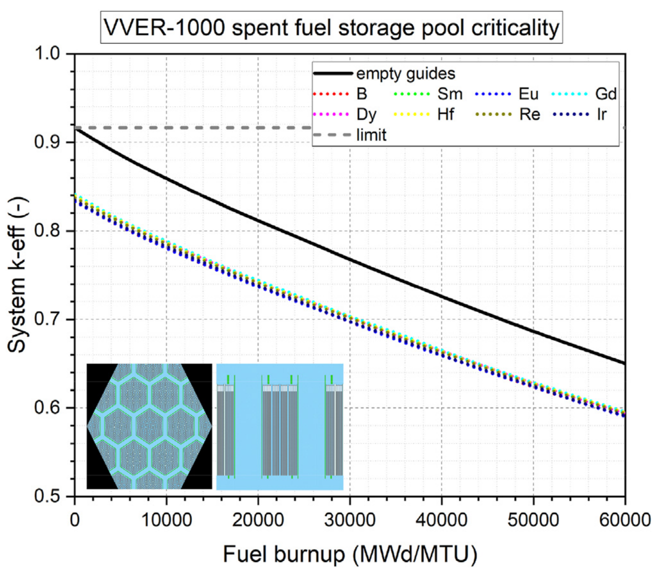


Fig. 7. VVER-1000 spent fuel pool criticality with fixed neutron absorbers.

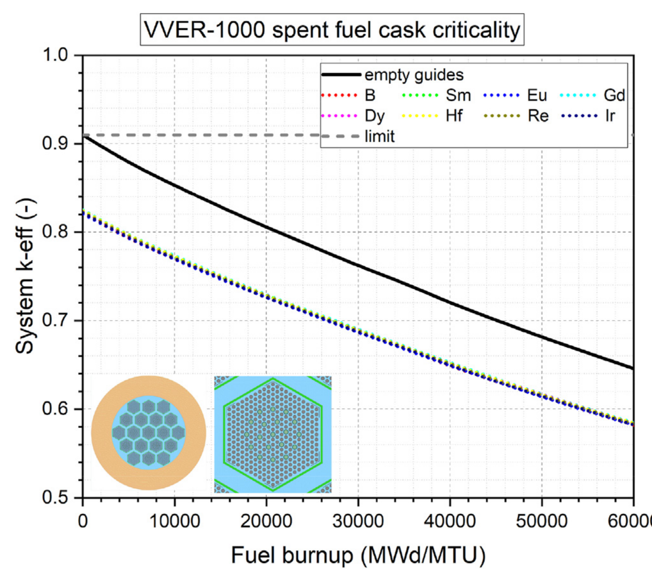


Fig. 9. CASTOR spent fuel cask criticality with fixed neutron absorbers.

Table 2
VVER-1000 spent fuel pool capacity increase while using fixed neutron absorbers.

Absorber	Relative pool capacity	Absorber	Relative pool capacity
empty	1.000	empty	1.000
Gd	1.180	Re	1.195
Hf	1.188	Ir	1.212
Sm	1.191	Eu	1.221
Dy	1.192	B	1.219

inner diameter decreases while the shielding wall thickness of 405 mm remains unchanged. Cask wall mass savings are listed in Table 3. The use of fixed neutron absorbers results in a CASTOR-1000/19 cask mass reduction of about 10%. This is comparable to the 8% mass reduction observed by introducing fixed absorbers to spent PWR fuel in the GBC-32 cask.

Spent fuel cask economics is mainly based on material price. Price of one dual purpose spent fuel cask is around $700,000 in 2009 prices [12], that is around $1M in 2023 prices (taking into account FED inflator multiplier 1.36 [13]). For CASTOR spent fuel cask, around 70 kg of neutron absorbers are required to achieve 10 % cask wall mass cost reduction. Neutron absorber material costs are summarized in Table 4, prices are relevant to a large world material supplier ChemPUR. Oxides with 99% purity are required for neutron absorbers, higher purity tied with higher costs is relevant for other industrial purposes (electronics). Gd, Hf and Sm absorbers are expected to improve material economics, because their price for 70 kg is much lower than $100,000 saved on cask mass.

Altenatively, it is possible to trade using fixed neutron absorbers for increased fuel enrichment. The cask with 5.0 wt% U-235 fuel

Table 3
CASTOR spent fuel cask wall mass savings while using fixed neutron absorbers.

Absorber	Relative cask wall volume	Absorber	Relative cask wall volume
empty	1.000	empty	1.000
Gd	0.915	Re	0.908
Hf	0.912	Ir	0.902
Sm	0.911	Eu	0.899
Dy	0.911	B	0.899

Table 4
Neutron absorber material costs.

Absorber	$/kg	Absorber	$/kg
Gd	466	Re	15400
Hf	455	Ir	161000
Sm	570	Eu	7500
Dy	1800	B	10000

enrichment without the absorbers has the reactivity of around 10.0 wt% U-235 fuel enrichment when 13 fuel assemblies are loaded with fixed neutron absorbers.

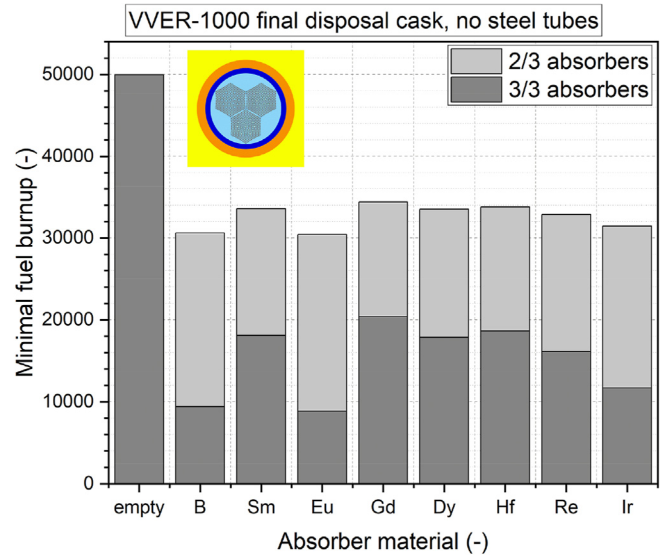


Fig. 11. VVER-1000 final disposal cask criticality with fixed neutron absorbers.

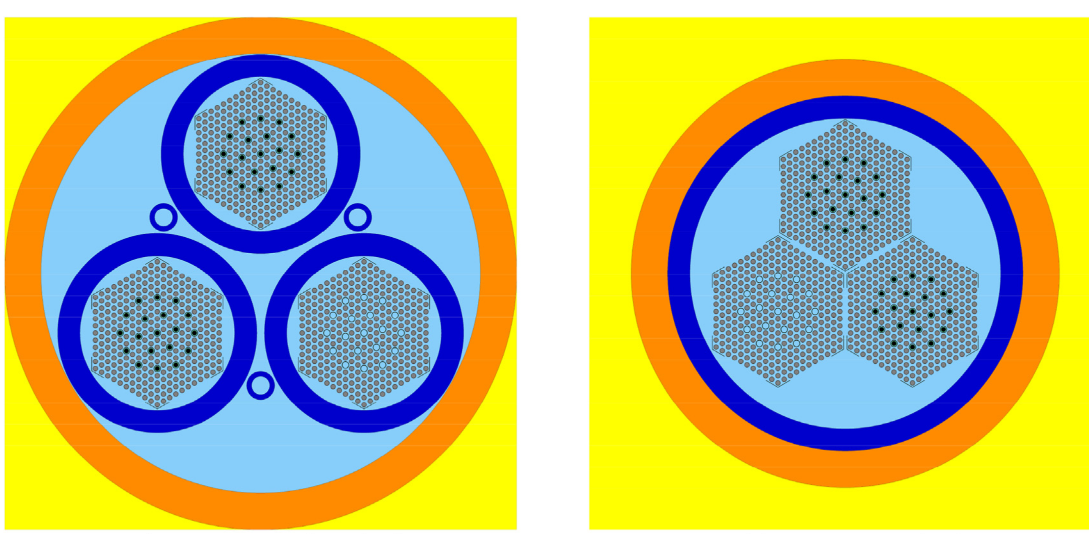
5. Calculation analysis of VVER-1000 final disposal cask

SKODA-1000/3 final disposal cask for three VVER-1000 spent fuel assemblies was recently designed for deep geological repository. The possibility of using fixed neutron absorbers for the cask was subsequently analyzed in [14], [16] and [17]. Two designs were proposed, compact design with close fuel assembly packing, and conservative design with cylinder steel tubes around each fuel assembly for improved cask lifetime and structural properties, see Fig. 10.

Compact cask is loaded by three fuel assemblies without borated parts and require burnup credit methodology that can be replaced by fresh fuel assumption and fixed neutron absorbers. Comparison of all elements in Fig. 12 shows that there are numerous element options. The most promising elements are compared in Fig. 13 and divided in 3 selection groups. All neutronic calculations are using only the eight most efficient absorbers from stable non-radioactive elements. The selection of eight elements for VVER-1000 final disposal cask is the same as selection calculated for GBC-32 cask [9].

Minimum burnup of spent fuel for compact cask is around 50000 MWd/MTU without absorbers. Loading fixed neutron absorbers inside 2 fuel assemblies reduce minimum burnup to the interval between 20000 MWd/MTU and 30000 MWd/MTU. Some of the assemblies from the pool can be used to loading of all 3 fuel assemblies in the cask. In this case, minimum allowable burnup for all absorbers is around 10000 MWd/MTU, see Fig. 11.

Conservative cask has large criticality margins due to large neutron trap volume and it fulfill criticality criteria even for fresh fuel. Therefore, fixed neutron absorbers are not required. On the other hand, cask wall costs are higher by 75 %. Nevertheless, if fixed neutron absorbers are already in the fuel, it can be beneficial for the cask safety. As cask criticality is lower, subcritical multiplication of the neutron source from the spent fuel is reduced. Neutron source strength is lower by 5 % and all radioactive nuclides generated by neutron activation will have 5 % lower activity [17].



a) Conservative design   b) Compact design

Fig. 10. VVER-1000 final disposal cask criticality model in Serpent 2.

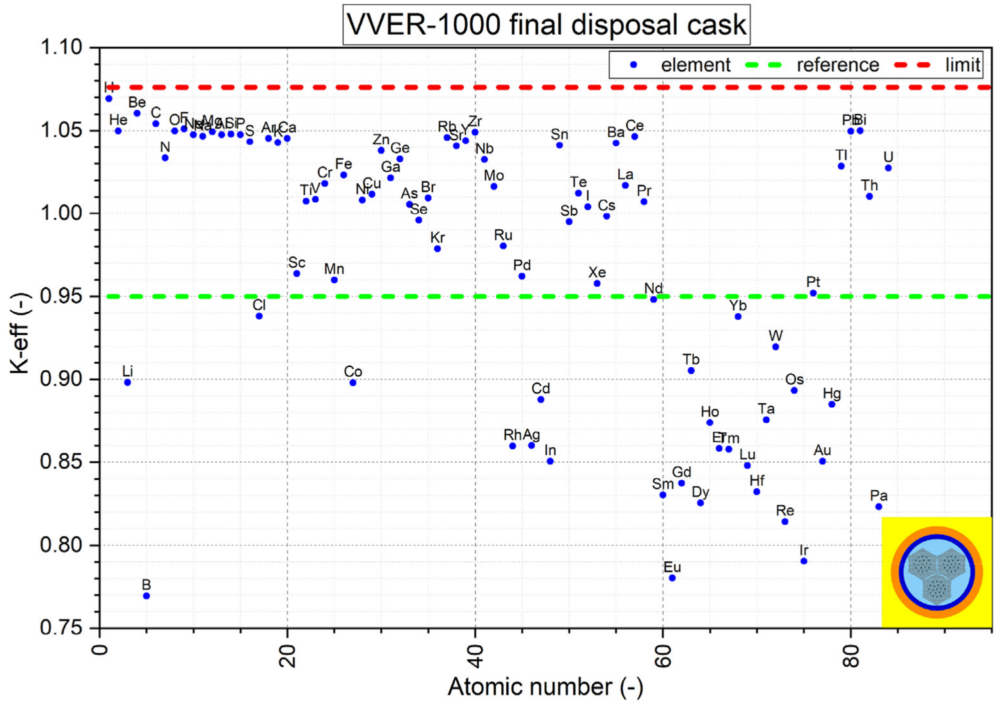


Fig. 12. VVER-1000 final disposal cask criticality with fixed neutron absorbers.

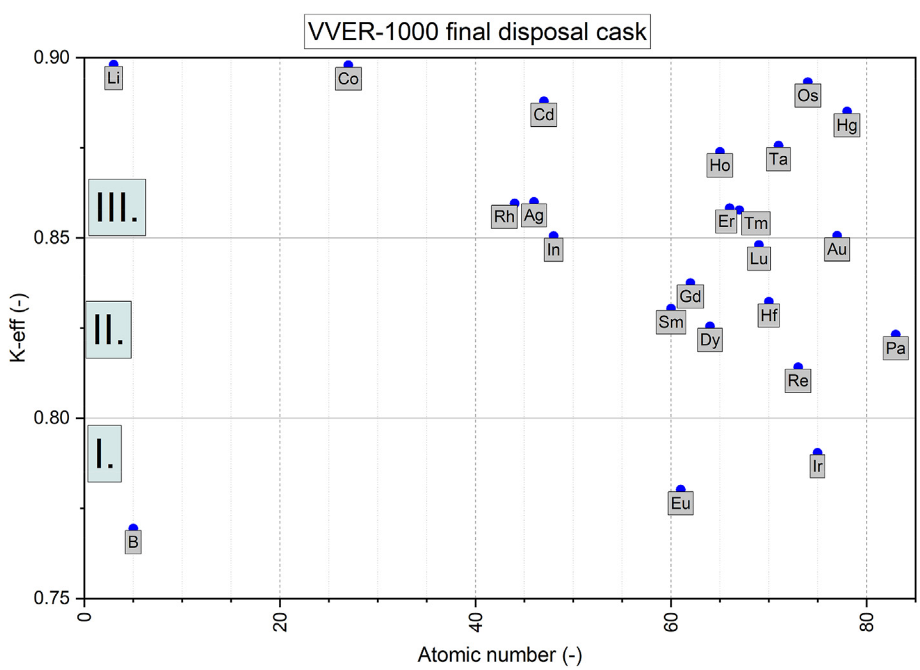


Fig. 13. Groups of the most promising fixed neutron absorbers.

6. Experimental verification of fixed neutron absorber manufacturing and efficiency

Verification of calculation analysis was performed experimentally in a zero power LR-0 reactor core [18]. The reactor has a versatile core, seven fuel assemblies with neutron absorbers inside the central one were chosen for the measurements. Criticality state of core loaded by neutron absorbers was prepared for four states. In the first state, there are no absorbers in the core. In the second and third state, 6 absorber rods of different absorber material are compared. Lastly, all 18 guide tube positions are filled by absorber rods, see Fig. 14.

Gadolinium and samarium oxide powders were used to manufacture absorber rods by press down the powder inside steel cladding. Six gadolinium and twelve samarium rods were measured. Reactivity in LR-0 reactor is controlled by water

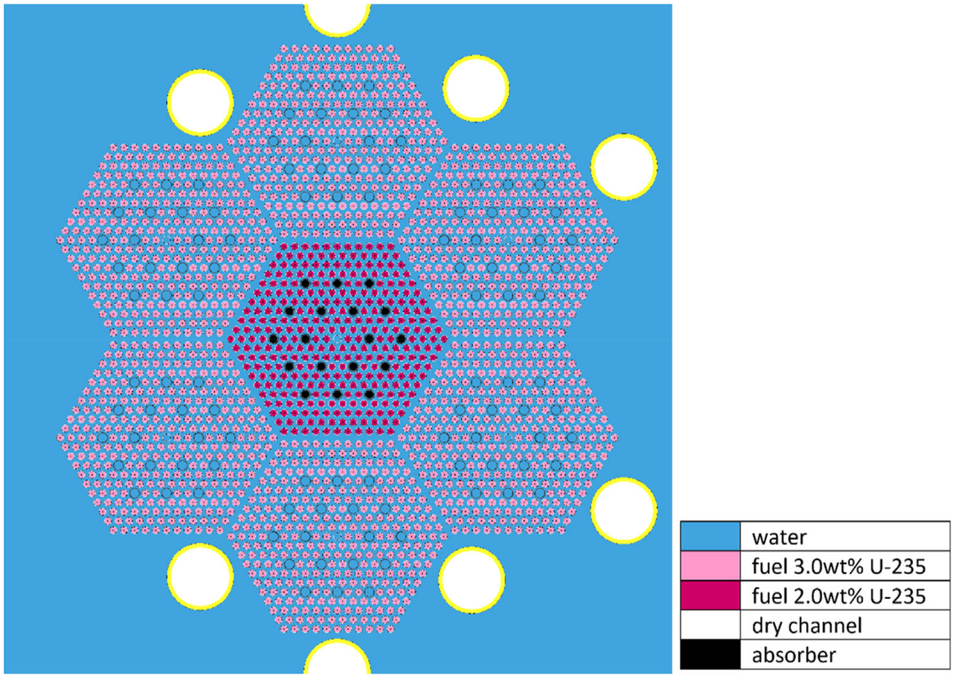


Fig. 14. Neutron absorber loading in VVER-1000 fuel of LR-0 reactor core.

moderator level in the reactor pool. Water moderator was measured as well calculated for experimental verification of fixed neutron absorber efficiency. Experimental verification of fixed neutron absorbers reactivity worth has been evaluated based on critical water moderator level. Calculation of all four states with the same calculation tools as previous calculation analysis (Serpent 2 + ENDF/B-VIII.0) showed great agreement with differences under 30 pcm, the results are described in more detail in [19] and [20].

It was experimentally verified that chosen absorber steel cladding diameter of 10 mm is the limit for placing the rods inside 11 mm inner diameter guide tube. However, since LR-0 uses shortened VVER-1000 fuel with around a third of active fuel column height and physically non-irradiated fuel, the diameter used for the spent fuel from a large reactor unit should be reduced to 8 mm to be comparable to cluster rods for reactor regulation.

Using oxide powder has the disadvantage in the filling volume fraction inside the steel cladding. Manually, it was possible to load only about a half of the volume with oxide powder, resulting in oxide powder density less than 3 g/cm^3. Pressed powder pellets or metals are advised to be used for back-end applications.

7. Manufacturing options for inseparable fixation of the absorbers

The absorber is required to be inseparably fixed to the fuel assembly to be accepted by a regulatory body. Two main options were analyzed, mechanical-based and chemical-based junction for VVER-1000 nuclear fuel. The junction location is at the top nozzle since it is the place where standard control rod cluster is inserted.

There are three holes in the fuel assembly top nozzle that was proposed to lock the plug after it is inserted into the nozzle as the basis of mechanical-based junction. The plug in Fig. 15 itself is a stainless steel disc with the following elements:

- 18 holes with threads for mounting fixed neutron absorbers
- locks for handling the plug
- 3 threaded holes for mounting locking elements

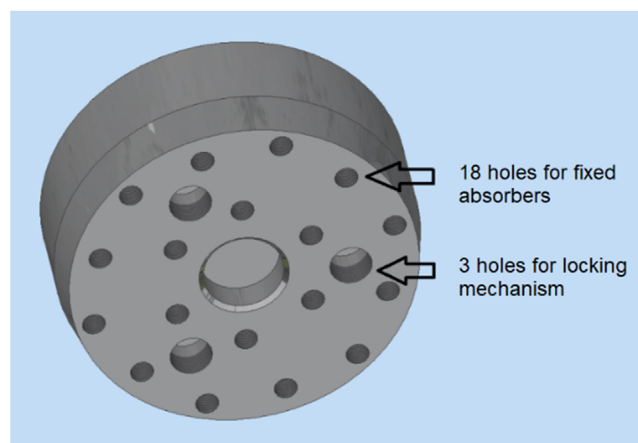


Fig. 15. Mechanical junction – plug with holes for absorbers and lock thorns.

- groove for securing the cover cap after locking the plug

Mechanical junction locking mechanism can be manufactured by either push thorns or pull thorns. The thorns and fixed neutron absorbers are inserted into the holes of the plug locking mechanism and locked after pressing the cover cap against the thorns in the plug, see Fig. 16. The cover cap installation subsequently makes the junction permanent without the possibility of unlocking it.

Chemical-based junction of the fixed neutron absorbers and the fuel assembly top nozzle was proposed by potting as a common industrial junction in electronics, automotive etc. Utility model of the fixed neutron absorbers [21] and its chemical junction to the fuel assembly was obtained [22]. Potting of two-component chemical technology compound utilize resins based on epoxy and polyurethane. For the fixed neutron absorbers, biresin was chosen as the candidate material. Its density is 1.23 g/cm^3, chemical composition $C_{15}H_{10}N_2O_2$ and thermal stability up to 65 °C that is

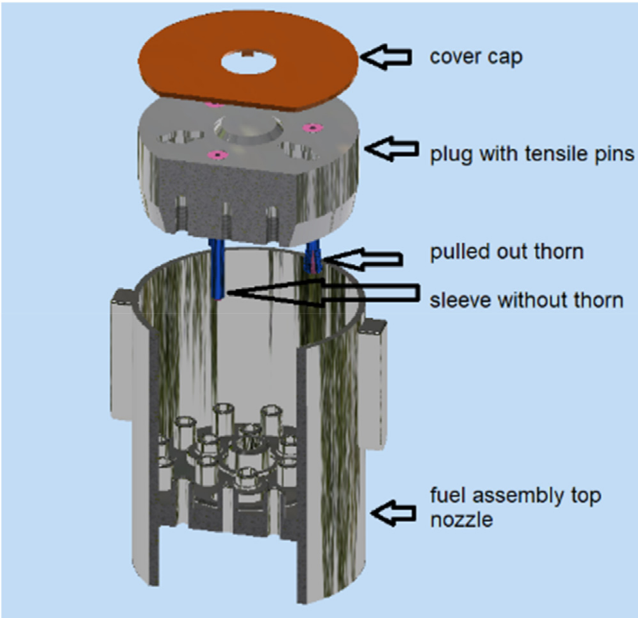


Fig. 16. Mechanical junction – fuel assembly top nozzle and mechanical plug.

feasible for fuel top nozzle environment in wet storage and final disposal. Composition of irradiated biresin was calculated by 2-D fuel assembly depletion calculations in Serpent 2 code, only 0.16 % of the isotopic material changes, mainly due to the production of C-14 radioactive carbon. The dominant part of total neutron fluence emitted in the environment from the fuel is in the final disposal cask (96 %), long-term storage accounts for 3 % of neutron fluence and only 1 % of neutron fluence in emitted in the spent fuel pool. On the other hand, photon fluence is more evenly distributed in the fuel handling facilities (27 % pool, 22 % long-term storage, 51 % final disposal) due to much shorter half-lives of fission products generating photons compared to actinides with spontaneous fission emitting neutrons.

Fig. 17. Chemical junction – potting inside the plug and absorbers holder.

Potting was experimentally verified in 10 m water depth pressure. Sample after potting can be seen in Fig. 17.

8. Conclusions

Fixed neutron absorbers are proposed for various nuclear fuel and fuel handling facilities to improve nuclear safety and fuel back-end economics. The most promising absorbing materials include B, Sm, Eu, Gd, Dy, Hf, Re and Ir. Absorbers are placed inside a steel cladding, loaded into the empty guide tubes of spent fuel assemblies and permanently and inseparably fixed to the assembly top nozzle by potting.

Placing fixed neutron absorbers in current spent fuel handling facilities would decrease system reactivity and increase criticality safety even with higher enriched fuel. Improved nuclear safety can be accompanied or replaced by better back-end economics while achieving the same level of nuclear safety.

Fixed neutron absorbers in guide tubes are more effective than neutron flux trap created by an empty unused volume between adjacent fuel assemblies inserted into the absorbing tubes. Therefore, fixed neutron absorbers result in decreased assembly pitch in the fuel handling facilities. In the spent fuel pool, it can be used for 20 % capacity expansion. For spent fuel casks with a defined capacity, decrease of the cask wall inner diameter leads to 10 % reduction of the cask wall mass without changing the cask wall thickness for shielding purposes.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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