Nuclear Safety Analysis for Transport Cask TK-6 (for VVER-440) and Cover for Fresh Assemblies (for VVER-1000) in Implementation of New Fuel Types at Ukrainian NPPs

Yevgen Bilodid
ei_beloded@sstc.kiev.ua
Iurii Kovbasenko, Olena Dudka
State Scientific and Technical Center for Nuclear and Radiation Safety

ABSTRACT

According to the fresh fuel management procedure, fuel assemblies – after nuclear fuel delivery to the NPP fresh fuel unit - are vertically loaded into a cover intended for the delivery of fuel assemblies into the containment of the NPP reactor compartment. The cover is placed into a universal jack in the reactor pool, and then the fresh fuel assemblies are loaded into the reactor core. Based on the nuclear safety analysis carried out by the Russian Research Center "Kurchatov Institute" for regular VVER-1000 fuel, it has become necessary to limit the number of fuel assemblies loaded into a cover below its designed capacity (12 FA instead of 18 FA as initially designed). Such a decision leads to worse economic performances in fuel transportation.

Transport cask TK-6 for spent fuel assemblies was designed quite a long time ago and, as shown in this paper, the requirement on the maximally permissible neutron multiplication factor of the loaded cask for individual states to be analyzed in compliance with Ukrainian regulations is not met. First of all, this concerns the cask criticality analysis in optimal neutron slow-down (cask filling with water-air mixture with optimal density). The paper shows potential ways for TK-6 burnup credit loading with the maximum number of fuel assemblies and partial cask loading.

Two systems for transportation of VVER nuclear fuel are analyzed.

This paper considers two systems for VVER nuclear fuel transportation dealing with the issue associated with incompliance with Ukrainian regulatory requirements on nuclear safety, and proposes solutions to this issue. All calculations were performed with control module CSAS26 from SCALE code package [1, 2]. Some additional calculations were performed by with MCNP 4b code [3].

1 Cover for Fresh Assemblies 1152.89.00

Fuel assemblies of new design – fuel assemblies "alternative" (FA-A) – have been under implementation at Ukrainian NPPs in recent years. Basic FA-A improvements are as follows:

- force frame which consists of six corners of radiation-resistant E635 alloy with increased mechanical properties, spacer grids from E110 alloy welded to them and guide tubes of E635 alloy;
- application of the same type of construction material (zirconium alloy) for all FA components located in the core;
- application of burnable absorber integrated into fuel (gadolinium oxide).

Thereby we need to perform nuclear safety analysis and to check compliance of NPP components related to fuel treatment with nuclear safety requirements.

The cover for fresh assemblies is one of such components. It is designed to store no more than 18 FA-A in the fresh fuel storage facility and to be transported to the reactor compartment.

The cover constitutes a cylindrical vessel made of steel shell and bottom welded all together. Two horizontal intermediate plates are mounted on central vertical supporting rod. Barrels for spacing FA from each other are inserted in the plates.

Transverse and longitudinal sections of the cover for fresh assemblies are presented in Figure 1.

According to Ukrainian regulatory documents in force [4, 5], nuclear safety analysis should take into consideration the distribution and density of moderator with the moisture corresponding to K_{eff} maximum value. Therefore the presence of water or air-water mixture inside the cask was taken into account in all calculations. Mathematically it is modeled in criticality calculations by using non-borated water, whose density can vary from 0 to 1 g/ccm, as a moderator which fills the fuel storage system.

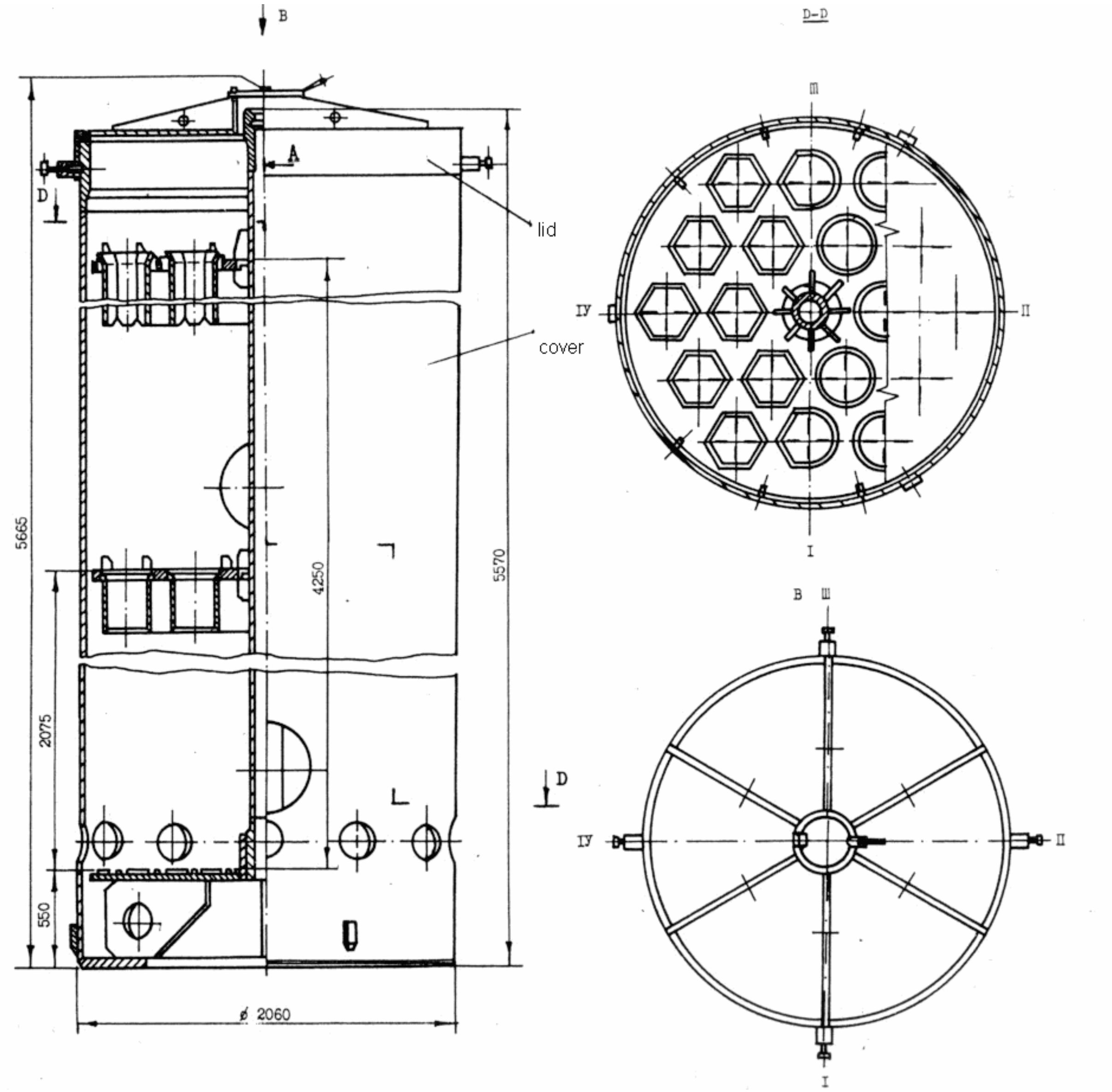


Figure 1 - Transverse and longitudinal section of the cover for fresh assemblies

Figure 2 presents the results of K_{eff} calculations depending on the moderator density for cask loaded with FA-A. The calculations were performed without fuel burnup credit, i.e. according to the regulatory requirements in force [4] the fuel was considered fresh.

The results provided in Figure 2 show that the largest value of K_{eff}= 0.9867 ± 0.0007 is reached under optimum water density, which constitutes 0.2 g/ccm. Thus, requirement [4] K_{eff}<0.95 is not met under optimum water density equal to 0.2 g/ccm.

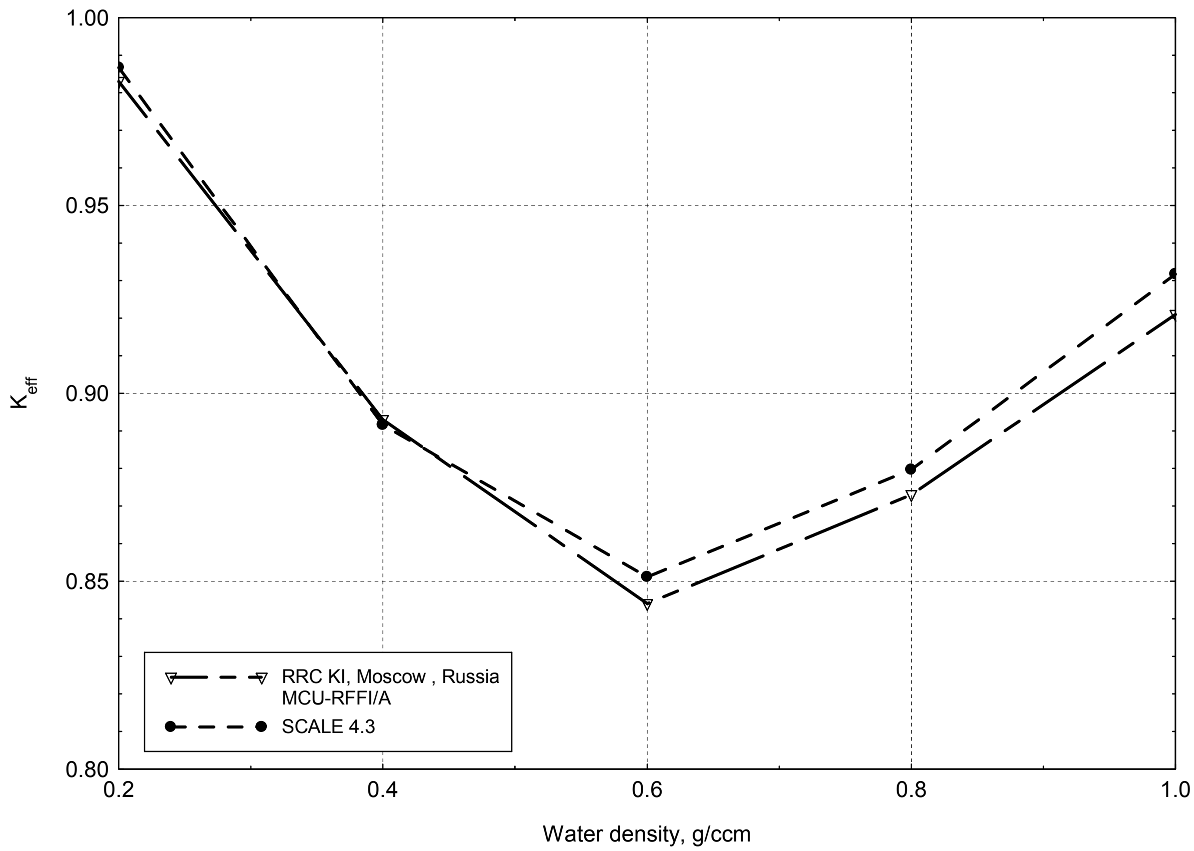


Figure 2 - Dependence of K_{eff} of cover for fresh assemblies loaded with 18 FA-A on water density

Below are calculation results for the variant that leads to the largest value of neutron multiplication factor, namely, when water density in the cover is equal to 0.2 g/ccm, which is loaded by regular FA enriched to 4.4% and FA-A with burnable absorber in six fuel pins, Table 1.

Table 1 - Dependence of K_{eff} on cover loading (water density is 0.2 g/ccm)

Cover for fresh assemblies loading	$K_{eff}\pm\sigma$
18 FA-A 4.39% without taking Gd into account	0.9867 ± 0.0007
18 FA-A 4.39% taking Gd into account	0.9368 ± 0.0005
18 regular FA 4.4%	0.9435 ± 0.0008

Based on Table 1, it can be concluded that if gadolinium in isotope composition of FA-A is taken into account in calculations, loading 18 FA-A into the cover not only permits compliance with nuclear safety conditions, but also allows improving nuclear safety of the cover as compared with its loading with 18 regular FA. However, in accordance with requirements [4], nuclear safety assessment of fresh and spent fuel treatment systems for FA containing burnable absorbers should assume the absence of absorbers. But in this case nuclear safety conditions are not met for the cover loaded with 18 FA-A enriched to 4.39%. Therefore substantiation was performed for partial loading of the cover for fresh assemblies with 12 FA-A located along the cover periphery (Figure 3).

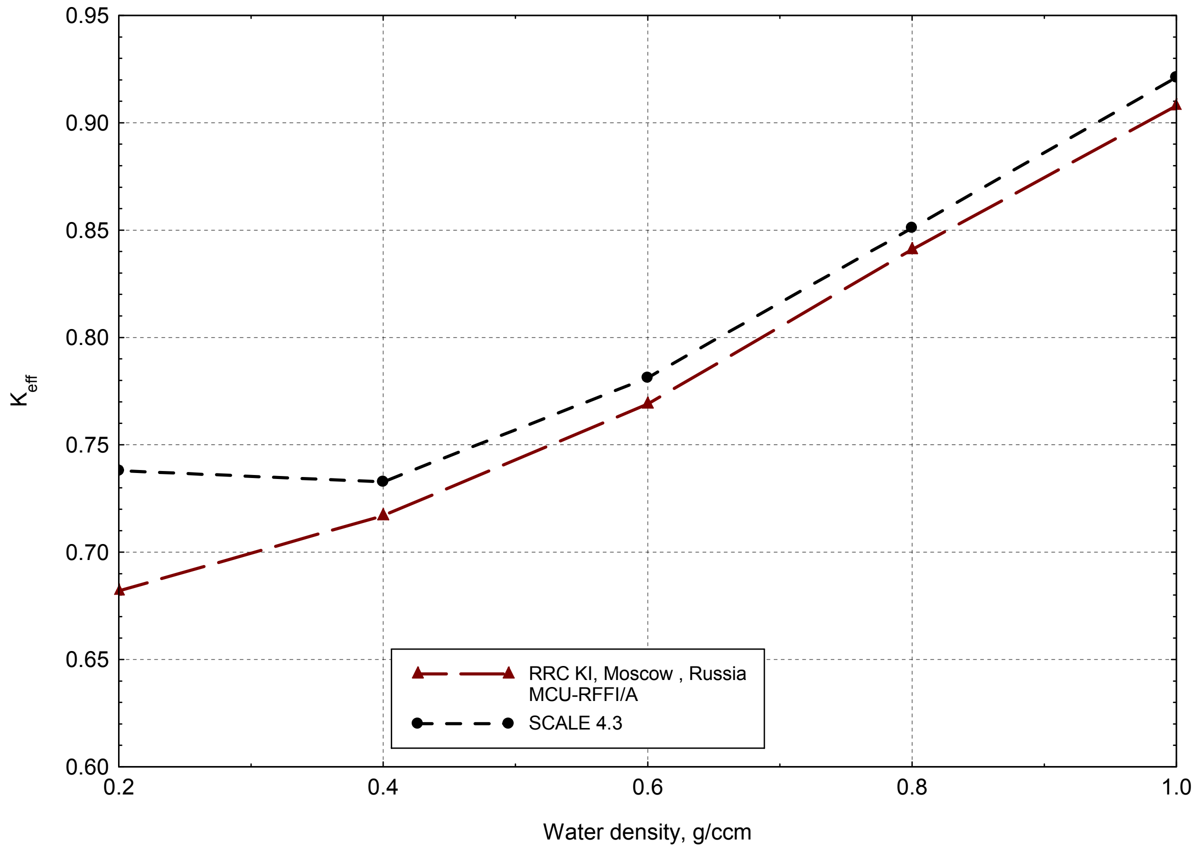


Figure 3 – Dependence of K_{eff} of cover for fresh assemblies loaded with 12 FA-A on water density

As Figure 3 indicates, requirement of Ukrainian regulatory document [4] to ensure K_{eff}<0.95 is met only in loading of the cover for fresh assemblies with 12 FA-A.

2 TK-6 Transport Cask

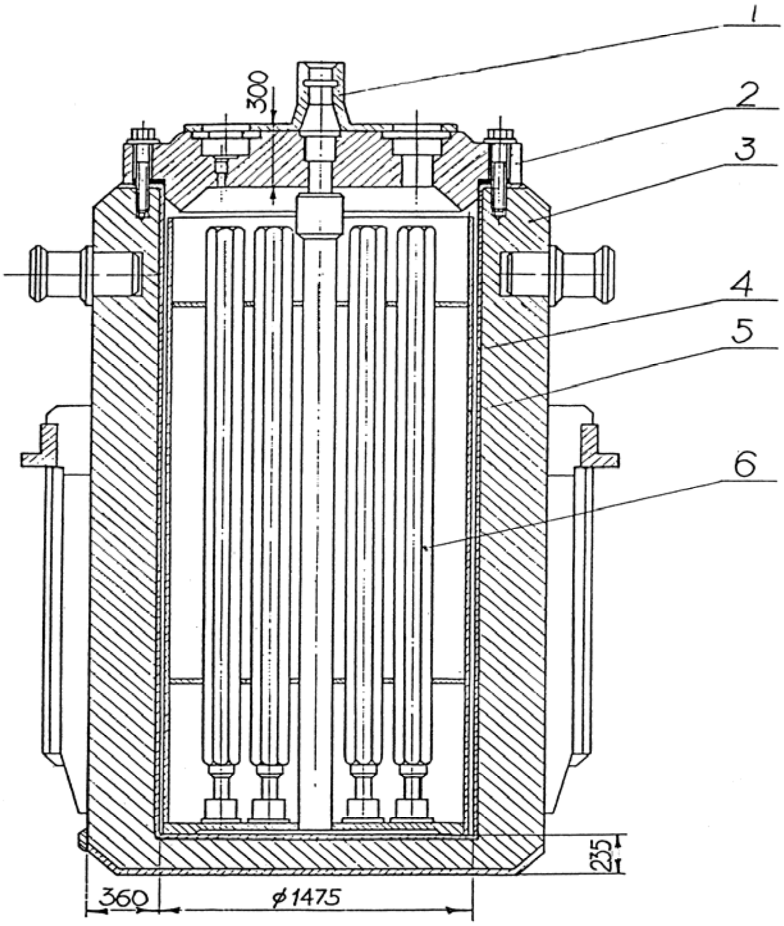
TK-6 transport cask [6, 7] is designed for transportation of spent fuel assemblies (FA) – working assembly (WA) and control rod fuel assemblies of VVER-440 reactors after their preliminary cooling in the reactor pool. The maximum amount of assemblies that are transported in the cask can be not more than 30.

The cask (Figure 4) is thick-walled cylindrical casing (3, Figure 4), closed by a hermetic lid (2, Figure 4). The internal surface of the cask is coated with corrosion-resistant steel (4, Figure 4).

To space and maintain integrity of fuel assemblies during transport operations, a cover for FA loading is inserted in the cask.

The cover (5, Figure 4) constitutes a welded cylindrical structure consisting of bottom, shell course, central tube and two spacer grids with seat providing for specified location of FA in the cover.

To provide for thermal mode, the internal cavity of the cask can be filled with liquid or gas.



1 – cask gripping device, 2 – cask lid; 3 - casing; 4 – casing corrosion-resistance coating; 5 - cover; 6 – fuel assembly

Figure 4 - Cross-section of TK-6 cask

The cask was designed a long time ago and assumed the use of fuel with the largest initial enrichment no more than 3.6% by ^{235}U. The distinguishing feature of this cask is the absence of any kind of absorber in structural material.

Recently, the fuel cycles on Rovno NPP units 1 and 2 have undergone considerable changes. Fuel enrichment has increased to 4.4% by ^{235}U, fuel service life in the core has increased to 5 years. Increase in fuel enrichment leads to failure to comply with requirement for the largest neutron effective multiplication factor value of TK-6 cask (K_{eff}<0.95) for some states whose analysis is required by regulatory documents. First of all this concerns criticality analysis of the cask when it is filled with air-water mixture with optimal moderator density. In turn this leads to problems with licensing of the cask and difficulties with its use in spent fuel removal to the Russian Federation.

Partial loading of the cask with fuel with lower enrichment or account of changes in spent fuel isotopic composition is one of the solutions to this issue.

Until recently, nuclear safety assessment of spent fuel treatment systems was carried out without burnup credit by all countries. Also, spent fuel was regarded as fresh in calculations of multiplication properties of spent fuel treatment systems. It was associated with difficulties in estimation of inaccuracy in determining the isotopic composition of spent fuel and influence of this inaccuracy on reliability of multiplication properties of nuclear-hazardous systems. Formally, current Ukrainian regulatory requirements do not prohibit the use of burnup as a safety parameter in nuclear safety analysis. However, this approach cannot be currently applied at Ukrainian NPPs since there are no approved methodologies for nuclear safety analysis with credit of irradiated fuel isotopic composition, nor instrumentation for burnup monitoring. Therefore, TK-6 nuclear safety analysis was first carried out without burnup credit of fuel loaded into the cask, which was filled with water with density of 1 g/ccm.

Table 2 - Criticality of cask loaded with 30 WA with different enrichment at moderator normal density (ρ_{water} = 1.0 g/ccm)

$K_{eff} \pm \sigma$			
WA (1.6%)	WA (2.4%)	WA (3.6%)	WA (4.4%)
0.6863±0.0007	0.7752±0.0007	0.8513±0.0008	0.8867±0.0007

According to Ukrainian regulatory requirements in force, in substantiating nuclear safety of fuel storage systems, regardless of the type of storage (dry or wet), it is necessary to analyze the case of filling the storage system with water-air mixture in such water/air proportion which leads to the maximum neutron multiplication factor. So all subsequent calculations considered the presence of water or air-water mixture inside the cask. Mathematically it is modeled in criticality calculations by using water whose density can vary from 0 to 1 g/ccm, as a moderator which fills the fuel storage system.

Figure 5 presents the results of K_{eff} calculations depending on the moderator density. It was assumed in the calculations that the cask was loaded with WA of 1.6%, 2.4%, 3.6%, and 4.4% enrichment. The calculations were performed without fuel burnup credit, i.e. according to the regulatory requirements in force [4] the fuel was considered fresh.

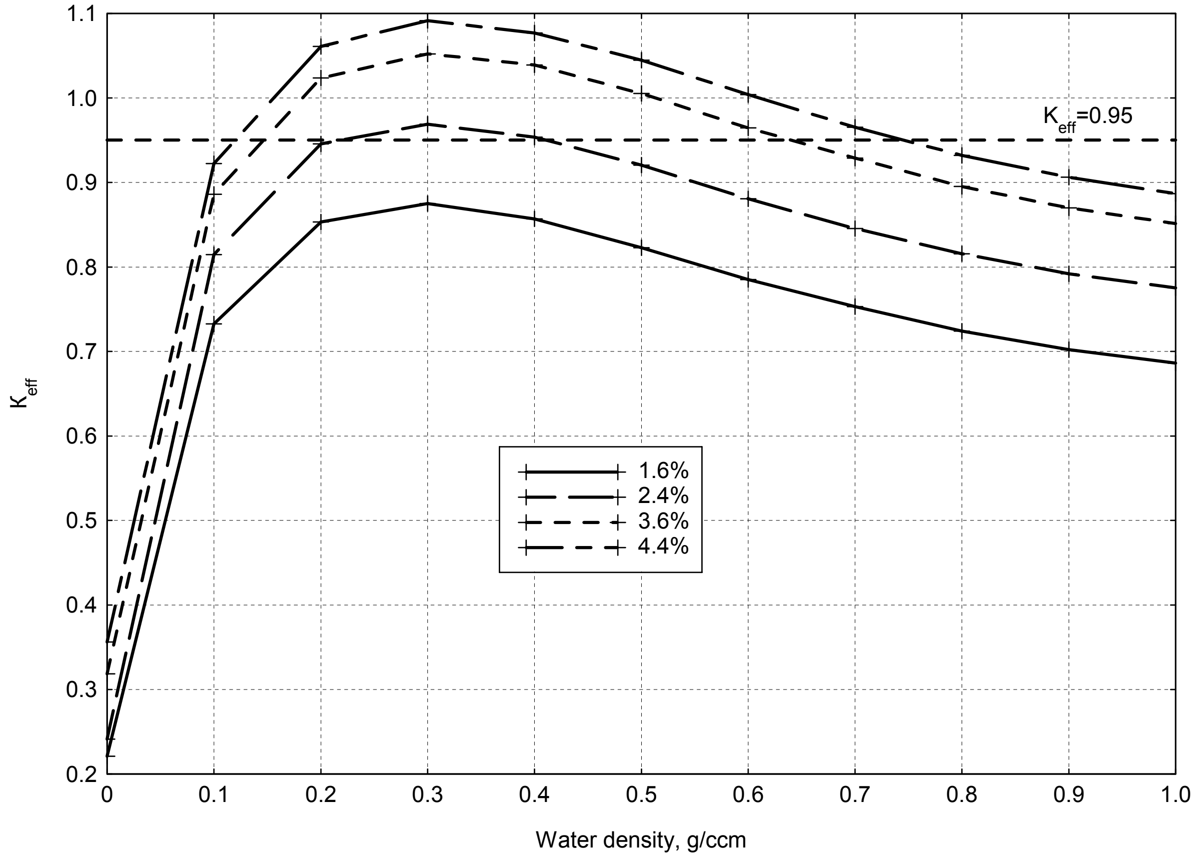


Figure 5 - K_{eff} dependence on water density in cask

As these results indicate, the maximum K_{eff} is achieved if the optimum water density is approximately equal to 0.3 g/ccm. At that, the requirement K_{eff}<0.95 of regulatory document [4] is not met in the wide range of the density water change (≈ 0.1÷0.7g/ccm) both for WA with 4.4% fuel enrichment and for WA with 3.6% fuel enrichment. In this calculation such enrichment of fuel was searched whose loading in the TK-6 cask would assure meeting the requirements of regulatory document [4] K_{eff}<0.95.

To meet the requirement K_{eff}<0.95 after fuel loading into TK-6 cask, appropriate fuel enrichment was found through calculations. Values of the effective neutron multiplication factor for cask loading with differently enriched fuel at moderator optimal density are provided in Table 3. As shown in Table 3, the requirement K_{eff}<0.95 at moderator optimal density is met only when the cask is loaded with WA enriched to no more than 2.0%.

Table 3 - Cask criticality for different fuel enrichment with moderator optimal density (ρ_{water} = 0.3 g/ccm)

K_{eff}±σ				
WA (1.6%)	WA (2.0%)	WA (2.4%)	WA (3.6%)	WA (4.4%)
0.8749 ± 0.0010	0.9197 ± 0.0007	0.9690 ± 0.0007	1.0521 ± 0.0008	1.0916 ± 0.0007

Calculations of Incomplete and Mixed Loading of TK-6 Cask Filled with Air-Water Mixture

The simplest way to improve TK-6 nuclear safety is its partial loading with fuel assemblies, when some part of cells remains non-loaded, and also cask loading with fuel assemblies with different enrichment. This section provides results of such calculations. The calculations demonstrate only the possibility to decrease the criticality to the required value by partial cask loading.

Four variants of loading in the cask with WA with 4.4% initial enrichment were considered in calculations. At that, the empty cells are filled with water. At the second stage, fuel of 1.6% initial enrichment was installed in the empty cells. Then the maximum enrichment was decreased to 3.6%, and TK-6 loading with 1.6% and 3.6% enriched WA was considered.

WA arrangement in the cask considered in the calculations is shown in Figure 6. Results of the calculations are provided in Table 4. Among all the cases considered, the neutron multiplication factor is lower than 0.95 only in three of them – when 12, 18 and 24 WA with 4.4.% enrichment are loaded into the cask (loading variants 1a, 1b and 1c, Figure 6, respectively).

Table 4 - Cask criticality for different loading variants

Cask loading: WA 4.4%		Cask loading: WA 4.4%/ WA 1.6%		Cask loading: WA 3.6%/ WA 1.6%	
Variant (Figure 6)	$K_{eff}\pm\sigma$	Variant (Figure 6)	$K_{eff}\pm\sigma$	Variant (Figure 6)	$K_{eff}\pm\sigma$
variant 1a	0.7070±0.0008	variant 2a	***0.9803±0.0007***	variant 3a	***0.9599±0.0007***
variant 1b	0.7919±0.0008	variant 2b	***0.9998±0.0007***	variant 3b	***0.9757±0.0008***
variant 1c	0.9335±0.0008	variant 2c	***1.0333±0.0008***	variant 3c	***1.0042±0.0008***
variant 1d	***0.9634±0.0009***	variant 2d	***1.0445±0.0009***	variant 3d	***1.0158±0.0009***

If the cask is loaded partially, non-loaded cells must be sealed so as to prevent loading of fuel assemblies into them. Otherwise, additional analysis is needed to consider an emergency caused by mistaken, single loading of a fuel assembly with the maximum enrichment into any free cell of the cask (so-called human factor account).

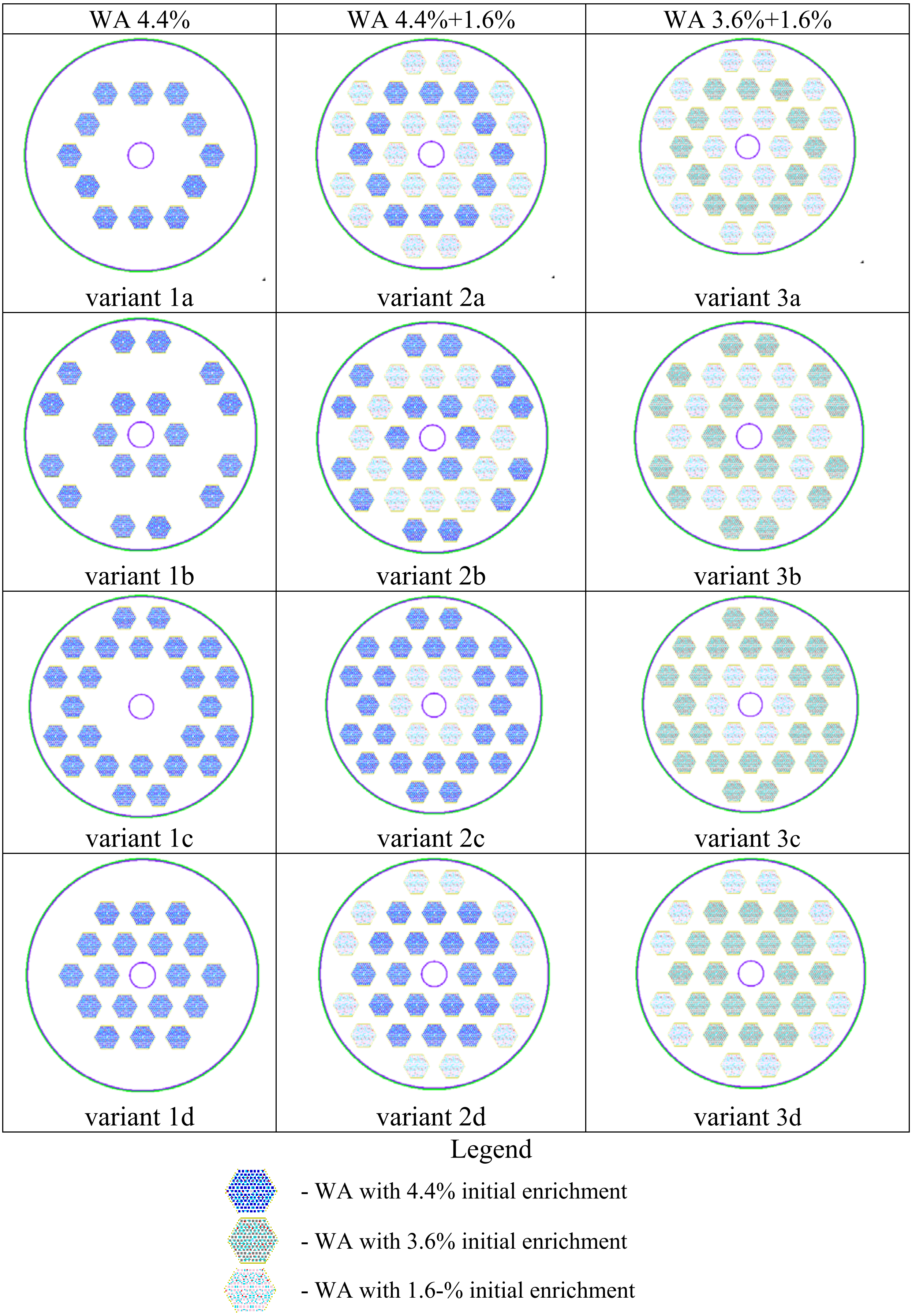


Figure 6 - Variants of WA arrangement in TK-6 cask

Hence, an emergency associated with mistaken loading of one fresh WA with the maximum enrichment was considered for variants 1a, 1b and 1c, Figure 6 (for which K_{eff}<0.95 requirement is met). This emergency involves the situation when one fresh WA is mistakenly loaded into any free cell of the cask, and the enrichment of this WA corresponds to the maximum enrichment of WA from the reactor pool. For VVER-440 this will be WA with 4.4% enrichment. As shown by calculations, only variants 1a and 1b can be used for partial loading of the cask with fresh fuel – this leads to substantial underload of the cask (not less than 12 WA) and, as a result, to essential economic losses in spent fuel transportation. In this regard, the next section deals with TK-6 nuclear safety analysis with burnup credit of the working assemblies loaded into the cask.

NUCLEAR SAFETY ANALYSIS OF TK-6 CASK WITH SPENT FUEL BURNUP CREDIT

General Comments on TK-6 Criticality Analysis with Burnup Credit

If spent fuel is regarded as fresh in nuclear safety analysis (as done in the previous section), the values of the calculated neutron multiplication factor will be greatly overestimated as compared to its actual value (excessive conservatism). Given such conservative results, nuclear safety assurance, as shown above, may lead to substantial economic losses associated with the need for incomplete loading of casks. Burnup credit technique is used for analysis of more realistic isotope composition. Preliminary results of research associated with burnup credit for VVER fuel are provided in publications [8, 9, 10, 11]

Calculations of TK-6 Criticality with Burnup Credit

In analysis of burnup impact on TK-6 cask criticality, only uranium and plutonium isotopes were taken into account: ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu, ^{241}Pu.

As stated in the certificate on TK-6 cask [7], no more than 24 SFA, including those with different enrichment, can be loaded into TK-6 cask if instrumental burnup monitoring is not conducted at NPP, provided that burnup requirements are met (Table 5). Six central cells of the cover should remain non-loaded.

If NPP conducts instrumental burnup monitoring, 30 FA can be loaded into a cask provided that burnup requirements are met (Table 5). In doing so, SFA loaded into one TK-6 in the amount of 30 items should have the same initial enrichment and fuel type (of natural or regenerated uranium).

Table 5 - WA characteristics permitted for transport in TK-6 cask filled with water [7]

Burnup, MW·d/kgU	1.6	2.4	3.6	4.4
no less*	-	-	-	34
no more	24.5	34	42(40**)	60(50**)

* - if 30 FA are loaded into cask; minimal burnup is not regulated in loading of 24 FA
** - for FA loaded into periphery cells

Fuel has the same burnup along its height. If we assume that this value characterizes average FA burnup, this approach will be easier to implement but, as shown by numerous studies, will not be conservative. At the same time, according to common international practice, use of the average burnup on FA end pieces for the whole assembly is considered a conservative approach. A similar methodology is used in burnup credit nuclear safety justification of VVER VSC at Zaporizhya NPP SNFSF [12, 13, 14, 15].

First of all, multiplying properties of fuel loaded into the cask were assessed on the basis of the certificate on TK-6 task [**7**], Table 6.

In analysis of fuel burnup impact on the system criticality, the optimal density of water-air mixture was taken (0.3 g/ccm).

In modeling the cask loaded with 24 WA, it was assumed that the remaining 6 cells were sealed, so mistaken WA loading into these cells was not considered.

In order to improve reliability of the results, complete TK-6 loading with differently enriched fuel was modeled with another code based on the Monte Carlo simulation – MCNP. Results of the calculations are provided in Table 6.

At the beginning of the TK-6 nuclear safety assessment with burnup credit the "loading curve" was plotted. This curve demonstrates the maximum admissible fuel enrichment and its minimum burnup to satisfy the condition K_{eff}<0.95 with optimum water density (ρ_{opt}=0.3 g/ccm). The WA with 4.4%, 4.0%, 3.6%, 3.0%, and 2.4% initial enrichment were analyzed (Figure 7).

Table 6 - Cask criticality with incomplete and complete WA loading, as envisaged by certificate [7], for differently enriched fuel

	1.6%	2.4%	3.6%	4.4%
24 WA	0.7401 ± 0.0007	0.8244 ± 0.0007	0.8995 ± 0.0009	0.9335±0.0008
30 WA	0.8749 ± 0.0007	0.9690 ± 0.0007 0.95367 ± 0.00061*	1.0521 ± 0.0008 1.03674 ± 0.00068*	(without fuel burnup credit) 1.0916±0.0007 1.07612 ± 0.00073* (fuel burnup is 34 MW·d/kgU) 0.9655 ± 0.0008 0.95134 ± 0.00069*

* - results of independent verification calculations with MCNP [3] code

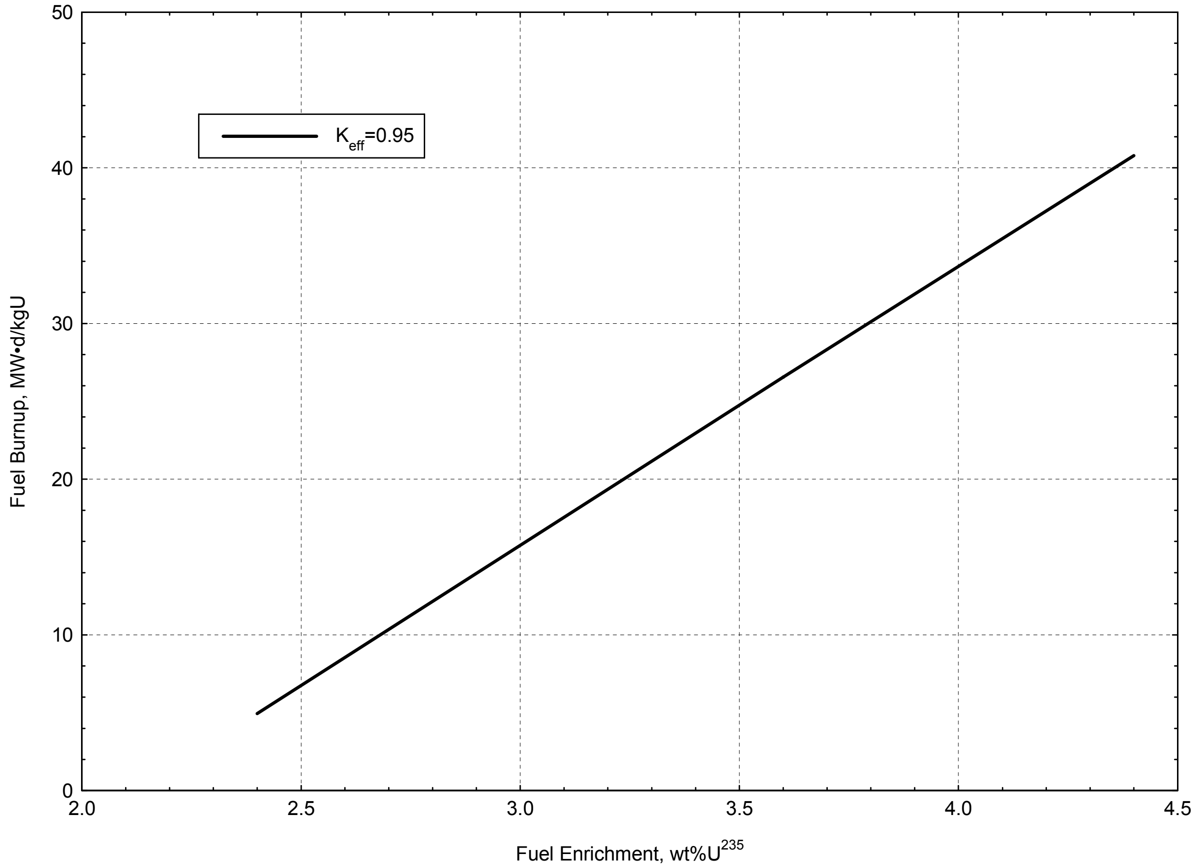


Figure 7 - Loading curve for TK-6 cask

The loading curve shows that TK-6 cask can be loaded with 30 WA with 3.6% initial enrichment and burnup not less than 26.54 MW·d/kgU, or 4.4% initial enrichment and burnup not less than 40.78 MW·d/kgU.

Additional Research of Minimally Permissible Burnup of Fuel Loaded into TK-6 Cask

This section provides results from calculations of the minimally permissible burnup of working assemblies with different initial enrichment as loaded into TK-6 cask, taking into account an emergency caused by mistaken loading of fresh WA with 4.4% enrichment (so-called human factor account [4]). Analysis of this emergency is not strictly required by regulatory documents, but is normally used by many countries in application of the burnup credit methodology.

Based on the analysis of the cask loaded with WA of the same burnup, taking into account the emergency associated with the human factor, TK-6 cask can be filled as follows:

- 30 cells with WA with 4.4% initial enrichment and burnup not less than 43 MW·d/kgU;
- 30 cells with WA with 4.21% initial enrichment and burnup not less than 37 MW·d/kgU;
- 30 cells with WA with 3.6% initial enrichment and burnup not less than 29 MW·d/kgU;
- 30 cells with WA with 2.4% initial enrichment and burnup not less than 6 MW·d/kgU;
- 30 cells - 18 of them are loaded with WA with 4.4% initial enrichment and burnup not less than 34 MW·d/kgU, and the central ring of cells is loaded with WA with 1.6% initial enrichment and burnup not less than 6 MW·d/kgU

Conclusions

The cover for transportation of fresh assemblies VVER-1000 can be loaded with no more than 12 fuel assemblies “alternative” (FA-A) located along the cover periphery. The requirement of current Ukrainian regulations to ensure 5% subcriticality can be met only in this case. Therefore, no more than 66% of the cover capacity is used.

As different from the fresh fuel cover, to justify loading of TK-6 transport cask the burnup credit methodology can be applied since spent fuel is transferred in TK-6 cask.

The analysis has shown that nuclear safety criteria are satisfied for TK-6 cask under the following conditions:

1) without fuel burnup credit, TK-6 cask can be loaded as follows:

- 24 WA with 4.4% initial enrichment if 6 central cells are sealed so as to avoid mistaken loading of assemblies into these cells;
- 18 WA with 4.4% initial enrichment if free cells remain unsealed.

In other words, if nuclear fuel burnup is not credited in TK-6 nuclear safety justification – i.e. transported fuel is regarded as fresh – up to 80% of the cask capacity can be used.

2) with fuel burnup credit, TK-6 cask can be loaded as follows:

- 30 WA with 4.4% initial enrichment with burnup not less than 43 MW·d/kgU;
- 30 WA with 4.21% initial enrichment with burnup not less than 37 MW·d/kgU;
- 30 WA with 3.6% initial enrichment with burnup not less than 29 MW·d/kgU;
- 30 WA with 2.4% initial enrichment with burnup not less than 6 MW·d/kgU;
- 30 WA – 18 of them are loaded with 4.4% initial enrichment and burnup not less than 34 MW·d/kgU, and the central ring of cells is loaded with WA with 1.6% initial enrichment and burnup not less than 6 MW·d/kgU.

Therefore, burnup credit ensures complete loading of TK-6 cask, but appropriate equipment and methodology for burnup instrumental monitoring are needed.

List of Nomenclature

FA	Fuel Assembly
FA-A	Fuel Assembly “Alternative”
NPP	Nuclear Power Plant
SFA	Spent Fuel Assembly
SNFSF	Spent Nuclear Fuel Dry Storage Facility
TK	Transport Cask
VSC	Ventilated Storage Cask
VVER	Water-Cooled Water-Moderated Power Reactor (Eastern Light-Water Reactor)
WA	Working Assembly
K_{eff}	Neutron Effective Multiplication Factor
σ	Standard Deviation, Statistic Inaccuracy

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