ASPECTS OF STATE TECHNICAL REVIEW OF NUCLEAR SAFETY JUSTIFICATION OF SPENT NUCLEAR FUEL STORAGE FACILITIES IN UKRAINE

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Abstract

At present, Ukraine has two spent fuel storage facilities under operation: wet spent fuel storage at Chernobyl NPP for RBMK-1000 fuel and dry spent fuel storage at Zaporizhzhya NPP for VVER-1000 fuel. Two more dry spent fuel storage facilities are under construction. The design of the ZNPP dry spent fuel storage facility was based on the VSC-24 interim spent fuel storage system used in the United States of America. Due to differences in the US and Ukrainian nuclear fuel, the loading of the ZNPP dry spent fuel storage facility could not be justified without additional measures. Some features of the wet spent fuel storage facility needed justification as well. This report presents the main approaches that were used in justification of the wet and dry spent fuel storages in Ukraine, as well as their state technical reviews.

1. INTRODUCTION

Ukrainian NPPs with VVER reactors were designed based on the concept of temporary storage and further processing of spent nuclear fuel (SNF) in the Russian Federation (RF). After the collapse of the USSR, Ukraine needed to build its own storage facilities for spent nuclear fuel.

The Zaporizhzhya NPP (ZNPP) with VVER reactor is the largest in Ukraine and includes six 1000 MW power units, and its needs in SNF storage was the most relevant: according to experts' forecasts, all ZNPP units would have to be shut down as early as 1998 because of the lack of free space in the cooling pools (CP). Replacement of the CP storage rack by compact ones allowed the problem to be postponed, but not solved. Therefore, a decision was made for ZNPP to build a spent fuel storage facility on the ZNPP site.

In agreement with the Ukrainian nuclear regulatory body, ZNPP announced an international tender for an interim storage facility for spent fuel. Upon the tender, the design of the Sierra Nuclear Corporation (SNC) and Duke Engineering & Services (DE&S) based on the dry ventilation container technology was selected. This storage technology has been recognized as the most environmentally friendly, practical, efficient, cost effective and relevant to the ZNPP needs. On 24 August 2001, the first container of the dry spent fuel storage facility (DSFSF) was installed on the ZNPP site.

Chernobyl Nuclear Power Plant (ChNPP), which consisted of four 1000 MW units with RBMK reactors, is another plant with its own capacities for storing spent fuel. For storage of spent fuel assemblies (SFA), wet interim spent fuel storage facility No. 1 (ISF-1) was constructed at ChNPP, where SFAs are stored in canisters under water. SNF-1 was put into operation in September 1986. Currently more than 21,000 SFAs from ChNPP power units 1, 2, 3 are stored in ISF-1. This storage facility is not designed for long-term storage, and its service lifetime expires in 2028. By that time, all SFAs from ISF-1 will be removed to dry interim spent fuel storage facility No. 2 (ISF-2), which will be put into operation in the near future.

Thus, today there are two storage facilities for spent nuclear fuel in operation on Ukraine: ISF-1 at the Chernobyl NPP and DSFSF at the Zaporizhzhya NPP. This report considers problems encountered in nuclear safety justification for both storage facilities and ways for their solution.

2. NUCLEAR SAFETY JUSTIFICATION OF ZNPP DSFSF

The ZNPP DSFSF design is based on the SNC and DE&S ventilated concrete casks for vertical storage of SFAs licensed by the US NRC. The design was selected for the following reasons:

— components can be fabricated by Ukrainian enterprises;
— the existing handling equipment of VVER-1000 units can be used;
— the geometric configuration of the VSC-24 casks designed to store square SFAs of PWR reactors was relatively simple to modify to store the hexagonal SFAs of VVER-1000.

24 SFAs are stored vertically in hexagonal guide tubes in a cylindrical multiplace sealed basket (MSB) made of carbon steel. After loading and sealing, MSB is a protective barrier that prevents the release of radioactive materials into the environment. The MSB is also a radiator that removes excess heat from SFAs to the ventilated concrete cask. The basket is filled with helium to create and maintain a dry inert heat-transfer medium.

According to the regulatory document [1], the main criterion of nuclear safety in spent fuel management is that the effective neutron multiplication factor must not exceed 0.95 in normal operation and design-basis accidents.

Technical characteristics of PWR and VVER SFAs are quite close, such as fuel composition, specific power density, fuel burnup, temperature criteria for individual elements, etc. However, there were significant differences between the Ukrainian and US designs.

The US VSC-24 casks were developed for FAs with multiplication properties corresponding to fresh fuel enriched to about 1.35 wt.% ^{235}U since burnup credit of fuel loaded into VSC-24 casks was used in justification of their nuclear safety. The maximum enrichment of FAs at ZNPP units is 4.4 wt.%, but in Ukraine a burnup credit in nuclear safety justifications for spent nuclear fuel systems was not used. Moreover, VVER-1000 FAs are about 400 mm longer than assemblies of most US PWR and contain more fuel rods, that is, they contain more fuel. All this resulted in a number of issues in nuclear safety justifications of VSC loading in design-basis conditions.

Loading of DSFSF casks with single-type fuel with enrichment from 1.6 to 4.4 wt.% ^{235}U was analyzed in the frame of state technical review. Pursuant to Ukrainian regulatory requirements, the analysis did not use burnup credit and assumed the optimal neutron moderation in the cask (cask is filled with unborated water with density of 1 g/cm3). The results of this analysis show that requirement $K_{eff} < 0.95$ is met only if the VSC is loaded with fuel enriched to 1.6%; beginning from 2.4%, the effective neutron multiplication factor exceeds 0.95.

2.1. Introduction of additional factors in nuclear safety justification of DSFSF casks

Since it was not possible to justify nuclear safety of the VSC without the use of additional approaches to ensure the required level of subcriticality, there was a need to take into account additional factors. The following additional factors influencing the criticality of containers (technical features and organizational measures) can be used:

— Incomplete VSC loading: the number of SFA is chosen not to exceed the effective neutron multiplication factor value of 0.95;
— Control rod credit as placement and fixation of the required number of absorbing rods in sfas;
— Use of homogeneous neutron absorbers in the MBS structure with control of the absorber concentration;
— Use of burnup credit as a nuclear safety parameter checked by a burnup monitoring system before SNF transfer to DSFSF;
— Combination of several factors.

2.1.1. Incomplete VSC loading

Use of incomplete VSC loading with maximally enriched fuel meets the nuclear safety requirements only if 10 SFAs are loaded into the cask (while its design capacity is 24 SFAs), which substantially increases the cost and size of the storage system.

2.1.2. Control rod credit

Loading of spent rods in each SFA for the optimal neutron moderation does not meet the requirement $K_{eff} < 0.95$ for SFAs with enrichment of 3.6% and higher what has been confirmed by state technical review.

2.1.3. Use of homogeneous neutron absorbers in the MBS structure

In case of using borated steel containing 2 wt.% ^{10}B isotope as a guide tube material, the requirement $K_{eff} < 0.95$ is not met for SFAs with enrichment of 4.4 wt.%. VSC loading nuclear safety can be ensured by simultaneous use of borated steel containing 2 wt.% ^{10}B isotope and Hf absorbing insertions between the guide tubes and steel plates which are parts of the MSB, but this would increase the cost of the storage system.

2.1.4. Burnup credit as a nuclear safety parameter

The burnup credit approach, i.e., consideration of fuel burnup as a nuclear safety parameter, is currently widely used in many countries in nuclear safety analyses of PWR and BWR spent fuel storage systems.

Since there are scarce experimental data on isotope concentrations for fuel types used in Ukraine, which are necessary to validate the computer codes for calculating the isotopic composition, it was decided to take into account changes in the concentration of only ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu, and ^{241}Pu isotopes to implement the burnup credit approach [2].

In order to implement this approach, a loading curve is commonly plotted for each storage system to show the maximum permissible fuel enrichment and minimum burnup at which the system complies with nuclear safety requirements. The curve for DSFSF VSC is shown in Fig. 1.

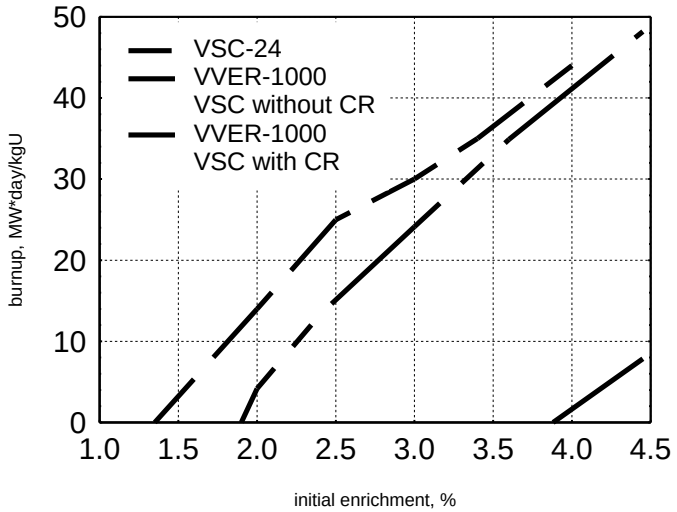

FIG. 1. Loading Curves for VSC-24 and VVER VSC.

It is clear from the results shown in Fig. 1 that burnup at which cask loading will comply with nuclear safety requirements is higher than 45 MW*day/kgU for SFAs with enrichment 4.4% ^{235}U, while a great number of SFAs to be loaded in DSFSF casks with the same initial enrichment but lower burnup is located in Zaporizhzhya NPP cooling pools.

The results of several real VSC loadings (SFAs with enrichment from 2.0 to 4.4% were loaded to the casks) which were conducted considering only burnup credit show that K_{eff} exceeds 0.95 in all what has been confirmed by state technical review.

Summarizing the above, it can be concluded that nuclear safety requirements for the full VSC loading cannot met if only one of the above approaches is used.

2.1.5. Combination of several approaches

The first three VSC loadings combined incomplete loading and placement of spent control rods into SFAs. Each cask was loaded with 22 SFAs with spent control rods in each SFA, and appropriate configuration of free cells was chosen. The experience in operation of these casks has shown that the permissible level of radiation on cask lids is exceeded if central cells are not loaded. This option was further excluded from consideration.

The option of simultaneous application of homogeneous neutron absorbers in the MBS structure and the use of spent rods was considered, but this option was also excluded from further consideration after a careful analysis because of a significant increase in the cost of the storage system.

Today, a joint use of burnup credit and control rod credit is accepted in nuclear safety justifications of VSC loadings, which requires nuclear safety analysis for each VSC loading.

2.2. Nuclear safety justification of DSFSF casks with additional approaches

ZNPP DSFSF was the first spent fuel storage facility in Ukraine that used burnup credit as a nuclear safety parameter.

To use the burnup credit principle and ensure fuel burnup instrumental control in ZNPP DSFSF nuclear safety justification, the following industry documents were developed.

(a) Guideline on Implementation of Spent Fuel Burnup Control at the Stage of DSFSF VSC Loading [3].
(b) Guideline on Burnup Credit Principle in Nuclear Safety Justification for DSFSF VSC Loading [4].

The Guideline [3] is intended to be used for spent fuel burnup control at the stage of DSFSF VSC loading, establishes the procedure for burnup control and record keeping, and identify success criteria for burnup control.

Guideline [4] establishes the scope and procedure for nuclear safety justification for spent fuel loading into a cask using the burnup credit approach, including:

— Conservative determination of SFA burnup and consideration of non-uniform burnup distribution along the FA height;
— List of isotopes that are taken into account in calculations of K_{eff} and procedure for determining their concentrations;
— Scope of nuclear safety analyses of cask loading with fuel burnup credit;
— Requirements for the cask mathematical model and the scope of calculations;
— Requirements for documenting and submitting the calculation results to the nuclear regulatory body;
— Scope and procedure for fuel burnup control at the stage of cask loading.

2.2.1. Requirements for criticality calculations of DSFSF VSC

When fuel burnup is used as a nuclear safety parameter, calculations of K_{eff} for each VSC loading should be performed taking into account the following requirements:

— The effective neutron multiplication factor should not exceed 0.95 even when the container is filled with water and when the quantity, distribution and density of the water-air mixture as a result of initiating events are such that lead to maximum K_{eff};
— The effective neutron multiplication factor should not exceed 0.95 with displacement of all sfas within guiding tubes;
— Possible inaccuracies of computer methods and the fissile isotopes concentration should be taken into account;
— The not fixed absorbing elements present in sfas and VSC structural elements and the absorbers dissolved in the CP water are not taken into account;

— The presence of a reflector at the model boundaries is foreseen;
— Human error in K_{eff} calculations should be taken into account by loading of one fresh FA with the maximum multiplication properties (from the ones available in the CP) instead of a spent FA, and the replacement should lead to an increase in K_{eff}.

2.2.2. Nuclear safety justification for DSFSF VSC operating conditions

The nuclear safety justification of the VSC loading takes place as follows:

— For the SFAs selected for loading, a conservative burnup profile is determined (the burnup is considered to be constant in height and equal to the average value between the burnup of the lower and upper (least burned) SFA layers).
— Isotopic composition is calculated in accordance with the specific burnup profile.
— The VSC loading scheme corresponding to the minimum K_{eff} is determined.
— If the minimum K_{eff} is greater than 0.95, control rods are used in SFAs loaded into the casks to appropriately decrease the neutron multiplication factor. Conservatively, the concentration of boron in control rods decreases by 25% for their burnup during operation in the reactor core.
— Emergencies caused by mistaken nonloading of a control rod or potential loading of one fresh FA with the maximum multiplication properties instead of a spent FA must be taken into account (human error).
— Simultaneous axial displacement of all absorber rods and displacement of all SFAs toward the MSB center within hexagonal tubes are analyzed.

As an example, Fig. 2 shows VSC loading and Table 1 shows the maximum K_{eff} value obtained for several VSC loadings[1].

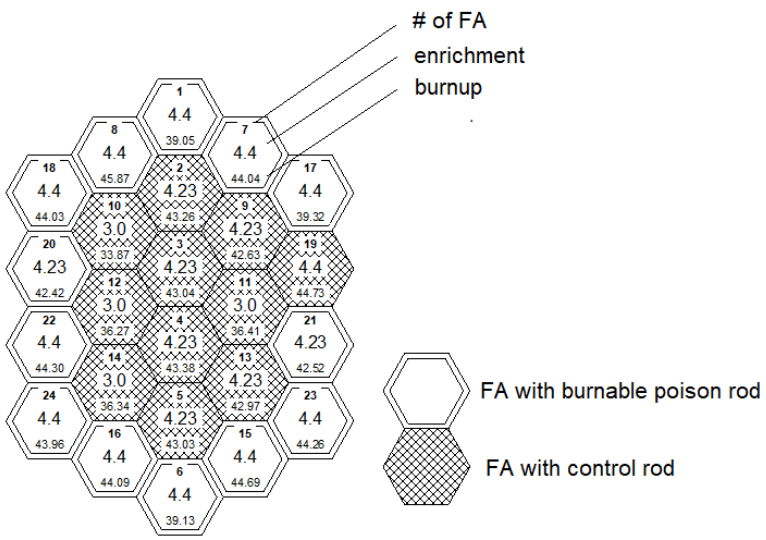

FIG. 2. The DSFSF VSC Loading Scheme.

TABLE 1. MAXIMUM Keff IN DSFSF VSC LOADING

Unit No.	Keff ±σ
1	0.94307 ± 0.00066
2	0.94420 ± 0.00076
3	0.9465 ± 0.0007
4	0.9444 ± 0.0009

[1] All results presented in this report were performed by the SCALE calculation code.

5	0.94441 ± 0.00081
6	0.94530 ± 0.00086

The VSC loading is approved only after a nuclear and radiation safety state technical review, during which verification calculations are performed using an independent calculation model and code.

3. NUCLEAR FUEL JUSTIFICATION OF CHNPP ISF-1

ChNPP ISF-1 is the main building of the common-plant storage system for spent nuclear fuel at ChNPP. It is intended for the reception and monitored storage of spent nuclear fuel. The storage facility consists of five compartments. The design capacity of ISF-1 is about 22,000 fuel assemblies.

SFAs are stored in water-filled canisters hung vertically on the consoles in CP compartments, which are cooled by the CP water. In this case, the canisters isolate SFAs from the CP water so that no mixture of waters occurs.

The result obtained in the frame of state technical review showed the maximum effective neutron multiplication factor in the CP compartments of ISF-1 (Fig. 3), without taking into account fuel burnup exceeded 0.95for the optimal moderator (water-air mixture) distribution in the system, which is ensured when the moderator density is 0.0 g/cm^3 in the CP and 0.8 g/cm^3 in in the canisters.

That is, as in the case of ZNPP DSFSF, nuclear safety of ISF-1 cannot be justified without the use of additional factors. The use of fuel burnup as a safety parameter became such a factor for ISF-1.

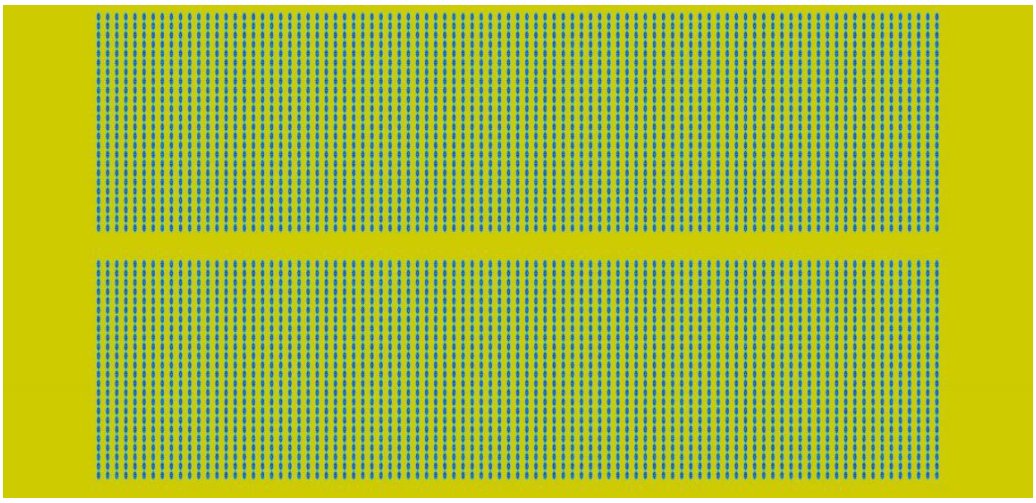

FIG. 3. Computational Scheme for ChNPP ISF-2 Compartment.

3.1. Construction of loading curves for ISF-1 CP compartments

To implement this approach, loading curves for ISF-1 CP compartments were constructed. Two fuel configurations can be used in the CP compartments. The first configuration corresponds to fuel storage conditions. The second configuration corresponds to the case of handling operations in a CP compartment, when an additional FA with maximum enrichment (2.4% regenerated) and minimum (zero) burnup is moved between the half-rows of SFAs. Calculations were performed for optimal distribution of water-air mixture in CP. Figure 4 shows loading curves for fuel storage conditions and handling operations. They allow in some cases the resolution of issues relating to the implementation of nuclear safety requirements without further research. In this way, if the CP compartment is loaded with fuel that meets the following requirements:

— Regenerated, enrichment of 2.4%, SFA burnup over 1844 MW*day/FA;
— Nominal, enrichment of 2.4%, SFA burnup over 1522 MW*day/FA;
— Nominal, enrichment of 2.0%, SFA burnup over 914 MW*day/FA;
— Nominal, enrichment of 2.0%, SFA burnup over 581 MW*day/FA;

— Nominal, enrichment of 1.8%, any SFA, then in any operations with this fuel, for example, storage, transport, rearrangement, unloading, loading, the neutron multiplication factor will remain below the required value of Keff = 0.95 regardless of the loading pattern and the sequence of operations.

Analysis of the loading cartograms for ISF-1 CP compartments shows a significant amount of fuel that does not comply with the above conditions is located in each compartment. Therefore, loading curves cannot be used to justify nuclear safety of the existing loadings of compartments.

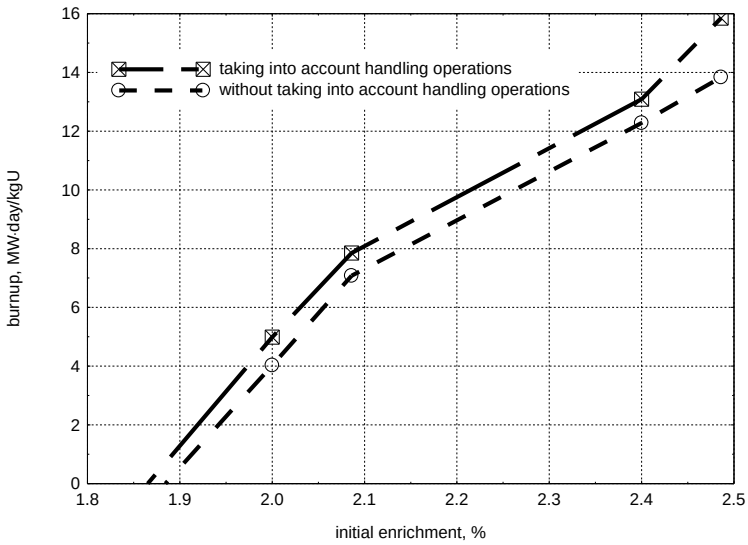

FIG. 4. Loading Curves for ISF-1 CP Compartment for SFA Storage and Handling Operations.

3.2. Results of burnup credit implementation in nuclear safety analysis of CP compartments at ChNPP ISF-1

Since the SFA configuration in CP compartments remains unchanged for many years, more realistic calculation models that take into account the loading specifics of each cell and each compartment can be used for nuclear safety justification of ISF-1 CP compartments.

Due to a large number of SFAs that are stored in the ISF-1 CP, the burnup range of the SFAs is divided into 5 intervals to simplify the simulation:

— In the range (0 ÷ 469) MW*day/FA, the SFA burnup is taken as 0 MW*day/FA (fresh fuel);
— In the range (470 ÷ 939) MW*day/FA, the SFA burnup is taken as 470 MW*day/FA;
— In the range (940 ÷ 1399) MW*day/FA, the SFA burnup is taken as 940 MW*day/FA;
— In the range (1400 ÷ 1869) MW*day/FA, the SFA burnup is taken as 1400 MW*day/FA;
— ≥ 1870 MW*day/FA, the SFA burnup is taken as 1870 MW*day/FA.

As a result, all SFAs in the CP compartment are divided into groups having one of the five burnup values: 0, 470, 940, 1400 and 1870 MW*day/FA.

Of course, considering that one compartment can accommodate 4380 FAs, the individual isotopic composition of each SFA located in each CP compartment is a time- and labor-intensive problem, associated with a high probability of errors in simulating the CP compartment loading. Therefore, calculated conservative loading of a CP compartment was formed. Based on the comparison of SFA parameters in all compartments, the characteristics of the SFAs that correspond to the highest enrichment and the lowest burnup among the SFAs located in a given cell in each CP compartment were chosen for each cell. Under the above optimal neutron moderation conditions, the effective neutron multiplication factor obtained taking into account the fuel burnup for the conservative loading of the CP compartment is as follows:

$$K_{eff} \pm 3\sigma = 0.9392. \quad (1)$$

Taking into account handling operations in CP, conservatively assuming that there is a canister with a fresh FA produced from regenerated fuel with enrichment 2.4% in each CP row (in the transport corridor), the neutron multiplication factor is:

$$K_{eff} \pm 3\sigma = 0.9447. \quad (2)$$

These results have been confirmed by state technical review using an independent calculation model and code. Thus, a more realistic description of the storage system using the fuel burnup credit as a safety parameter shows that even for conservative loading of the CP compartment and the optimal neutron moderation, the requirement $K_{eff} \leq 0.95$ is not violated.

4. OTHER NUCLEAR FUEL STORAGE FACILITIES UNDER CONSTRUCTION IN UKRAINE

Except for six units of ZNPP, there are other nine power units with VVER-440 and VVER-1000 reactors in Ukraine, whose fuel is annually transported to the RF for storage and processing. To solve this problem, the Energoatom Nuclear Operator announced a tender for the construction of a centralized spent fuel storage facility (CSFSF) for VVER reactors of Ukrainian NPPs. Holtec International (USA) has won the tender.

The construction of the CSFSF was started in 2017 in the Chernobyl Exclusion Zone, where SNF from Rivne, Khmelnitsky and South-Ukrainian NPPs will be stored.

SNF from ChNPP ISF-1 will be transported to ISF-2, whose design was developed in 1999 by the French FRAMATOME Company in the framework of international financial and technical support to Ukraine. For a number of reasons, the contract with the French AREVA NP (FRAMATOME) Consortium was terminated, and Holtec International was chosen to complete the construction. Currently commissioning tests are being carried out at the ISF-2 site.

Both storage facilities will use the dry storage system with sealed containers located in vertical ventilated concrete casks (CSFSF) or in horizontal concrete modules (ISF-2).

The nuclear safety analysis of CSFSF and ISF-2 confirmed by state technical reviews shows that K_{eff} does not exceed 0.95 in normal operation and design-basis accidents. The systems subcriticality is ensured by the application of homogeneous neutron absorbers in structural elements of sealed containers.

5. SUMMARY

As stated before, there were some issues in nuclear safety justifications for spent nuclear fuel storage facilities in Ukraine. It should be noted that these issues were caused by excessive conservatism in Ukrainian regulations rather than by drawbacks of these systems. There were no appropriate mechanisms either that would allow the use of approaches to reduce the excessive conservatism.

For now Ukraine has developed appropriate procedures that allow the use of burnup credit as a basic approach for nuclear fuel storage as well as other approaches that significantly reduce the excessive conservatism, which was previously in nuclear safety justifications for spent fuel storage systems, without affecting the nuclear safety of these systems.

REFERENCES

[1] Safety Rules for Storage and Transport of Nuclear Fuel at Nuclear Power Facilities, PNAE G 14-029-91, Gospromatomnadzor USSR, Moscow, 1992.

[2] KOVBASENKO, YU. P., EREMENKO, M. L., BILODID, I. I., DUDKA, O. O., Conservatism in Safety Assessment of Fresh and Spent Nuclear Fuel Systems, Nuclear and Radiation Safety, Special Issue, 2002.

[3] Guideline on Implementation of Spent Fuel Burnup Control at the Stage of DSFSF VSC Loading, 00.OB.YY.МУ.05, Zaporizhzhya NPP, Energodar, 2003.

[4] Guideline on Burnup Credit Principle in Nuclear Safety Justification for DSFSF VSC Loading, 00.OB.YY.МУ.09, Zaporizhzhya NPP, Energodar, 2003.

[5] DUDKA, O. O., KOVBASENKO, YU. P., Use of Neutron Absorbers to Ensure Nuclear Safety of Dry Spent Fuel Storage Facility at Zaporizhzhya NPP, Collection of Scientific Papers, Sevastopol Institute of Nuclear Energy and Industry, No. 15, 2005.

[6] KOVBASENKO, YU. P., EREMENKO, M. L., BILODID, I. I., DUDKA, O. O., KOSTYUSHKO, YA. V., Implementation of Modern Methods of Nuclear Safety Assessment for Spent Fuel Management System at Ukrainian NPPs, Nuclear and Radiation Safety, No. 1, 2008.

[7] DUDKA, O. O., KOVBASENKO, YU. P., BILODID, I. I., Use of Axial Burnup Profile in Nuclear Safety Analysis for Spent Fuel Storage System at Ukrainian NPPs, Nuclear and Radiation Safety, No. 3(55), 2012.