CRITICALITY AND RADIATION SAFETY EVALUATION OF THE CANISTERS THAT COULD BE USED FOR RBMK-1500 SNF DISPOSAL

A. ŠMAIŽYS, E. NARKŪNAS, P. POŠKAS
Lithuanian Energy Institute
Kaunas, Lithuania
Email: arturas.smaizys@lei.lt

Abstract

It is envisaged that all spent nuclear fuel generated during the operation of the RBMK-1500 reactors at the Ignalina NPP will be stored in dry storage facilities for at least 50 years prior to its disposal into a deep geological repository. According to the Radioactive Waste Management Development Programme (approved in 2015) the construction of the repository is planned to be completed in 2066, and all SNF should be disposed of until 2073. Before the construction of the repository, various preparatory activities shall be performed: site selection, repository concept and designing, environmental impact studies, safety analysis, etc. There are two geological formations in the territory of Lithuania potentially suitable for the construction of the repository – crystalline rock and clayey formations. Dry storage casks that are currently used for RBMK-1500 SNF interim storage at Ignalina NPP site cannot be used for the disposal purposes. Therefore, SNF reloading from the storage casks into appropriate disposal canisters will be necessary. The type of the disposal canister depends on the geological formation in which the repository is constructed. According to the existing knowledge, copper canisters are considered appropriate for disposal into crystalline rock and steel canisters are suitable for clayey formations. This paper presents preliminary criticality and radiation safety evaluation of copper and steel canisters containing RBMK-1500 spent fuel. Radiation characteristics and dose rates on the surfaces of the canisters are modelled assuming SNF disposal after 50 and 100 year interim storage.

1. INTRODUCTION

The whole spent nuclear fuel in Lithuania has been generated during the operation of the Ignalina NPP. Ignalina NPP has two RBMK-1500 type reactors. After the final shutdown of the Unit 1 in 2004 and Unit 2 in 2009 the total amount of spent fuel is 21 646 fuel assemblies (about 2 400 tHM). There are two dry storage facilities at the Ignalina NPP site. A part of SNF is stored in CASTOR®RBMK-1500 and CONSTOR®RBMK-1500 casks that are located in the first dry storage facility since 2000. Intensive defueling process of the remaining spent fuel from the at-reactor storage pools has been stared in 2017. During this process spent fuel assemblies are placed into CONSTOR®RBMK1500/M2 casks and afterwards are transferred into the second dry storage facility. It is foreseen that all spent fuel will be placed into the dry storage facilities until 2022. The design lifetimes of the first and second dry storage facilities are until 2050 and 2067, respectively.

After an interim storage the spent fuel is planned to be disposed of into a deep geological repository. Dry storage duration of spent fuel can be prolonged, however, this is not considered as an alternative to the disposal. According to the Radioactive Waste Management Development Programme that was approved by Lithuanian Government in 2015 the construction of the repository is planned to be completed in 2066 and all spent fuel should be disposed of until 2073.

The first feasibility studies on RBMK-1500 spent fuel disposal into a deep geological repository in Lithuanian have started in 2002. Possible host rocks for a deep geological repository have been identified, the repository concepts for a certain host rock formation were proposed and some safety issues were considered [1]–[3]. According to the performed investigations there are two potential rocks in the territory of Lithuania than can host the repository – crystalline rock and clay medium. For crystalline rock it is recommended to adopt KBS-3 (Sweden) concept and for clay medium – Nagra's (Switzerland) concept. According to these concepts after interim storage period spent fuel assemblies from the dry storage casks are encapsulated into copper or steel disposal canisters. Afterwards these canisters are moved into the repository's emplacement tunnels. The disposal canister shall ensure the containment of spent fuel, be durable in the predicted chemical environment of the repository, resist the expected mechanical loads, surface temperature should not exceed 100°C, surface dose rate should be less 1 Sv/h, canister loaded with spent fuel must be subcritical, and etc. Results of the criticality safety analysis and calculations of the surface dose rates for copper and steel canisters that could be used for RBMK-1500 spent fuel disposal are presented in this paper.

2. DISPOSAL CANISTERS

Depending on the chosen host rock for the repository copper or steel canisters could be used for disposal. Both types of canisters have cylindrical shape. Respective dimensions for conceptual copper and steel canisters are as follows: height – 4070 mm and 4270 mm; outer diameter – 1050 mm and 1250 mm. Bottom, lid and side wall thicknesses of 50 mm are accepted for the copper canister and for steel canister these thicknesses are 150 mm. Canisters contain a cast iron inserts with channels for the fuel bundles (see Fig. 1). Canister can be loaded with 32 RBMK-1500 spent fuel bundles. It shall be noted, that RBMK-1500 fuel assembly consists of two fuel bundles that are joined axially. After removal from the reactor core spent fuel assembly is cut into two fuel bundles and all further spent fuel management steps (wet and dry storage) are performed with fuel bundles. About 1350 canisters would be required for spent fuel disposal in Lithuanian.

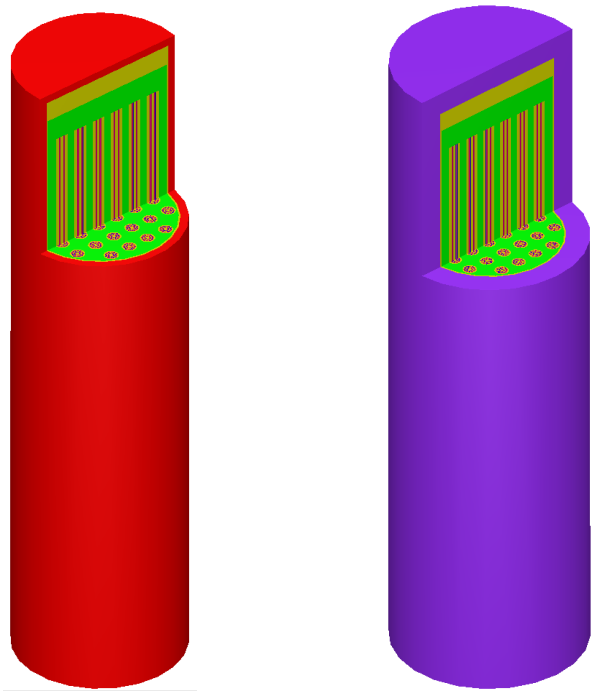

FIG. 1. Schematic view of copper (left) and steel (right) canisters loaded with RBMK-1500 fuel bundles

Fuel assemblies with different U-235 enrichments were used during Ignalina NPP operation. Fuel assemblies with 2.0% U-235 enrichment were used solely until mid of 1995. Afterwards the uranium-erbium type fuel with 2.4%, 2.6%, 2.8% U-235 enrichments was used until permanent shutdown of Ignalina NPP. The majority part (more than 60% of total amount) of spent fuel to be disposed is fuel bundles with 2.0% U-235 enrichment. However, for criticality analysis and dose rate calculations it is assumed than canisters contain 32 fuel bundles with 2.8% U-235 enriched fuel.

3. CRITICALITY ANALYSIS

Criticality analysis of copper and steel canisters loaded with 32 RBMK-1500 fuel bundles was performed using sequence CSAS5 of SCALE 6.1 code system. Presently, there are no specific requirements for criticality safety analysis of SNF disposal systems, therefore assumptions accepted in the modelling are based on requirements that are applied for spent fuel storage casks. Long-term processes that take place over thousands of years in the repository can cause corrosion and degradation of materials, this subsequently can affect geometrical configuration of fuel bundles and resulting unfavourable conditions from criticality safety point of view can occur. In comparison, only 50–100 year duration processes are considered as long-term for the dry storage casks. Also impacts of initiating events on storage casks and disposal canisters can be different. For

instance, dry storage cask can overturn during seismic event and minor geometrical rearrangements of fuel bundles inside the cask can take place. According to performed study on effects of large earthquakes on a KBS-3 repository [4], shaking of emplacement holes will not damage canisters, however, if the fractures, shear displacement are large across emplacement holes canister can suffer severe deformations and geometrical rearrangements.

Effective neutron multiplication factor (k_{eff}) is calculated assuming that copper and steel canisters are loaded with fresh fuel bundles with 2.8% U-235 enriched fuel. If burnup credit is considered k_{eff} values would be about 20% lower. Discrete description of fuel rods, bundles, insert, and canisters components in three-dimensional geometrical model was provided in CSAS5 input file. Fuel rods consist of UO_2 pallets and cladding tubes (Zr+1%wt Nb), the insert is made from carbon steel, canister body – copper or steel shell, respectively. On purpose to model the most reactive state it was assumed that inner cavities of canister and insert are homogeneously filled with moderator (water) of different densities.

The variation of k_{eff} with water density for copper and steel canisters is presented in Fig. 2.

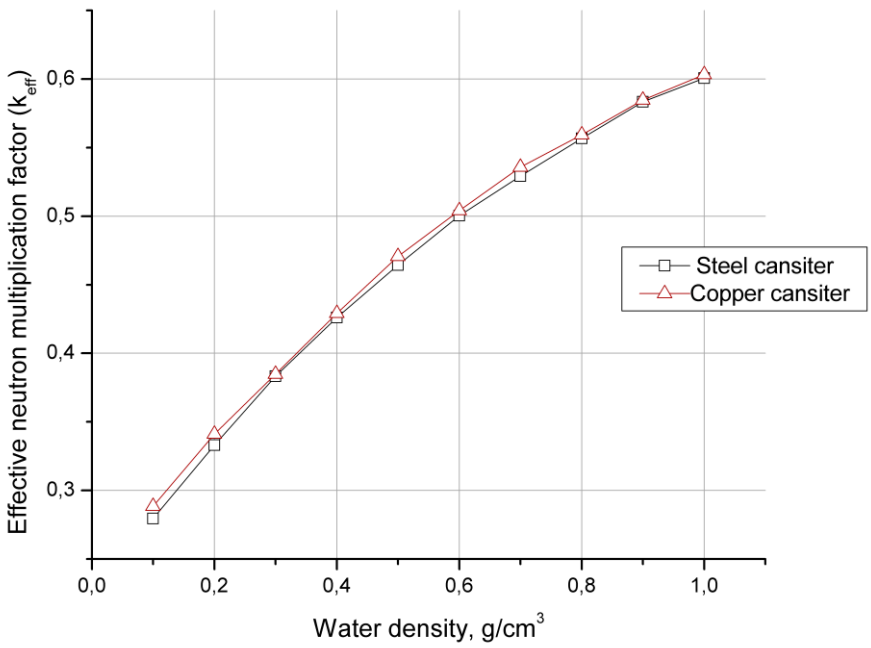

FIG. 2. Variation of k_{eff} with the moderator density

The results of criticality analysis show that k_{eff} values for both canisters continuously increase when water density is increasing. Maximal k_{eff} values of approx. 0.60 are reached when water density is 1.0 g/cm^3. The main requirement for the criticality safety of spent fuel storage systems is that k_{eff} must be less than 0.95. If the same limit is applied for the disposal canister, the criticality safety margin is rather considerable. Moreover, this margin becomes even bigger if burnup credit is considered. However, for comprehensive criticality safety analysis of the repositories the long-term processes (corrosion, degradation, etc.) shall be taken into account.

4. RADIATION SAFETY

MAVRIC sequence of SCALE 6.1 codes systems was used for modelling of dose rates on the surface of canisters. MAVRIC performs three-dimensional radiation transport modelling, calculates neutron and gamma fluxes and resulting dose rates exterior to a canister. Neutron and gamma source inside the canister was described as cylinder homogenizing 32 spent fuel bundles with 2.8% U-235 enriched fuel and insert. Input data on neutron and gamma fluxes and their energy spectrums that corresponds 50 and 100 year interim storage periods was based on fuel inventory modelling results presented in [5]. Spent fuel bundles with 2.8% U-235 initial enrichment have the highest burn-up value, therefore activities of fission products and actinides are higher

in comparison to spent fuel bundles with other enrichments. For instance, activity values for certain radionuclides in spent 2.0% and 2.8% enriched RBMK-1500 fuel differ by 10–20%.

Dose rate calculation results on the copper and steel canister surfaces are presented in Fig. 3 and Fig. 4 respectively. Since the same thicknesses of canister's lid and bottom materials were accepted in modelling and the gaps between homogenized cylinder of radiation source and lid or bottom are equal, therefore calculated dose rate values on lid and bottom surfaces are identical.

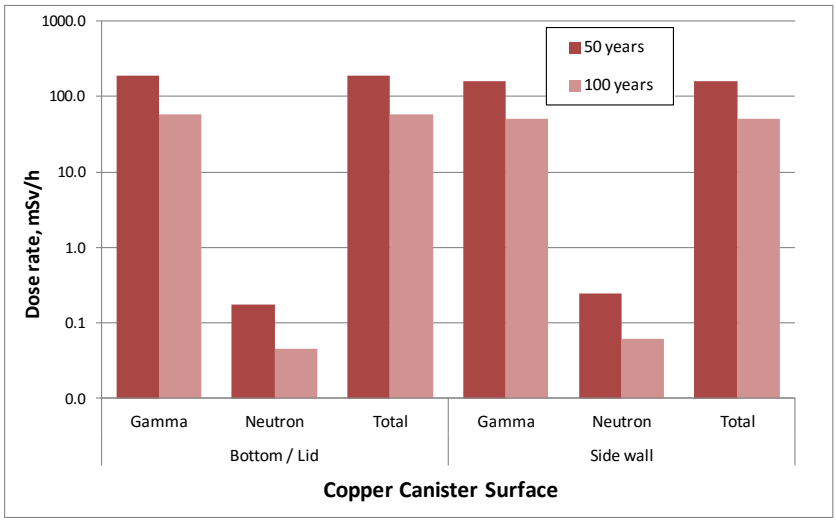

FIG. 3. Dose rate on the copper canister surface

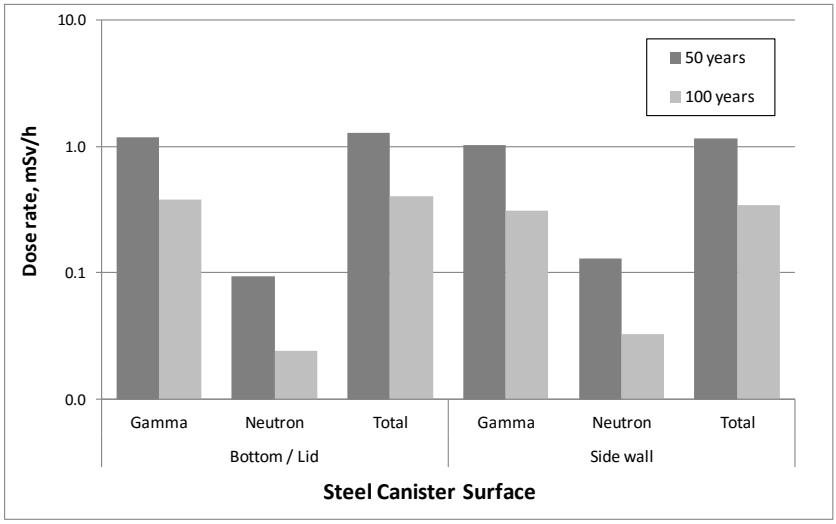

FIG. 4. Dose rate on the copper canister surface

It can be seen, that gamma dose rate is dominant for both canisters. Due to the thicker canister body total dose rate on the surface of steel canister is slightly more than 1 mSv/h, in case of copper canister – total surface dose rate is about 200 mSv/h. Total dose rates decrease more than 3 times if canisters are loaded with fuel bundles that were stored in dry storage facility for 100 years.

There are no specific design criteria for canister surface dose rate. For reduction of personnel radiation exposure additional shielding overpack or remote handling equipment could be used when copper canisters are transferred into repository's emplacement tunnels. Based on dose rate calculation results such overpack would not be necessary for steel canisters.

Surface dose rate shall be considered when canister is emplaced into tunnel and surrounded with bentonite buffer which can become saturated with ground water. An intensive radiation could cause the water radiolysis and this can lead to the generation of oxygen that accelerates corrosion process. According to SKB

(Sweden) evaluations [6], radiolytic generation of oxygen from bentonite buffer will be negligible for canisters with surface dose rate up to 500 mGy/h (i.e. 500 mSv/h for gamma radiation). Preliminary calculation results for copper and steel canisters show that surface doses for the canisters loaded with 32 spent RBMK-1500 fuel bundles is below this value.

5. CONCLUSIONS

Criticality analysis of concept copper and steel canisters loaded with RBMK-1500 spent fuel disposal has revealed that the canisters remain subcritical under optimal neutron moderation conditions and assuming that fuel bundles contain fresh fuel. While evaluating the impact of long-term processes (i.e. corrosion, material degradation) on criticality safety it is reasonable to consider the burnup credit in the analysis. These and other issues that can jeopardise the criticality safety will be analyzed and evaluated in the safety case for repository before its construction in the selected site.

Dose rate calculations have showed that surface dose rate for copper canister is rather high – about 200 mSv/h. For instance, for spent RBMK-1500 fuel dry storage casks the surface dose rate is limited to 1 mSv/h. Additional shielding overpack or remote handling equipment could be necessary for copper canisters handling operations. Due to the thicker canister body total dose rate on the surface of steel canister is slightly over 1 mSv/h. Both canisters when emplaced into disposal tunnel and surrounded with bentonite buffer will not cause the water radiolysis.

Performed criticality and dose rate calculations show that canisters are suitable for disposal of spent RBMK-1500 fuel. From criticality and radiation safety point of view the amount of loaded spent fuel bundles can be increased, however, surface temperature shall be modelled and justified that temperature is less than 100°C.

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