Criticality Safety Analysis of Disposal Canisters Filled with Spent Nuclear Fuel from Krško NPP

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ABSTRACT

Criticality safety analysis of the disposal canisters filled with the NPP Krško spent fuel is presented in this paper. It is a summary of the work done for Slovenian Agency for radwaste management (ARAO) [1]. Disposal of canisters filled with a high-level radioactive waste and spent fuel in a deep geological repository is now considered as one of the possible solutions for the back-end of the nuclear fuel cycle. KBS 3 repository concept is well known deep geological repository model developed by SKB (Swedish Nuclear Fuel and Waste Management Co). Their concept model has been adopted also by Finland who is already building a final disposal at Olkiluoto site. KBS 3 concept has been adopted also as one of the possible reference solutions for generic repository for spent nuclear fuel in Slovenia [2]. One of the main repository safety functions is to ensure a complete containment of radionuclides for at least 100,000 years. This can be achieved only if all safety requirements are fulfilled even before actual disposal commence. This paper covers only the nuclear criticality aspect of the canister design. Actual NPP Krško spent fuel data are considered. The basic criticality criterion is that the effective neutron multiplication factor should not exceed 0.95. In the presented paper only normal operating conditions are considered. Calculations have been performed with the MCNP5 and SCALE codes. Minimal fuel burnup requirements have been determined (loading curve) to assure subcriticality at normal operating conditions. Based on the current NEK spent fuel inventory and obtained loading curve, number of disposal canisters has been estimated.

1 INTRODUCTION

All types of radioactive waste require responsible management in facilities under the institutional supervision to ensure the safety of residents, environmental protection and safety from natural disasters or deliberate human intrusion into the facility. The long-term strategy for dealing with radioactive waste is to place them in isolated environment where they won’t need ongoing active institutional control. Such is the concept of geological disposal. Geological repository is suitable for the disposal of spent nuclear fuel (SF), high-level radioactive waste (HLW) arising from decommissioning or from reprocessing of nuclear fuel and other radioactive wastes that generate large amounts of heat or contain long-lived radionuclides.
2 GEOLOGICAL REPOSITORY CONCEPT

KBS-3 is the most advanced geological repository concept, developed by the Swedish agency for radioactive waste management SKB. In KBS-3V concept, copper canisters with a cast iron insert containing spent nuclear fuel and HLW are surrounded by bentonite clay and deposited vertically at approximately 500 m depth in hard rock (Figure 1). The distance between boreholes is 6m.

Beside underground disposal part there are also above ground technological facilities and buildings which allow proper handling and encapsulation of SF and HLW into canisters. The surface part is connected with the underground part through access shaft and waste transportation ramp.

3 DISPOSAL OF SPENT FUEL AND HIGH LEVEL WASTE IN SLOVENIA

According to a revised referenced scenario for the geological disposal facility in hard rock [2] the present scenario assumes 40 years of NPP Krško operation and eventual extension of operational time for additional 20 years till year 2043. Disposal scenario includes the following assumptions:

- Only direct disposal of SF is considered, currently no reprocessing is foreseen,
- The concept of the repository is KBS-3V,
- Development phase of the repository includes the periods of construction and operation of the underground test facility at the proposed location,
- The estimated SF inventory of NEK is based on realistic data (current inventory and currently 18-month fuel cycle schedules for life time until 2023 and 2043),
- To ensure the optimum loading (4 fuel assemblies in one canister) sufficiently long period of cooling is required,
- Disposal of fuel assemblies after 45 years and alternatively after 100 years of temporary storage is considered.

Besides the geological design, the encapsulation facilities, where the emplacement of the fuel in the canisters takes place, is also a part of the reference scenario. In those facilities
the fuel assemblies are placed in copper canisters and prepared for the disposal. Capacity and the time of disposal operations are adapted to the operating period of the Krško NPP:

- 10 years of service for expected 389 canisters for disposal (1553 fuel assemblies) for 40 years of operation of the NPP,
- 15 years of service for expected 571 canisters for disposal (2281 fuel assemblies) for 60 years of NPP operation in case of a 20-year extension.

Expected minimum numbers of required canisters were calculated by optimizing the loading of canisters considering the limitation of maximal thermal output 1600 W per canister and determination of minimum required period of cooling [4]. In this way, the maximal load of four fuel assemblies in each canister was determined.

4 CANISTER MODEL DESIGN

Canister design model in Monte Carlo codes MCNP and SCALE consist of two major components - copper overpack and massive cast iron insert. Diameter of cast iron insert is 950 mm with the additional 50 mm thick shell of copper. The outside diameter of a canister is 1050 mm. The wall thickness of steel tubes is 10 mm. The cross section of the canister is presented in Figure 2.

![Figure 2: Cross-section of the canister with the dimensions [5]](image)

One fuel assembly is loaded in each channel of the canister. After inserting the spent fuel assemblies into the canister, the lid of the canister is sealed. The fuel assembly was modeled based on geometry and materials of the fuel used in NPP Krško [6]. The 16 × 16 square array comprises 235 fuel rods. Twenty-one positions in the array are empty, since they are reserved for the control rods and in-core instrumentation. Criticality calculations were performed with MCNP [7] and SCALE [8] computer programs in 3D geometry. Two models were prepared, which cover the use of canisters under normal conditions:

- canister in the spent fuel pool, which covers the process of loading the fuel in the canisters,
- undamaged canister in the disposal cell of the repository.

Each canister is disposed in a vertical hole in the bedrock with a diameter of 175 cm subsequently filled with a bentonite. In normal conditions it is assumed that the canister is leach tight. In this case there is no water in the canister. Concerning the process of loading the fuel in the canister all four possible scenarios are studied:

- the canister is filled with water, air is around the canister,
the canister is filled with water, water is around the canister,
• the canister is filled with air, air is around the canister,
• the canister is filled with air, water is around the canister.

5 CRITICALITY CALCULATIONS RESULTS

Repository for spent fuel is a nuclear facility, subject to strict safety requirements. Criticality analysis is just one of many safety requirements. The basic criteria is that the effective neutron multiplication factor should not exceed 0.95 including uncertainties. Since the repository is a passive facility with no direct control on the neutron population, it is necessary to meet the safety requirements under normal and abnormal conditions prior to disposal.

The results of multiplication factor for a given configuration in the repository are presented, taking into account the fresh and irradiated fuel. In addition, the scenarios that are possible during the loading process were analyzed.

5.1 Fresh fuel analysis

In the following analysis the effect of fresh fuel on the criticality for all four scenarios, defined in section 4 has been analyzed. The most conservative approach was adopted - the canisters located next to each other and the highest allowable fuel enrichment of 5% $^{235}\text{U}$. Results obtained with the MCNP code version 5.1.40 and ENDF/B-VII.0 evaluated nuclear data library are given in Table 1. Uncertainties listed in the table represent statistical error of 1σ.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Multiplication factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>water inside – air around</td>
<td>1.03675 ± 11 pcm</td>
</tr>
<tr>
<td>water inside – water around</td>
<td>1.01863 ± 11 pcm</td>
</tr>
<tr>
<td>air inside – air around</td>
<td>0.32079 ± 4 pcm</td>
</tr>
<tr>
<td>air inside – water around</td>
<td>0.25840 ± 4 pcm</td>
</tr>
</tbody>
</table>

It can be seen that the most restrictive scenario is the canister filled with water and air around the canister. The effect of fuel enrichment is shown in Table 2.

<table>
<thead>
<tr>
<th>Fuel enrichment [% $^{235}\text{U}$]</th>
<th>Multiplication factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.84562 ± 9 pcm</td>
</tr>
<tr>
<td>3</td>
<td>0.93965 ± 10 pcm</td>
</tr>
<tr>
<td>4</td>
<td>0.99737 ± 11 pcm</td>
</tr>
<tr>
<td>5</td>
<td>1.03675 ± 11 pcm</td>
</tr>
</tbody>
</table>

It can be concluded that the criticality criteria could be met with the fresh fuel of low enrichment ~ 2% $^{235}\text{U}$. Namely, the value of the multiplication factor increased by the calculation uncertainty, uncertainty arising from manufacturing tolerances and material properties has to be less than 0.95.

5.2 Burnup analysis

To fulfill criticality requirements burnup credit methodology is applied. Criticality calculations of the fuel with burnup 20000 MWd/tU and 40000 MWd/tU and with different
fuel enrichments have been performed. The isotopic composition was calculated by a computer program package CORD-2 [9] developed at the Department of Reactor Physics, Jožef Stefan Institute. In the calculations the operating conditions that give the highest multiplication factor were considered. Criticality analysis shows that in general the burnup of the fuel will give enough decrease of the reactivity to meet the criticality criteria. Results are presented in Table 3. The analyses were performed using MCNP and SCALE code versions 4.4 and 5.1 using the 44-group ENDF/B-V derived cross section library 44GROUPNDF5.

Table 3: Multiplication factor versus fuel burnup and different initial enrichments

<table>
<thead>
<tr>
<th>Enrichment [% $^{235}$U]</th>
<th>Burnup [MWd/tU]</th>
<th>Multiplication factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MCNP</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0.84562 ± 9 pcm</td>
</tr>
<tr>
<td></td>
<td>20000</td>
<td>0.77857 ± 9 pcm</td>
</tr>
<tr>
<td></td>
<td>40000</td>
<td>0.74604 ± 9 pcm</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0.93965 ± 10 pcm</td>
</tr>
<tr>
<td></td>
<td>20000</td>
<td>0.84429 ± 10 pcm</td>
</tr>
<tr>
<td></td>
<td>40000</td>
<td>0.78886 ± 10 pcm</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0.99737 ± 11 pcm</td>
</tr>
<tr>
<td></td>
<td>20000</td>
<td>0.89709 ± 10 pcm</td>
</tr>
<tr>
<td></td>
<td>40000</td>
<td>0.83259 ± 10 pcm</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>1.03675 ± 11 pcm</td>
</tr>
<tr>
<td></td>
<td>20000</td>
<td>0.93863 ± 11 pcm</td>
</tr>
<tr>
<td></td>
<td>40000</td>
<td>0.87190 ± 10 pcm</td>
</tr>
</tbody>
</table>

The effect of using different nuclear codes and libraries could be several hundred pcm. Thorough criticality analyses would require extensive code verification and bias determination. However, such analysis would be outside of the project scope. Therefore a conservative generic 2% calculation uncertainty was applied as it was considered in the reference [5].

5.3 Criticality analysis in the repository

Under normal repository conditions it can be assumed that the void space in the canister is filled with air. The multiplication factor of this system, containing the fresh fuel with the enrichment of 5% $^{235}$U, is deeply sub-critical. Effective multiplication factor is $0.27597 ± 4$ pcm, when the distance of the disposal cells is minimal and $0.27432 ± 4$ pcm when the distance between disposal cells is 6 m. Therefore, it can be concluded that the geometry of the disposal system under normal conditions almost does not affect the multiplication factor.

6 UNCERTAINTY ASSESSMENT DUE TO DIMENSIONAL VARIATIONS

In the criticality assessment it is necessary to consider any dimensional and material variation that can affect the multiplication of neutrons. The effect of the dimensional changes due to the dimensional tolerances on the multiplication factor has been analysed as in [10]. Detailed analyses are presented in reference [1]. Final uncertainty of the multiplication factor due to the dimensional changes is determined considering the 99.7% confidence interval (so called standard ± 3σ interval). The final uncertainty is the sum of individual effects resulting in a 0.03834 penalty.
7 LOADING CURVE

To determine a loading curve it is necessary to evaluate the influence of horizontal and axial burnup distribution. In general the neutron flux and power are not uniform throughout the core during the operation of NPP. As a result, the fuel assembly has regions with lower and higher burnup than the average. Consequently, in some instances the multiplication factor can be higher than in the uniform burnup case. Calculations of those effects are complicated. For this reason, we have estimated the effect using the values reported in the spent fuel pool reactivity analysis [11].

Considering the uncertainty calculations, 0.02 in section 5.2 and 0.03834 in section 6, the limiting multiplication factor 0.89166 is obtained. Dependence of multiplication factor on fuel enrichment and burnup is shown in Figure 3.

![Figure 3: Multiplication factor versus fuel enrichment and burnup](image)

The loading curve given in Table 4 is obtained by the polynomial fit, considering an extra 3 σ confidence interval and finding the intersection with the value of 0.89166. It should be emphasized that the curve is determined for the limiting values of enrichment and burnout. When the adequacy of loading the canisters is concern, it is necessary to increase the nominal fuel enrichment for the enrichment uncertainty and decrease the fuel burnup for the factor of burnup uncertainty.

<table>
<thead>
<tr>
<th>Enrichment [% ²³⁵U]</th>
<th>Burnup [MWd/tU]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.43</td>
<td>0</td>
</tr>
<tr>
<td>3.78</td>
<td>20500</td>
</tr>
<tr>
<td>5.33</td>
<td>44500</td>
</tr>
</tbody>
</table>

8 NPP KRŠKO FUEL ANALYSIS

In Figure 4, 984 NPP Krško fuel assemblies from the spent fuel pool are presented. Fuel assemblies that do not meet the condition (k < 0.89166) are located below the loading curve. Only 22 assemblies don’t meet the required conditions. Assuming that the number of assemblies that don’t meet the criticality condition will increase linearly, there will be 33
additional unsuitable assemblies in the year 2023 (total 89) and 49 by the year 2043 (total 105). If those assemblies are emplaced in the canister by only filling three positions out of four than the required number of canisters is 396 and 579 respectively.

9 CONCLUSION

The criticality safety study for the canister suitable for the geological repository of the Krško spent fuel has been studied with the MCNP and SCALE programs based on the Monte Carlo method.

The results showed that the canister in the repository is deeply sub-critical under normal condition. Due care should be taken during the emplacement processes, since there is a water in the canister. In those scenarios the multiplication factors are highest and we need relatively high fuel burnup to provide subcritical system. The loading curve was determined by the limiting 0.95 value in the multiplication factor respecting the uncertainty in the calculation procedure, tolerances in the dimensions of the canister and fuel, inaccuracies in determining the isotopic composition of the fuel and consideration of the burnup profiles. This curve defines the minimum allowable fuel burnup for any initial enrichment. Based on the obtained curve and the current inventory of fuel, it is estimated that at the end of 2023, 396 canisters (1,553 fuel assemblies), and in the case of the life extension to 2043 a total 579 canisters (2281 fuel assemblies) are needed.

To obtain the final number of canisters it is necessary to analyze abnormal conditions and, if necessary develop a new loading curve. Current analyses have shown that the process of emplacement of fuel in canisters and the period of temporary storage are more restrictive than the process of disposal in the repository. As we have seen from the analysis of thermal loading [4], it is possible to perform optimization of the loading process. Some additional restrictive conditions could be set for specific highly reactive fuel assemblies, which presently occupy 3 out of 4 positions in the canister. Additional restrictions on accompanied assemblies or prescribed minimum canisters distance could relax obtained loading curve. This would enable the disposal of highly reactive fuel assemblies in the full cast positions, 4 out of 4.
REFERENCES


[6] NEK, USAR, Rev. 17, chapter 4


[10] SKB AB, Design analysis report for the canister, TR-10-28, April 2010