Criticality safety calculations of the nuclear waste disposal canisters for twelve spent fuel assemblies

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CRITICALITY SAFETY CALCULATIONS FOR THE NUCLEAR WASTE DISPOSAL CANISTERS

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Summary
The criticality safety of the copper/iron canisters developed for the final disposal of the Finnish spent fuel has been studied with the MCNP4B code based on the Monte Carlo technique.

Two rather similar types of spent fuel disposal canisters have been studied. The differences between the canisters result from properties of the spent fuel assemblies planned to be disposed of in them. One canister type has been designed for 12 hexagonal VVER-440 fuel assemblies used at the Loviisa nuclear power plant ("IVO canister") and the other one for 12 square BWR fuel bundles used at the Olkiluoto nuclear power plant ("TVO canister"). In both canister types each bundle will be in a separate emplacement hole. Between the holes there are a layer of cast iron with the thickness of at least 4 cm.

A spent fuel disposal canister must meet the normal criticality safety criteria. The effective multiplication factor must be less than 0.95 also when the canister is in the most reactive credible configuration (optimum moderation and close reflection). Uncertainties in the calculation methods may necessitate the use of an even lower reactivity limit.

Based on the results of this study the IVO canister loaded with twelve similar fresh VVER-440 assemblies with the initial enrichment of 4.2% fulfills the criticality safety criteria. The TVO canister loaded with twelve fresh BWR assemblies of so-called ATRIUM 10x10 type with the initial enrichment of 3.8% and without burnable absorbers meets the same criteria. The assumptions applied in the study are very conservative, i.e. they lead to an overestimation of the reactivity of the canisters and canister lattices.

Keywords: Encapsulation plant, spent fuel disposal canister, criticality safety calculations, MCNP4B
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ABSTRACT

The criticality safety of the copper/iron canisters developed for the final disposal of the Finnish spent fuel has been studied with the MCNP4B code based on the Monte Carlo technique.

Two rather similar types of spent fuel disposal canisters have been studied. The differences between the canisters result from properties of the spent fuel assemblies planned to be disposed of in them. One canister type has been designed for 12 hexagonal VVER-440 fuel assemblies used at the Loviisa nuclear power plant ("IVO canister") and the other one for 12 square BWR fuel bundles used at the Olkiluoto nuclear power plant ("TVO canister"). In both canister types each bundle will be in a separate emplacement hole. Between the holes there are a layer of cast iron with the thickness of at least 4 cm.

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Keywords: Encapsulation plant, spent fuel disposal canister, criticality safety calculations, MCNP4B
Suomalaisilta ydinvoimalaitoksilta kertyvän käytetyn ydinpolttoaineen loppusijoituskapselien kriittisyysturvallisuustuutta on tutkittu Monte Carlo -teknikkaan perustuvalla MCNP4B-ohjelmalla.


Käytetyn ydinpolttoaineen loppusijoituskapselin on täytettävä normaalit kriittisyysturvallisuuskriteerit. Sen efektiivisen kasvutekijän tulee olla pienempi kuin 0,95 tehokkaimmissa mahdollisissa moderointi- ja heijastinosuhteissa. Laskentamenetelmiin liittyvä epävarmuus voi edellyttää vieläkin pienempää kasvutekijän raja-arvoa.

Tehtyjen laskujen perusteella voidaan todeta, että IVO-kapseli täyttää kriittisyysturvallisuusvaatimukset, jos se täytetään tuoreilla VVER-440-polttoainenpuilla, joiden väkevöinti on 4,2% tai pienempi. Vastaavasti TVO-kapseliin voidaan ladata 12 tuoretta ATRIUM 10x10 -tyypistiä nippua, joiden keskimääräinen väkevöinti on 3,8% tai alempi.

Avainsanat: Käytetyn polttoaineen ksselointilaitos, loppusijoituskapseli, kriittisyysturvallisuus, MCNP4B
1 INTRODUCTION

According to the present plans the spent fuel from the Finnish nuclear power reactors (OL 1 and 2 at the Olkiluoto nuclear power plant and Loviisa 1 and 2 at the Loviisa plant) will be placed into copper/iron canisters for final disposal deep in the Finnish bedrock. A spent fuel disposal canister consists of a copper mantle and of a massive nodular cast iron insert. In the insert there are 12 emplacement holes, in each of which a fuel bundle can be loaded. Between the holes there is a layer of cast iron with the thickness of at least 4 cm. Two quite similar types of canisters will constructed: one for square BWR fuel bundles of the OL reactors and another for hexagonal VVER-440 (PWR) fuel assemblies of the Loviisa units (later called the TVO and IVO canisters, respectively).

A spent fuel disposal canister must meet the normal criticality safety criteria. The effective multiplication factor must be less than 0.95 also when the canister is in the most reactive credible configuration (optimum moderation and close reflection). Uncertainties in the calculation methods may necessitate the use of an even lower reactivity limit.

Based on the results of this study the IVO canister loaded with twelve similar fresh VVER-440 assemblies with the initial enrichment of 4.2% fulfills the criticality safety criteria. The TVO canister loaded with twelve fresh BWR assemblies of so-called ATRIUM 10x10 type with the initial enrichment of 3.8% and without burnable absorbers meets the same requirements.

2 MCNP4B COMPUTER CODE AND ITS DATA LIBRARIES

MCNP4b is according to its User's Manual "a general-purpose, continuous-energy, generalized geometry, time-dependent, coupled neutron-photon-electron Monte Carlo transport code system" (Briesmeister). A user can apply the code to quite complicated problems almost without any geometric approximations and get accurate results in a reasonable time when having modern workstations or PCs.

The recommended cross section sets of the standard MCNP4B data libraries based on the ENDF/B-VI evaluated data library were used in these calculations.
3 CRITICALITY SAFETY CRITERIA

A canister used for storage of the (spent) nuclear fuel must be subcritical also under very unfavorable conditions, i.e. for instance, when

- the fuel and the whole canister have the most reactive credible configuration,
- the moderation by water is at its optimum and
- the neutron reflection on all sides of the canister is as effective as credibly possible.

The criticality safety criteria require that the effective multiplication of the system studied is less than 0.95. If the calculation methods are not thoroughly enough validated or if the codes applied are known to predict too low reactivity values, the limit shall be even lower.

Concerning the criticality safety calculations of the spent fuel disposal canisters the application of the so-called burnup credit would be a reasonable procedure, because the canisters are planned to be filled with irradiated fuel assemblies. However, in this study only the fresh fuel assemblies without burnable absorbers have been assumed to be loaded in the canisters.

4 INPUT DATA

4.1 Geometry and material composition of the canisters

The horizontal cross sections of the TVO and IVO canisters for are shown in Fig. 1. The canister versions are in this respect very similar, the biggest differences being the form of the holes in the cast iron insert, in which the spent fuel assemblies will be placed. The TVO canister is also longer than the IVO canister. The canisters have room for twelve bundles.

In Fig. 1 there are shown four extra holes (in the TVO canister), which may be used to guarantee the quality of cast iron inserts. In the following their impact on the reactivity of the TVO canister has been studied. It has been assumed that the effect would be of similar importance in the case of the IVO canister.
The following data describe the horizontal layouts of the canisters:

A) Copper mantle:
   - Outer radius 52.6 cm
   - Thickness of the mantle 5.0 cm
   - Density of copper 8.96 g/cm³

B) Cast iron insert:
   - Outer radius 47.5 cm
   - Density of nodular cast iron 7.1 g/cm³
   - Composition of cast iron
     FeFe 92.8 wt%
     C 3.2 wt%
     Mg 0.05 wt%
     Si 2.15 wt%
     Mn 0.8 wt%
     Ni 1.0 wt% (Werme & Ericsson 1995)

The extra holes in the TVO canister were assumed to be at the distance of 39 cm from the centre of the canister. Their radius was set to be 4 cm.

The canisters were assumed to be homogenous in the axial direction. Even then some data concerning the whole canisters and the fuel bundles had to be defined:

<table>
<thead>
<tr>
<th>Canister type</th>
</tr>
</thead>
<tbody>
<tr>
<td>BWR</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>Bundle geometry</td>
</tr>
<tr>
<td>Bundles in an canister</td>
</tr>
<tr>
<td>Length of the fuel rod (cm)</td>
</tr>
<tr>
<td>Uranium per bundle (kg)</td>
</tr>
<tr>
<td>Number of fuel rods in a bundle</td>
</tr>
</tbody>
</table>

* The BWR fuel bundle was assumed to be of the ATRIUM 10x10-9Q type.

The horizontal geometry of the fuel bundles and the canisters were described almost exactly in the basic MCNP4B calculations. The exceptions were that the gap between the fuel pellet and the clad was homogenized with the clad and that the inner water channel box of the ATRIUM bundle was omitted.
Figure 1. Radial cross sections of the spent fuel disposal canisters for the TVO (BWR) and IVO (VVER-440) fuel (TVO and IVO canisters, respectively).
4.2 Geometry and material compositions of the fuel bundles

4.2.1 IVO fuel bundle

The fuel assemblies used in the Loviisa reactors up till now have been almost identical regarding their geometry and material compositions. The changes made already and planned to be made may have only a minor impact from the point of the criticality safety. In this respect, the discharge burnup and initial enrichment of the spent fuel are the most important variables.

In this study, a fuel assembly to be loaded in an IVO canister was defined as follows (the values given correspond to room temperature):

- A hexagonal bundle consisting of a regular lattice of 127 hexagonal unit pin cells and of a hexagonal channel box (shroud); At the centre of the assembly there is an instrumentation rod surrounded by six layers of the identical fuel rod cells.

- Unit pin cell
  Pitch (cm) 1.22

- Fuel rod
  Outer radius (cm)
  - of the central hole *
  - of the pellet 0.3775
  Fuel rod clad
  - inner radius (cm) 0.3775**
  - outer radius (cm) 0.456

- Instrumentation rod (described as a tube)
  - inner radius (cm) 0.427
  - outer radius (cm) 0.515

- The channel box (shroud)
  - outer pitch (cm) 14.40
  - thickness (cm) 0.15

* The central hole of the VVER-440 fuel rods homogenized with the fuel
** The gas gap between the fuel pellet and the clad homogenized with the clad
The material compositions and the densities were defined as follows (at room temperature):

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Fuel: UO₂</td>
<td>9.969</td>
</tr>
<tr>
<td>- Clad: ZrNb1 (one wt% of Nb)</td>
<td>5.813</td>
</tr>
<tr>
<td>- Instrumentation rod: ZrNb1</td>
<td>6.55</td>
</tr>
<tr>
<td>- Shroud: ZrNb2.5</td>
<td>6.58</td>
</tr>
</tbody>
</table>

The spacers were not taken into account in MCNP4B calculations.

Up till now, all fuel rods in a VVER-440 fuel assembly of Russian origin have had the same enrichment and none of them have contained any kind of burnable absorbers (BA). For these calculations the enrichment was chosen to be 4.2%, which is much higher than the present one (3.6%). In the axial direction the MCNP4B model was homogenous and infinite.

### 4.2.2 TVO fuel bundle

The geometry of the fuel assemblies used in the TVO reactors has changed remarkably during the last ten years: from original 8*8 bundles first to 9*9 bundles and then to 10*10 bundles with water channels and part length fuel rods.

In this study, a fuel bundle of ATRIUM 10x10-9Q type supplied by Siemens AG and used in the OL1 reactor was chosen to be analyzed. The conclusions based on calculations with this bundle type are considered to be valid for other bundle types, because again the discharge burnup and average initial enrichment of the spent fuel are the most important variables.

An ATRIUM 10x10 fuel bundle can be defined as follows (the values given correspond to room temperature):

- a square bundle consisting of a regular 10x10 lattice of pin cells of similar size, one pin pitch away from the centre of lattice there is a water channel occupying the space of a 3x3 pin cell lattice
- Unit pin cell (square)
  Pitch (cm) 1.295

- Fuel pellet
  Outer radius (cm) 0.4335

- Fuel rod clad
  - inner radius (cm) 0.4335
  - outer radius (cm) 0.5025
  - the gas gap between the fuel pellet and the clad was homogenized with the clad in MCNP4B calculations

- Inner water channel (not described in MCNP4B calculations)

- The channel box
  - inner pitch (cm) 13.40
  - thickness (cm) 0.23

At both ends of the ATRIUM bundles there is a so-called axial blanket made of natural uranium, the impact of which has been omitted in this study. The part length fuel rods were not described in the axially homogenous and infinite MCNP4B model. The presence of burnable absorber rods was not taken into account. A flat enrichment distribution (of 3.8%) was used in the calculations. All these assumptions are conservative; they lead to a large overestimation of the reactivity of the TVO canister.

### 4.3 Comparison of the IVO and TVO fuel bundles

The fuel and water volumes and masses per unit height of the IVO and TVO fuel rod cells are rather similar, but the fuel-to-water mass ratio in the IVO canister is ca. 15% higher that of the TVO canister. More detailed information is given at Table 1.
Table 1. The amount of the fuel (uranium dioxide) and water per unit height in the IVO and TVO fuel bundles and canisters.

<table>
<thead>
<tr>
<th></th>
<th>IVO</th>
<th>TVO</th>
</tr>
</thead>
<tbody>
<tr>
<td>A) Fuel rod cell</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel (uranium dioxide)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Volume (cm(^3)/cm)</td>
<td>0.4477</td>
<td>0.5904</td>
</tr>
<tr>
<td>- Mass (g/cm)</td>
<td>4.4631</td>
<td>6.0809</td>
</tr>
<tr>
<td>Water (density 1 g/cm(^3))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Volume (cm(^3)/cm)</td>
<td>0.6386</td>
<td>0.8838</td>
</tr>
<tr>
<td>- Mass (g/cm)</td>
<td>0.6386</td>
<td>0.8838</td>
</tr>
<tr>
<td>Fuel-to-water mass ratio</td>
<td>6.989</td>
<td>6.981</td>
</tr>
<tr>
<td>B) Disposal canister</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel (uranium dioxide)/emplacement hole</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Volume (cm(^3)/cm)</td>
<td>56.4</td>
<td>53.7</td>
</tr>
<tr>
<td>- Mass (g/cm)</td>
<td>562.3</td>
<td>553.4</td>
</tr>
<tr>
<td>Water (density 1 g/cm(^3))/emplacement hole</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Volume (cm(^3)/cm)</td>
<td>137.4</td>
<td>155.5</td>
</tr>
<tr>
<td>- Mass (g/cm)</td>
<td>137.4</td>
<td>155.5</td>
</tr>
<tr>
<td>Fuel-to-water mass ratio</td>
<td>4.09</td>
<td>3.56</td>
</tr>
</tbody>
</table>

5 MAIN RESULTS

A dry disposal canister

Both types of the nuclear waste disposal canister are deeply subcritical when dry. The MCNP4B calculations gave the following multiplication factors for the isolated canisters (a dry canister in the vacuum without any reflector):

- an IVO canister filled with twelve fresh VVER-440 fuel assemblies having the enrichment of 4.2% 0.2570 ± 0.0003
- a TVO canister filled with twelve fresh ATRIUM fuel bundles having the enrichment of 3.8% 0.2408 ± 0.0003
If a dry canister is assumed to be in a tight infinite lattice having the pitch of 110 cm, its reactivity is increased a little:

- an IVO canister \[ 0.3579 \pm 0.0004 \]
- a TVO canister \[ 0.3379 \pm 0.0004 \]

The presence of four extra holes in the cast iron insert increases the multiplication factor of the TVO canister to the value of \( 0.3409 \pm 0.0004 \). The reason is the decreased amount of iron in the system.

**A wet disposal canister**

Both types of nuclear waste disposal canister are subcritical also when filled and surrounded with water. The MCNP4B calculations gave the following multiplication factors for the isolated canisters:

- an IVO canister \[ 0.9209 \pm 0.0013 \]
- a TVO canister \[ 0.9246 \pm 0.0010 \]

If a dry canister is assumed to be in a tight infinite lattice having the pitch of 110 cm, the reactivity is again increased a little:

- an IVO canister \[ 0.9224 \pm 0.0012 \]
- a TVO canister \[ 0.9266 \pm 0.0012 \]

The presence of four extra holes in the cast iron insert decreases the multiplication factor of the TVO canister in an infinite lattice (pitch 110 cm) to the value of \( 0.9146 \pm 0.0011 \). This is caused by the increased amount of water in the system. Therefore, more fast neutrons is thermalised outside the fuel bundles and can not any more reach the fuel rods.

**The impact of the size of the emplacement holes**

The impact of the size of the emplacement holes on the reactivity of an infinite wet lattice
of canisters (the lattice pitch being again 110 cm) was studied in the case of the IVO canister. The multiplication factor of the lattice is as a function of the radius of the hole as follows:

<table>
<thead>
<tr>
<th>Radius of the emplacement holes (cm)</th>
<th>Infinite multiplication factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.5 (nominal)</td>
<td>0.9224 ± 0.0012</td>
</tr>
<tr>
<td>8.75</td>
<td>0.9148 ± 0.0010</td>
</tr>
<tr>
<td>9.0</td>
<td>0.9070 ± 0.0010</td>
</tr>
</tbody>
</table>

**The effect of the moderator temperature**

The effect of the moderator (water) temperature on the multiplication factor of the wet disposal canisters was studied by changing the water density and by defining the scattering cross sections of hydrogen as a linear combination of the values at 300 and 400 Kelvin degrees (This method has not yet been validated extensively enough). However, the infinite multiplication factors at three temperatures were as follows:

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>IVO canister</th>
<th>TVO canister*</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>0.9224 ± 0.0013</td>
<td>0.9147 ± 0.0011</td>
</tr>
<tr>
<td>323</td>
<td>0.9196 ± 0.0012</td>
<td>0.9129 ± 0.0011</td>
</tr>
<tr>
<td>353</td>
<td>0.9120 ± 0.0011</td>
<td>0.9109 ± 0.0012</td>
</tr>
</tbody>
</table>

* With four extra holes in the cast iron insert

The water temperature has only a minor impact on the reactivity of the canister lattice. In both cases an increase of the moderator temperature seems to result in a lower infinite multiplication factor.

**The effect of the enrichment**

The effect of the enrichment on the multiplication factor of the canister types in an infinite lattice was studied by defining an enrichment of 3.8% for the IVO fuel bundles and that of
3.6% for the TVO bundles. These values are closer to the present average enrichment than the base values.

A) IVO canister

<table>
<thead>
<tr>
<th>Enrichment (%)</th>
<th>Multiplication factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2</td>
<td>0.9224 ± 0.0012</td>
</tr>
<tr>
<td>3.8</td>
<td>0.9018 ± 0.0009</td>
</tr>
</tbody>
</table>

B) TVO canister

<table>
<thead>
<tr>
<th>Enrichment (%)</th>
<th>Multiplication factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.8</td>
<td>0.9266 ± 0.0013</td>
</tr>
<tr>
<td>3.6</td>
<td>0.9140 ± 0.0010</td>
</tr>
</tbody>
</table>

An infinite lattice of water-filled canisters in the air

The interaction between the nuclear waste disposal canisters in an (infinite) lattice is carried out by fast neutrons. Therefore, one could assume that the most reactive system is a lattice of water-filled canisters in a dry environment. This was studied by a series of MCNP4B calculations (where a dry environment was described as a vacuum).

The infinite multiplication factors were as follows:

<table>
<thead>
<tr>
<th>Lattice pitch (cm)</th>
<th>IVO canister</th>
<th>TVO canister</th>
</tr>
</thead>
<tbody>
<tr>
<td>110 (wet environment)</td>
<td>0.9224 ± 0.0012</td>
<td>0.9266 ± 0.0013</td>
</tr>
<tr>
<td>110 (dry)</td>
<td>0.9530 ± 0.0011</td>
<td>0.9535 ± 0.0010</td>
</tr>
<tr>
<td>130 (dry)</td>
<td></td>
<td>0.9507 ± 0.0010</td>
</tr>
<tr>
<td>160 (dry)</td>
<td></td>
<td>0.9497 ± 0.0009</td>
</tr>
</tbody>
</table>

In both cases the multiplication factor of an infinite lattice of water-filled canisters in a dry
environment is higher than the criticality safety limit (0.95), when the lattice pitch is short (less than about two meters).

However, the results should be interpreted very cautiously. The assumed lattice system is highly improbable. The only place where it could be constructed is the encapsulation plant, where the fuel bundles will be loaded into the canisters. There will, of course, be only finite lattices of disposal canisters. According to the present plans the largest configuration will be a 4x3 lattice with the pitch of 160 cm in the buffer storage of the plant. One may assume that only taking into account the radial neutron leakage in a realistic geometry would lower the multiplication factor well below the safety limit. That hypothesis was tested in the case of the TVO canisters. A MCNP4B calculation gave a value of 0.9339 ± 0.0004 for the multiplication factor (for the 4x3 canister lattice surrounded with water the corresponding result was 0.9248 ± 0.0004). If those twelve canisters would be placed as close as possible, i.e. the pitch of the lattice would be set to 106 cm, then the multiplication factor of the lattice would increase to 0.9429 ± 0.0004.

Besides, with four extra holes in the cast-iron insert the multiplication factor of an infinite lattice of TVO canisters in the dry environment (the pitch of the lattice 110 cm) fulfills the criticality safety criteria the multiplication factor being 0.9332 ± 0.0011.

6 CONCLUSIONS

The criticality safety of the copper/iron canisters developed for the final disposal of the Finnish spent fuel (IVO and TVO canisters) has been studied with the MCNP4B code based on the Monte Carlo technique.

According to the results of this study the IVO canister loaded with twelve similar fresh VVER-440 assemblies with the initial enrichment of 4.2% fulfills the criticality safety criteria in all probable cases either in the encapsulation plant or in the spent fuel repository, where the canisters will be placed in a sparse lattice. The TVO canister loaded with twelve fresh BWR assemblies of so-called ATRIUM 10x10 type with the initial enrichment of 3.8% and without burnable absorbers meets the same criteria.

For both canister types, the multiplication factor of an infinite lattice of water-filled canisters in the dry environment (vacuum) is higher than 0.95, if the pitch of the lattice is short enough. This kind of configuration is highly improbable. The only place, where it could be constructed in practice, is the buffer storage of the encapsulation plant, but there
only a lattice of 4x3 canisters will be allowed. The pitch of the lattice is planned to be 160 cm. This configuration fulfills the criticality safety criteria.

REFERENCES


