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Criticality Safety Calculations for Three Types of Final Disposal Canisters

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ABSTRACT

The criticality safety of the copper/iron canisters developed for the final disposal of the Finnish spent nuclear fuel has been studied with the MCNP4C Monte Carlo code.

Three types of spent fuel disposal canisters have been analysed. The differences between the canisters result from the size and geometry of the spent fuel assemblies to be disposed of in them. One canister type has been designed to contain 12 hexagonal VVER-440 fuel assemblies used at the Loviisa nuclear power plant ("VVER canister"). The second type is for 12 square BWR fuel bundles used at the Olkiluoto 1 and 2 units ("BWR canister") and the third type is for four fuel assemblies of the Olkiluoto 3 unit to be constructed in the near future ("EPR canister"). Each canister type is of similar size in the radial direction, but the axial lengths vary significantly.

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. However, no systematic uncertainty analysis was carried out during this study.

It has been proved in an earlier study that a version of the VVER canister loaded with twelve similar fresh VVER-440 assemblies with the initial enrichment of 4.2% fulfils the criticality safety criteria. Also an earlier design of the BWR canister loaded with twelve fresh BWR assemblies of so-called ATRIUM 10x10-9Q type with the initial enrichment of 3.8% and without burnable absorbers has been proved to meet the safety criteria. Therefore, in this study only a few calculations have been carried out for the present versions of VVER and BWR canisters and the results are in good agreement with the previous ones. The main emphasis of this study has been on the EPR canister. This new canister type fulfils the criticality safety criteria only if the so called burnup credit principle is applied in calculations. The fuel bundles to be loaded in an EPR canister should have been irradiated at least to a burnup of 20 MWd/kgU.

Keywords: Encapsulation plant, spent fuel disposal canister, criticality safety calculations, burnup credit MCNP4C

KOLMEN LOPPUSIJOITUSKAPSELITYYPIN KRIITTISYYSTURVALLISUUS-LASKUT

TIIVISTELMÄ

Suomalaisilta ydinvoimalaitoksilta kertyvän käytetyn ydinpolttoaineen loppusijoituskapselien kriittisyysturvallisuutta on tutkittu Monte Carlo -tekniikkaan perustuvalla MCNP4C-ohjelmalla.

Tutkimuksessa on tarkasteltu kolmea kapselityyppiä, joiden perusratkaisut, kuten ulkohalkaisija ja materiaalit (valurauta ja kupari), ovat yhtenevät. Erot kapselien välillä aiheutuvat niihin sijoitettavaksi aiotun ydinpolttoaineen toisistaan poikkeavista geometrisista ominaisuuksista. Yhteen kapselivaihtoehtoon ladataan Loviisan ydinvoimalaitokselta kertyviä kuusikulmaisia VVER-440-nippuja ("VVER-kapseli"), toiseen Olkiluodon voimalaitoksen kahdella BWR-yksiköllä käytettyjä neliöllisiä nippuja ("BWR-kapseli") ja kolmanteen tulevan Olkiluoto-3-yksikön isoja PWR-nippuja (EPR-kapseli).

Käytetyn ydinpolttoaineen loppusijoituskapselin on täytettävä normaalit kriittisyysturvallisuuskriteerit. Sen efektiivisen kasvutekijän tulee olla pienempi kuin 0,95 tehokkaimmissa mahdollisissa moderointi- ja heijastinolosuhteissa. Laskentamenetelmiin liittyvä epävarmuus voi edellyttää vieläkin pienempää kasvutekijän raja-arvoa. Tässä tutkimuksessa ei ole kuitenkaan tehty mitään systemaattista epävarmuusanalyysiä.

Aiemmassa tutkimuksessa on todettu, että VVER-kapseli täyttää kriittisyysturvallisuusvaatimukset, jos se täytetään tuoreilla VVER-440-polttoainenipuilla, joiden väkevöinti on 4,2 % tai pienempi, ja jollei epävarmuuksien mahdollisesti edellyttämää alikriittisyysmarginaalien suurentamista oteta huomioon. Vastaavasti BWR-kapseliin voidaan ladata 12 tuoretta ATRIUM 10x10-9Q -tyyppistä nippua, joiden keskimääräinen väkevöinti on 3,8 % tai alempi, vaikka nipuissa ei olisi lainkaan palavaa absorbaattoria sisältäviä sauvoja. Nykyisille kapseliversioille tehdyt laskut vahvistavat aiemman tutkimuksen johtopäätökset. Suuret EPR-niput ovat kriittisyysturvallisuuden näkökulmasta ongelmallisia. EPR-kapseli ei täytä asetettuja vaatimuksia, jollei nipun kokemaa palamaa oteta huomioon laskuissa.

Avainsanat: Käytetyn polttoaineen loppusijoitus, loppusijoituskapseli, kriittisyysturvallisuus, burnup credit -periaate, MCNP4C

CONTENTS

1 INTRODUCTION

According to the present plans the spent nuclear fuel from the Finnish nuclear power reactors will be placed into copper/iron canisters for the final disposal deep in the Finnish bedrock. A spent fuel disposal canister will consist of a copper overpack and of a massive nodular cast iron insert. In the insert there are a few emplacement holes, in each of which one fuel bundle can be loaded. At least three quite similar canister types will constructed: one for square BWR fuel bundles of the present units at the Olkiluoto nuclear power plant (‘BWR canister’), one for hexagonal VVER-440 fuel assemblies of the Loviisa units (‘VVER canister’) and one for large PWR bundles of the coming Olkiluoto 3 unit (‘EPR canister’)

According to the present Finnish safety regulations the 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. On the other hand, the discharge burnup of the fuel bundles can be taken into account (STUK 2002).

According to an earlier study (Anttila 1999) a version of the VVER canister loaded with twelve fresh VVER-440 assemblies with the initial enrichment of 4.2% fulfils the criticality safety criteria, if the impact of uncertainties is not taken into account. It was also proved that with the same assumptions a BWR canister loaded with twelve fresh BWR assemblies of the so-called ATRIUM 10x10-9Q type having the initial enrichment of 3.8% and without burnable absorbers meets the same requirements.

Because the changes in the designs of the VVER and BWR canister have been rather small since the earlier study, the main emphasis of the calculations performed now was on the new EPR canister, which has been designed to contain four large western PWR fuel bundles. It has shown already elsewhere (Agrenius 2002) that this type of the final disposal canister meets the safety criteria only if the discharge burnup of the fuel bundles is taken into account.

2 MCNP4C COMPUTER CODE AND ITS DATA LIBRARY

MCNP4C 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 2000). 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 MCNP4C data libraries based mainly on the ENDF/B-VI evaluated data library were used in these calculations.

3 CRITICALITY SAFETY CRITERIA

According to the safety criteria (STUK 2002) a canister used for the final disposal of the spent nuclear fuel must be subcritical also under very unfavourable 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
- 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. The uncertainties in geometry and material composition may also be taken into account.

Concerning the criticality safety calculations of the spent fuel disposal canisters the application of the so-called burnup credit is a reasonable procedure, because the canisters will be filled with irradiated fuel bundles. It is also allowed in the Finnish Nuclear Regulatory Guides (STUK 2002).

The criticality safety criteria applied for the final disposal of the spent nuclear fuel may be clarified in the future. Furthermore, the codes should be validated also for this kind of applications.

4 INPUT DATA

4.1 Geometry and material composition of the canisters

The transverse cross sections of the cast iron inserts of three canister types studied are shown in Figures 1-3. The MCNP models of the canisters used in the calculations are given in Figures 4-6. The designs of the BWR and EPR canisters were changed a little again during this study. The distance between the centre points of the emplacement holes was increased in both cases (0.5 cm in the BWR canister and 1.0 cm in the EPR canister). It was decided not to repeat all the calculations, because the impact of the changes on the reactivity was quite small.

The VVER and BWR canister types are designed for twelve fuel bundles. They are very similar, the biggest differences being the form of the holes in the cast iron insert, in which the spent fuel bundles will be placed. The BWR canister is also longer than the VVER canister. The EPR canister is horizontally of the same size as the VVER and BWR canisters, but because an EPR fuel bundle is much larger than a VVER or BWR bundle, an EPR canister can contain only four bundles.

The following data describe the horizontal layouts of the canisters (the measures shown in the figures 1-3 may differ from those given below or from the values in (Raiko 2005), but the differences were assumed to be within the manufacturing tolerances):

A) Copper overpack:

- Outer radius		52.6 cm
- Thickness of the overpack		5.0 cm
- Density of copper		8.96 g/cm^3

B) Cast iron insert:

- Outer radius		47.5 cm
- Density of nodular cast iron		7.1 g/cm^3
- Composition of cast iron	Fe	92.8 wt%
	C	3.2 wt%
	Mg	0.05 wt%
	Si	2.15 wt%
	Mn	0.8 wt%
	Ni	1.0 wt%

The composition of cast iron insert was taken from the reference (Werme & Ericsson 1995). It may vary to some extent (Raiko 2005), but the values used in these calculations were assumed to be representative. However, due to the large volume of the insert the composition of cast iron may have such a large impact on the reactivity that it should be known quite exactly, when the final criticality safety analyses will be performed.

C) Steel tubes:

- Thickness		1.0/1.25 cm
- Density of steel		7.85 g/cm^3
- Composition of steel	Fe	98.3 wt%
	C	0.2 wt%
	Mn	1.5 wt%

The steel composition was defined according to the reference (Raiko 2005). Following data were used to describe the canister types:

	Canister type		
	BWR	**VVER**	**EPR**
- Bundle geometry	Square	Hexagonal	Square
- Bundles in an canister	12	12	4
- Length of the fuel rod (cm)	368	242	420
- Length of the canisters	480	360	525
- Uranium per bundle (kg)	180	120	530
- Number of fuel rods in a bundle	91*	126	265

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

The canisters were usually assumed to be homogenous in the axial direction. All results of this report are from basically two-dimensional calculations.

The horizontal geometry of the fuel bundles and the canisters were described almost exactly in the basic MCNP4C calculations. The exceptions were of very small importance from the criticality safety point of view.

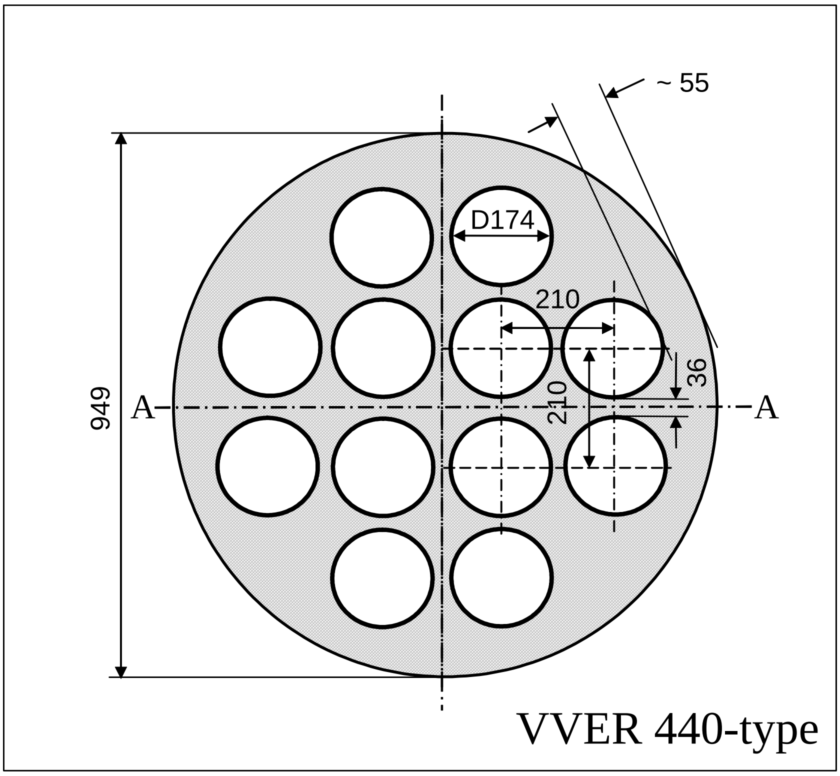

Figure 1. *Transverse cross-section of the insert of the VVER final disposal canister*

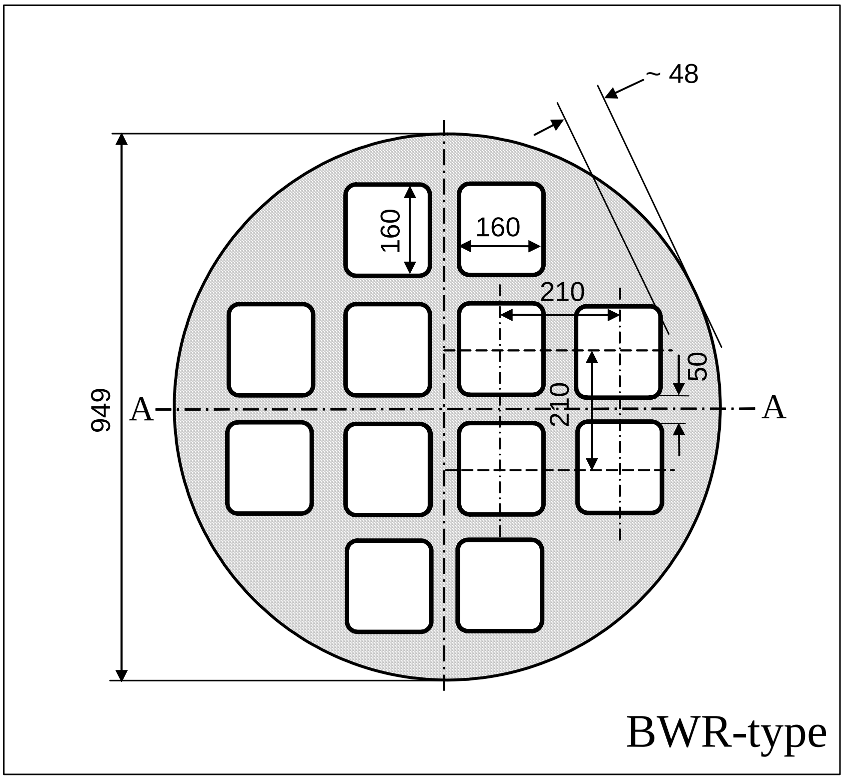

Figure 2. *Transverse cross-section of the insert of the BWR final disposal canister*

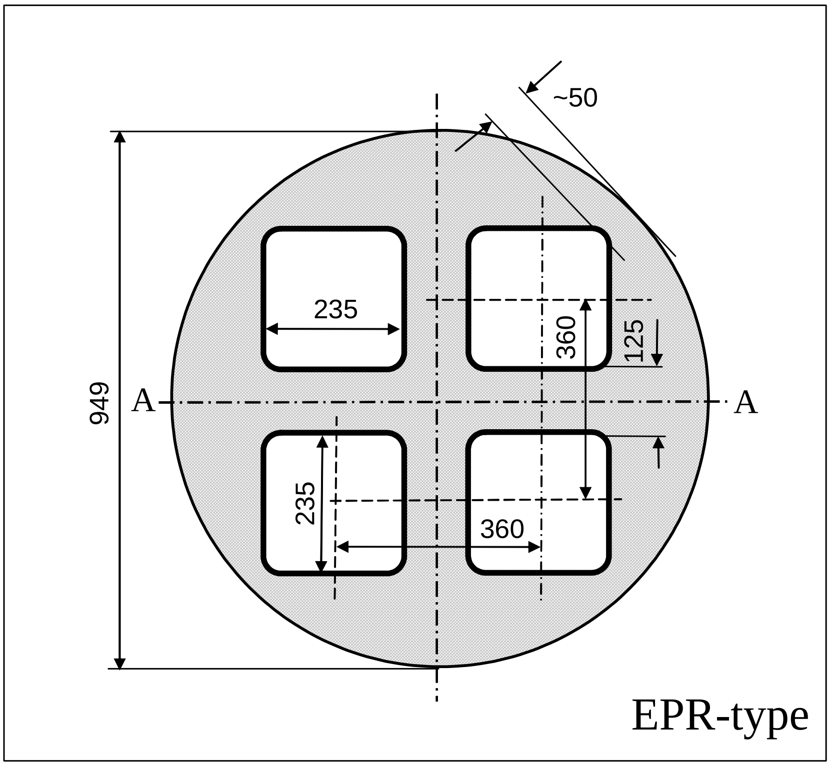

Figure 3. *Transverse cross -section of the insert of the EPR final disposal canister*

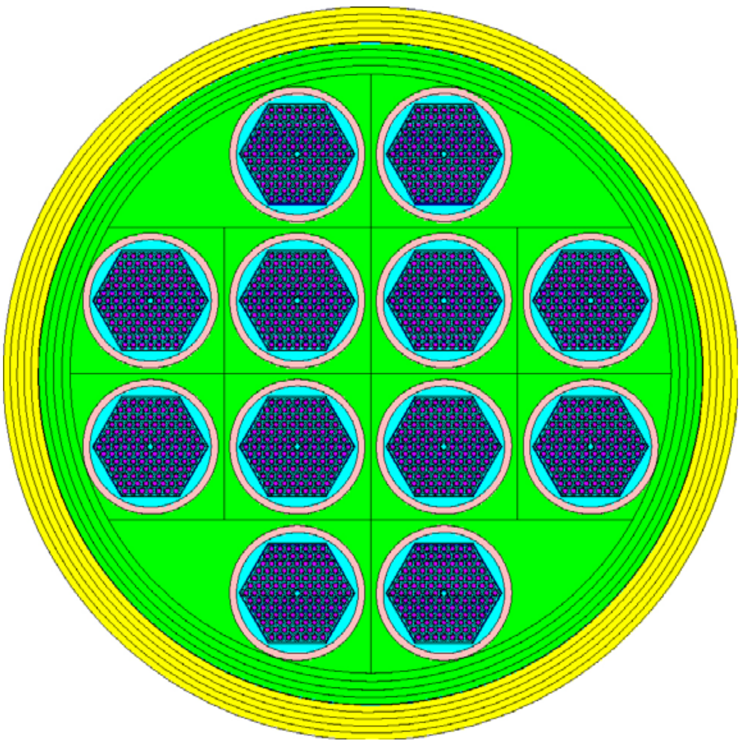

Figure 4. *Transverse MCNP model of the VVER final disposal canister*

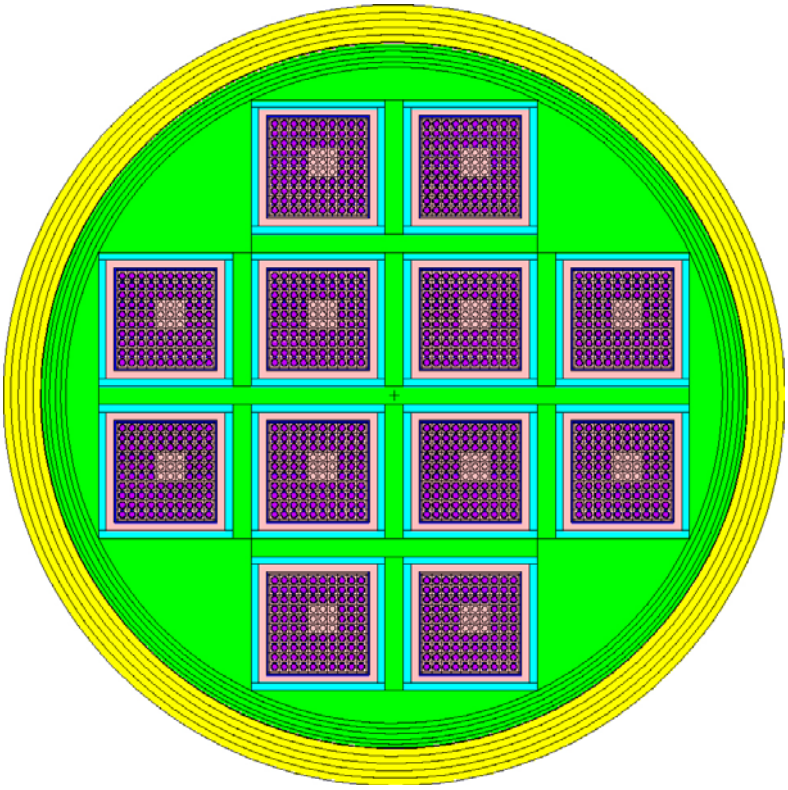

Figure 5. *Transverse MCNP model of the BWR final disposal canister*

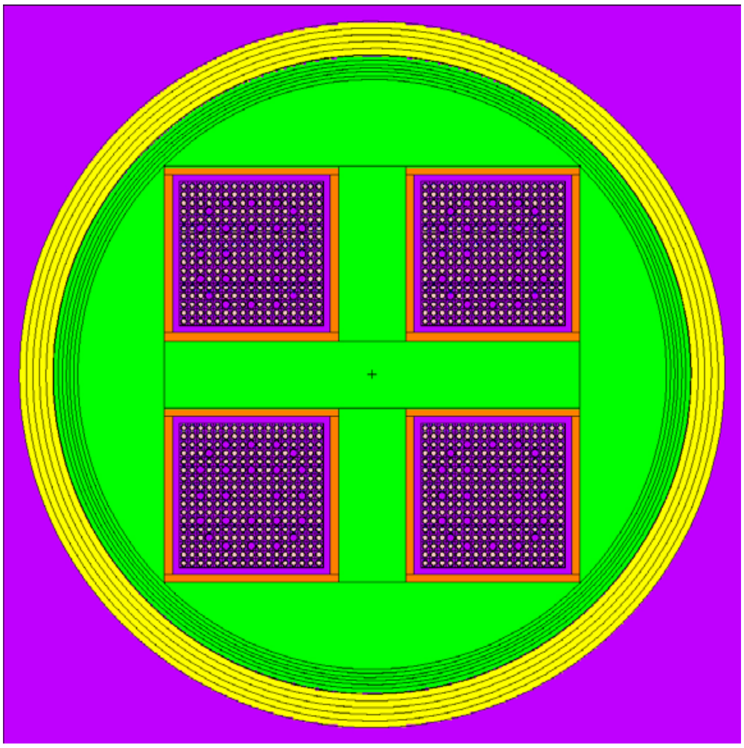

Figure 6. *Transverse MCNP model of the EPR final disposal canister*

4.2 Geometry and material compositions of the fuel bundles

4.2.1 VVER-440 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 a VVER 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)	
- Central hole	*
- Pellet	0.3775
Cladding	
- 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):

	Density (g/cm^3)
- Fuel: UO_2	9.969
- Clad: ZrNb1 (Zr with one wt% of Nb)	5.813
- Instrumentation rod: ZrNb1	6.55
- Shroud: ZrNb2.5	6.58

The spacers were not taken into account in MCNP4C calculations.

For these calculations it was assumed that all fuel rods have the same initial enrichment. The enrichment was chosen to be 4.2 wt%, which is conservatively higher than the highest initial enrichment up till now (4%). In the axial direction the MCNP4C model was homogenous and infinite.

4.2.2 BWR fuel bundle

The geometry and the details of the fuel assemblies used in the TVO reactors have changed remarkably during the last ten years from original 8x8 bundles first to 9x9 bundles and then to 10x10 bundles with water channels (or water crosses) 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 representative for other bundle types, because again the discharge burnup and average initial enrichment of the spent fuel are the most important variables. However, it can not be precluded that another bundle type might be a little more reactive than the type studied.

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
  - Gas gap between the fuel pellet and the clad was homogenized with the clad in MCNP4C calculations

- Inner channel box (not described in MCNP4C calculations)

- The channel box
  - Inner pitch (cm) 13.40
  - Thickness (cm) 0.23

The material compositions and the densities were defined as follows (at room temperature):

	Density (g/cm^3)
- Fuel: UO_2	10.45
- Clad: Zr	6.55
- Channel box: Zr	6.55

The spacers were not taken into account in MCNP4C calculations. 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 MCNP4C model. The presence of burnable absorber rods was not taken into account. A flat enrichment distribution was used in the calculations. All these assumptions are conservative, i.e. they lead to a large overestimation of the reactivity of the BWR canister.

4.2.3 EPR fuel bundle

Exact information of the fuel bundles of the OL3 unit was not yet available for this study. It was assumed that the OL3 fuel bundles will be similar to a typical 17x17-24 PWR fuel bundle (NEI 2004). The bundle was defined as follows:

- Unit pin cell (square)	
- Pitch (cm)	1.26
- Fuel pellet	
- Outer radius (cm)	0.4095
- Fuel rod clad	
- Inner radius (cm)	0.418
- Outer radius (cm)	0.475
- Guide tubes for control rods	
- Inner radius (cm)	0.5725
- Outer radius (cm)	0.6225

The material compositions and the densities were defined as follows (at room temperature):

	Density (g/cm^3)
- Fuel: UO_2	10.307
- Clad: Zr	6.55
- Guide tubes	6.55

A flat enrichment distribution without burnable absorber rods was assumed. The spacers were not taken into account in MCNP4C calculations.

4.3 Canister lattices

Three basic arrangements of the canister(s) were studied:

- An isolated canister
- A canister in a 3x4 lattice (lattice pitch of 160 cm)
- A canister in an infinite lattice (lattice pitch of 110 cm)

The first option aims at simulating the conditions in the repository, where the reactor-physical interaction between the canisters will be negligible. In fact, the final disposal canisters are almost always separated from each other from the criticality safety point of view.

The second lattice option corresponds to the so-called buffer storage of the encapsulation plant, where the disposal canisters may be stored before their transfer into the repository. It may be the largest group of canisters, which will occur during the disposal process according to the present plans.

The infinite lattice is the most reactive of the canister systems. The lattice pitch of 110 cm means that there will be a minimum gap of about 5 cm between the outer surfaces of the canisters. The reactivity of the infinite lattice is rather insensitive to the pitch (Anttila 1999).

In this study, the canisters were assumed to be either fully dry or fully filled with water. The canisters were either in the air (vacuum in the calculations) or in water. The most reactive combination is a wet canister in the dry environment (in fact assuming that there is water only in the emplacement holes but not in the gap between the cast iron insert and the copper overpack the reactivity is further increased).

5 MAIN RESULTS

5.1 VVER and BWR canisters

Only a few calculations were performed for the present versions of the VVER and BWR canister, because the changes made in their design since the earlier study (Anttila 1999) are quite small. The main results are shown in Table 1.

Table 1. *Infinite multiplication factors of the VVER and BWR final disposal canisters according to MCNP4C calculations*

- Infinite lattice of canisters
- Unit pitch of lattice 110 cm
- Reflective boundary conditions at the axial direction

A) Basic calculations

VVER canister

- Enrichment: 4.2%

	Canisters in	
	air (vacuum)	water
Dry canister	0.35116 ± 0.00014	0.25357 ± 0.00013
Water filled canister	0.94416 ± 0.00044	0.91125 ± 0.00043

BWR canister (newer design)

- Enrichment: 3.8%

	Canisters in	
	air (vacuum)	water
Dry canister	0.33478 ± 0.00014	0.23525 ± 0.00013
Water filled canister	0.93002 ± 0.00036	0.90560 ± 0.00036

***(Table 1.** continued)*

B) Comparison between two types of the BWR canister

- Enrichment: 3.8%

	Canisters in air (vacuum)	
	newer design	older design
Dry canister	0.33478 ± 0.00014	0.33080 ± 0.00014
Water filled canister	0.93002 ± 0.00036	0.93609 ± 0.00040

C) Impact of enrichment

BWR canister

- Water-filled canisters in air (vacuum)

Enrichment (%)	
3.8	0.93061 ± 0.00040
4.0	0.94215 ± 0.00041

VVER canister

- Water-filled canisters in air (vacuum)

Enrichment (%)	
4.2	0.94146 ± 0.00044
4.4	0.95100 ± 0.00041

The VVER and BWR canisters loaded with the fresh fuel bundles fulfil the nominal criticality safety criteria if the enrichments are 4.2% and 3.8%, respectively. However, either an increase of the initial enrichment or taking into account the various uncertainties may necessitate the application of the burnup credit principle.

5.2 EPR canister

Test calculations

In Ref. (Agrenius 2002) results of criticality safety calculations for the Swedish PWR canister, which is very similar to the EPR canister design, are reported. The Swedish calculations have been made with the SCALE code system (KENO V Monte Carlo Code). In the report there are not given all necessary input data. However, useful test calculations can be performed. Their main results are shown in Table 2, where also the main parameters of the reference case (case 0) are given.

Table 2. *Multiplication factor of a PWR canister of Swedish design*

- Four 17x17-(24+1) bundles
- Enrichment 4.2 wt%
- Water filled canister(s) in the air (vacuum)
- Water density 1 g/cm^3
- Steel/cast iron composition as defined for the Finnish EPR canister
- Steel/cast iron density always 7.85 g/cm^3
- Infinite lattice of 105x105 cm^2

Case	Modified parameter	Infinite multiplication factor
0		1.07037 ± 0.00041
1	water density 0.997 g/cm^3	1.06979 ± 0.00042
2	steel/cast iron = pure iron	1.08299 ± 0.00044
3	case 1 and combined	1.08256 ± 0.00041
4	density of the insert 7.2 g/cm^3	1.07176 ± 0.00044
5	bundles moved towards the centre	1.07427 ± 0.00040

The Swedish results are (Agrenius 2002):

Case 0	1.0868 ± 0.0012
Case 5	1.0903 ± 0.0012

The Finnish and Swedish results would be in good agreement with each other, if the composition of the insert had been defined to be pure iron in the Swedish calculations. The results of the test calculations indicate that the composition of the iron insert and maybe also the copper overpack should be known quite accurately in the criticality safety calculations.

EPR canister in isolation or in an infinite lattice

The reactivity difference between an isolated canister and the infinite lattice of canisters was estimated in the case of the EPR lattice (the older version, where the distance between the emplacement holes is one centimetre shorter than in the newer version). The results are given in Table 3.

Table 3. *Multiplication factor and its standard deviation of an EPR final disposal canister according to MCNP4C calculations*

- Fresh fuel
- Enrichment of 3.6%
- Unit cell of the infinite canister lattice: 110x100 cm^2

Case	Canister dry	Canister filled with water
Isolated canister		
A	0.23440 ± 0.00013	1.01918 ± 0.00044
B	0.23797 ± 0.00015	1.02153 ± 0.00041
Canister in an infinite lattice		
A	0.29893 ± 0.00014	1.04475 ± 0.00041
B	0.23822 ± 0.00013	1.02157 ± 0.00044

Case	
A	Canister(s) in air (vacuum)
B	Canister(s) in water (for the isolated canister cases, the canister is assumed to be at centre of a water-filled square of 160x160 cm^2

A dry EPR canister is always deeply subcritical. A water filled canister with fresh fuel bundles is always critical, even if the enrichment is not higher than 3.6%. The multiplication factor of a water filled canister depends on the material surrounding it. Surrounded by water the canisters are interacting very weakly with each other. In the air (vacuum) the multiplication factor of the infinite lattice of the water filled canisters is about 2 500 pcm greater than that of an isolated canister.

Impact of initial enrichment

The average enrichment of the fuel bundles of the Olkiluoto 3 unit will most probably be around 4 wt%, In Table 3 there are given the multiplication factors of two lattices of EPR canisters when loaded with the fresh fuel bundles having four different enrichments.

Table 4. *Multiplication factor and its standard deviation of two lattice types of EPR canisters (older type) as a function of enrichment according to MCNP4C calculations*

- Zero burnup
- Canisters filled with water
- Canisters in air (vacuum)

Enrichment (%)	Infinite lattice with a unit cell of 110x110 cm^2	3x4 lattice with a unit cell of 160x160 cm^2
3.6	1.04524 ± 0.00034	1.02951 ± 0.00033
3.8	1.05643 ± 0.00036	1.04122 ± 0.00036
4.0	1.06740 ± 0.00034	1.05148 ± 0.00038
4.2	1.07671 ± 0.00035	1.06039 ± 0.00037

An increase of enrichment by 0.2 wt% increases the multiplication factor by about 1 000 pcm. The reactivity of a 3x4 lattice is about 1 500 pcm lower than that of an infinite lattice.

Impact of discharge burnup

An EPR canister can not meet the criticality safety criteria without assuming that the fuel bundles to be loaded have a certain minimum discharge burnup, i.e. without the application of the so-called burnup credit principle (see also Agrenius 2002).

In this study, a burnup calculation was performed with the CASMO-4 fuel assembly burnup code for an assumed EPR fuel bundle. All fuel rods were assumed to have an initial enrichment of 4%. From this CASMO-4 calculation an average fuel composition was processed and written in the MCNP4C format at the burnups of 5, 10, 15 and 20 MWd/kgU. Two sets of compositions were produced. One set was processed according to the so-called actinide credit principle, i.e. only the changes of the concentrations of the uranium and plutonium isotopes and Am-241 were taken into account. The other set contained the atomic number densities of all CASMO-4 burnup nuclides, for which there are data in the MCNP4C standard library. All calculations were performed at room temperature without Xe-135 and other short-lived fission products. The results are given in Table 5a and 5b.

Table 5a. *Multiplication factors of two lattices of EPR final disposal canisters at the burnups of 0 and 20 MWd/kgU according to MCNP4C calculations*

- Initial enrichment of 4%
- Canisters filled with water in the air (vacuum)

Burnup (MWd/kgU)	Infinite lattice with a unit cell of 110x110 cm^2	3x4 lattice with a unit cell of 160x160 cm^2
0	1.06740 ± 0.00034	1.05122 ± 0.00036
20, case a	0.97528 ± 0.00034	0.96155 ± 0.00037
20, case b	0.97459 ± 0.00037	0.96026 ± 0.00034
20, case c	0.91946 ± 0.00033	0.90728 ± 0.00036

case a: actinide credit assumed (the actinide weight percents and the density of the fuel from the original CASMO-4-calculation)

case b: actinide credit assumed (the actinide weight percents and the density of the fuel from a CASMO-4 calculation using the actinide and oxygen atomic number densities as input)

case c: most of the CASMO-4 burnup nuclides included in the MCNP4C calculation

Table 5b. *Multiplication factor and its standard deviation of a 3x4 lattice of EPR final disposal canisters at five burnups according to MCNP4C calculations*

- Initial enrichment of 4%
- Canisters filled with water in the air (vacuum)

Burnup (MWd/kgU)	Actinide credit	Burnup credit*
0	1.05122 ± 0.00036	
5	1.03195 ± 0.00037	
10	1.00768 ± 0.00035	0.97123 ± 0.00034
15	0.98375 ± 0.00039	0.93877 ± 0.00035
20	0.96155 ± 0.00037	0.90728 ± 0.00036

* Average composition of all fuel rods according to a CASMO-4-calculation (most of the CASMO-4 burnup nuclides included)

The results of Tables 5a and 5b indicate that if the full burnup credit is accepted, the minimum discharge burnup of the EPR fuel is about 20 MWd/kgU. The application of only the actinide credit would increase the minimum burnup by about 10 MWd/kgU to about 30 MWd/kgU**.** Taking into account various uncertainties may still increase the value the lowest allowable discharge burnup

6 CONCLUSIONS

The criticality safety of the copper/iron canisters developed for the final disposal of the Finnish spent fuel (VVER, BWR and EPR canisters) has been studied with the MCNP4C code based on the Monte Carlo technique.

According to the results of this study the VVER canister loaded with twelve fresh VVER-440 assemblies with the initial enrichment of 4.2% fulfils the criticality safety criteria, if the possible need to increase the safety margin due to uncertainties in geometry and material compositions is not taken into account. The TVO canister loaded with twelve fresh BWR assemblies of the ATRIUM 10x10-9Q type with the initial enrichment of 3.8% and without burnable absorbers meets the same criteria. The results are in good agreement with those of an earlier study.

The fuel bundles of the new Olkiluoto 3 unit will be much larger than VVER-440 and BWR bundles. An EPR canister can contain only four bundles, when the radial dimensions of the canister have not been changed. However, it can not fulfil the criticality safety criteria, if the so-called burnup credit principle is not applied in the calculations. The results of this study indicate that the minimum allowable discharge burnup is about 20 MWd/kgU, if the initial enrichment is about 4%.

Taking into account various uncertainties in geometry and material compositions may call for the application of the burnup credit principle also in cases of the VVER and BWR canisters. On the other hand, it is necessary to review all assumptions used in this study. Some of them, for instance the definition of an infinite lattice as a basic geometry, may be overly conservative. The calculation system should also be validated more thoroughly for this kind of studies.

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