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Criticality safety calculations for the nuclear waste disposal canisters

Markku Anttila
VTT Energy

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POSIVA OY
Annankatu 42 D, FIN-00100 HELSINKI, FINLAND
Phone (09) 2280 30 (nat.), (+358-9-) 2280 30 (int.)
Fax (09) 2280 3719 (nat.), (+358-9-) 2280 3719 (int.)

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Posiva Oy
Annankatu 42 D, FIN-00100 HELSINKI, FINLAND
Puh. (09) 2280 30 – Int. Tel. +358 9 2280 30

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Markku Anttila
VTT Energy

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CRITICALITY SAFETY CALCULATIONS FOR THE NUCLEAR WASTE DISPOSAL CANISTERS

Tiivistelmä – Abstract

The criticality safety of the copper/iron canisters developed for the final disposal of the Finnish spent fuel has been studied with the MCNP4A code based on the Monte Carlo technique and with the fuel assembly burnup programs CASMO-HEX and CASMO-4.

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 hexagonal VVER-440 fuel assemblies used at the Loviisa nuclear power plant ("IVO canister") and the other one for square BWR fuel bundles used at the Olkiluoto nuclear power plant ("TVO canister").

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 eleven similar VVER-440 assemblies with the initial enrichment of 3.6% fulfills the criticality safety criteria, if the discharge burnup of the assemblies is more than 4 MWd/kgU. The TVO canister loaded with eleven BWR assemblies with the initial enrichment of 3.5% and without burnable absorbers meets the same criteria, if the discharge burnup of the assemblies is more than 10 MWd/kgU. An increase of the average enrichment by 0.1 percentage might be compensated by increasing the minimum discharge burnup by one MWd/kgU.

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KÄYTETYN YDINPOLTTOAINEEN LOPPUSIJOITUSKAPSELIEN KRIITTISYYS-TURVALLISUUS

Tiivistelmä - Abstract

Suomalaisilta ydinvoimalaitoksilta kertyvän käytetyn ydinpolttoaineen loppusijoituskapselien kriittisyysturvallisuutta on tutkittu sekä Monte Carlo -tekniikkaan perustuvalla MCNP4A-ohjelmalla että CASMO-HEX- ja CASMO-4-nippupalamaohjelmilla.

Tutkimuksessa on tarkasteltu kahta kapselityyppiä, joiden perusratkaisut, kuten ulkohalkaisija ja materiaalit, ovat yhtenevät. Erot kapselien välillä aiheutuvat niihin sijoitettavaksi aiotun ydinpolttoaineen toisistaan poikkeavista ominaisuuksista. Toiseen kapselivaihtoehtoon ladataan Loviisan ydinvoimalaitokselta kertyviä kuusikulmaisia VVER-440-nippuja ("IVO-kapseli") ja toiseen Olkiluodon voimalaitoksen kahdella BWR-yksiköllä käytettyjä neliöllisiä nippuja ("TVO-kapseli").

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

Yhdistämällä tuoreelle polttoaineelle tehtyjen MCNP4A-laskujen tulokset eri palama-arvoja vastaavien CASMO-4/CASMO-HEX-kasvutekijöiden kanssa voidaan arvioida, että tarkastellut loppusijoituskapselit täyttävät kriittisyysturvallisuusvaatimukset seuraavin ehdoin:

A) IVO-kapseli:
- Polttoaineen väkevöintiaste 3,6% tai pienempi ja poistopalama yli 4 MWd/kgU,

B) TVO-kapseli:
- Polttoaineen väkevöintiaste 3.5% tai pienempi ja poistopalama yli 10 MWd/kgU.

Jos polttoaineen keskimääräistä väkevöintiastetta korotetaan 0,1 prosenttiyksikköä, minimipoisto-palamaa pitää korottaa kummassakin tapauksessa 1 MWd/kgU.

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TABLE OF CONTENTS

Page

ABSTRACT
TIIVISTELMÄ

1 INTRODUCTION 1

2 COMPUTER CODES AND THEIR DATA LIBRARIES 2
2.1 MCNP4A 2
2.2 CASMO-4/CASMO-HEX 2

3 CRITICALITY SAFETY CRITERIA 3

4 INPUT DATA 4
4.1 Geometry and material composition of the canisters 4
4.2 Geometry and material composition of the fuel bundles 6
4.2.1 IVO spent fuel 6
4.2.2 TVO spent fuel 7
4.3 Comparison of the IVO and TVO spent fuel 9

5 RESULTS 10
5.1 Parametric studies with CASMO-HEX/CASMO-4 10
5.1.1 General 10
5.1.2 TVO canister 11
5.1.3 IVO canister 15
5.2 Main results of MCNP4A calculations 16
5.3 Minimum allowable burnup of the spent fuel 19

6 CONCLUSIONS 20

REFERENCES 21

1 INTRODUCTION

According to the present plans the spent fuel from the Finnish nuclear power reactors (TVO I and II 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 nine holes, where up to eleven fuel bundles can be placed. There are two quite similar types of canisters: one for square BWR fuel bundles of the TVO reactors and another for hexagonal VVER-440 (PWR) fuel assemblies of the Loviisa units (later called the TVO and IVO canisters, respectively).

The main goal of this study was to find the minimum discharge burnup of the fuel bundles, at which the criticality safety of the canister type studied would be guaranteed according to the criteria of the relevant standards. As shown later, an intact fuel canister filled with inert gas is always deeply subcritical. Only when a canister is damaged to such an extent so that water can fill it, its criticality safety may be endangered.

The reactivity of the whole canisters was calculated with the MCNP4A program based on the Monte Carlo technique. MCNP4A would allow very exact three-dimensional analyses, but in this study only axially homogenous (i.e. two-dimensional) systems were calculated. With the CASMO-4 and CASMO-HEX fuel assembly burnup codes some representative unit cells of the canister types were analyzed.

2 COMPUTER CODES AND THEIR DATA LIBRARIES

2.1 MCNP4A

MCNP4A 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" (RSIC CCC-200; 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 MCNP4A data library based on the ENDF/B-V evaluated data library was used in these calculations.

2.2 CASMO-4/CASMO-HEX

CASMO-4 is a multigroup, two-dimensional transport theory code for burnup and reactivity-point calculations on BWR and PWR fuel assemblies or similar lattices. The present standard version of the program can handle only systems with square geometry. A typical case is a square fuel assembly surrounded by one or two extra material layers (Knott & Edenius & Forssen, Edenius et. al.). CASMO-HEX is an adaptation of an earlier version of CASMO to hexagonal geometry. It was developed for calculations on VVER fuel assemblies (Anttila 1996a). Both programs have been used extensively and successfully for in-core fuel management calculations and other safety studies of the TVO and Loviisa units.

The CASMO programs use the special data libraries, which contain the necessary reactor physics constants in a 70 or 40 energy group structure. The 40-group versions are intended for production runs. Of these, the L version of the CASMO data library was used with CASMO-4 and a slightly modified G version with CASMO-HEX.

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 (Rosa, et al.):

- 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 is a reasonable procedure, because the canisters are planned to be filled (only) with irradiated fuel assemblies. In practice, one of the most important results of this type of studies is the determination of a minimum discharge burnup, which the fuel bundles must have reached during their irradiation in order to fulfill the criticality safety criteria.

4 INPUT DATA

4.1 Geometry and material composition of the canisters

The horizontal cross sections of the canisters for the TVO and IVO canisters 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 eleven bundles; the TVO canister can contain ten normal-size bundles and four ABB Atom's SVEA subbundles.

The following data describe the horizontal layouts of the canisters:

A) Copper mantle:

- Outer radius	49.1 cm *
- Thickness of the mantle	5.0 cm
- Density of copper	8.9 g/cm^3

* In the calculations the outer radius of the mantle was set to be 49.0 cm, because the gap of 0.1 cm between the copper mantle and the cast iron insert was omitted.

B) Iron insert:

- Outer radius	44.0 cm
- Density of nodular cast iron	7.1 g/cm^3
- Composition of cast iron	
- CASMO/CASMO-HEX-calculations	pure iron
- MCNP4A calculations	iron 92.8wt%; carbon 3.2wt%; magnesium 0.05wt%; silicon 2.15 wt%; manganese 0.8 wt%, nickel 1.0 wt% (Werme & Ericsson 1995)

The horizontal canister and bundle geometries were described almost exactly in the MCNP4A calculations. The minor exceptions concern the air gaps of the fuel pellets, which were homogenized with the neighboring material (see Ch. 4.2). In the CASMO-4/CASMO-HEX calculations only a part of the canister was described, a typical geometry being a fuel bundle surrounded by some extra layers of iron or water.

The canisters were assumed to be axially homogenous.

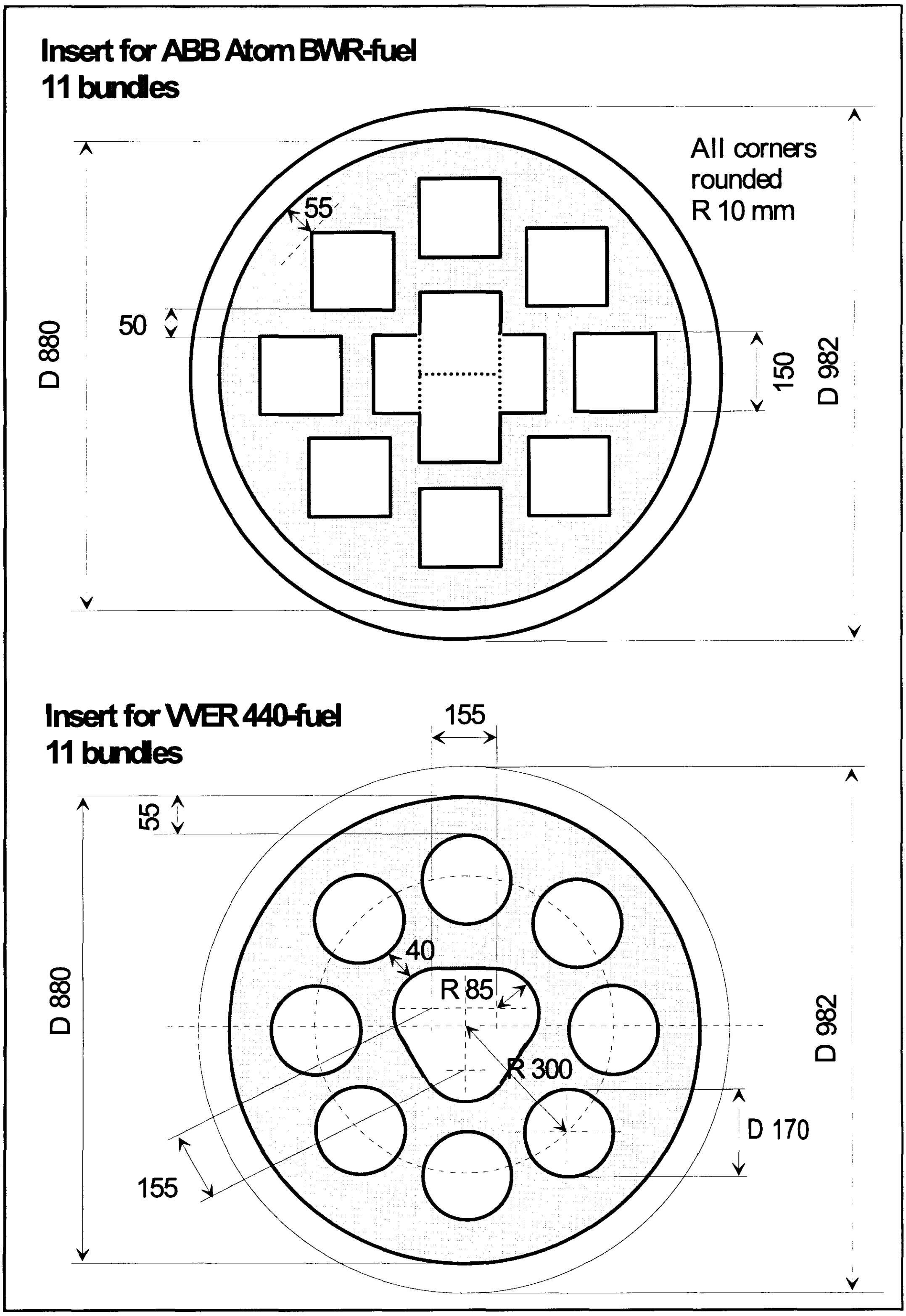

Figure 1. *Radial cross sections of the spent fuel disposal canisters for the TVO (BWR) and IVO (VVER-440) fuel (TVO and IVO canisters, respectively).*

4.2 Geometry and material compositions of the fuel bundles

4.2.1 IVO spent fuel

The fuel assemblies used in the Loviisa reactors 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. Of course, the impact of other variables must be studied and quantified.

In this study, a fuel assembly assumed 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)	1.228
- Fuel rod		
	Outer radius (cm)	
	- of the central hole	*
	- of the pellet	0.3783
	Fuel rod clad	
	- inner radius (cm)	0.388**
	- 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) 14.47 (14.40)
  - thickness (cm) 0.20 (0.15)
  - (The values in the brackets were used in MCNP4A calculations)

* The central hole of the VVER-440 bundles of Russian origin 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	9.9263
- Clad: ZrNb1 (one wt% of Nb)	5.79
- Instrumentation rod: ZrNb1	6.55
- Shroud: ZrNb2.5	6.58

The spacers were taken into account in CASMO-HEX calculations, but not in MCNP4A 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).

4.2.2 TVO spent fuel

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 9*9-1 fuel bundle supplied by Siemens AG and used in the TVO I reactor at the beginning of the 1990s 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.

A 9*9-1 fuel bundle can be defined as follows (the values given correspond to room temperature):

- a square bundle consisting of a regular lattice of 81 square pin cells and of a square flow channel, which, however, will be disposed separately, Therefore, the channel box was omitted in the criticality safety calculations. In a 9*9-1 fuel bundle there is one water rod, which was described exactly in CASMO-4 calculations, but was replaced by a fuel rod cell in MCNP4A calculations.

- Unit pin cell (square)

Pitch (cm)	1.445

- Fuel pellet

Outer radius (cm)	0.4555

- Fuel rod clad

- inner radius (cm)	0.465
- outer radius (cm)	0.5375

- the gas gap between the fuel pellet and the clad was homogenized with the clad in MCNP4A calculations

- Water tube

- inner radius (cm)	0.575
- outer radius (cm)	0.650

- The channel box

- inner pitch (cm)	13.40
- thickness (cm)	0.25

At both ends of the 9*9-1 bundles there has been a so-called axial blanket made of natural uranium, the impact of which has been omitted in this study. In the enriched part of the 9*9-1 assemblies used in the TVO I reactor the initial enrichment of a fuel rod has varied from 1.6% to 3.95% the average value having been 3.45%.

The BA content of the 9*9-1 bundles has not been constant. In one variant there have been eight BA rods at the bottom of the bundle and seven at the top and in the other type here have been nine BA rods in the whole enriched part.

4.3 Comparison of the IVO and TVO spent fuel

Besides the differences in the enrichment distributions and use of the BA rods, the fuel and water volumes and masses per unit height of the IVO and TVO fuel assemblies are rather different from each other. The fuel-to-water mass ratio of the IVO canister is ca. 15% higher that of the TVO canister. More detailed information is given at Table 2, where the bundle data are based on the input specification of the CASMO-4/CASMO-HEX calculations and the canister data on that of the MCNP4A calculations.

Table 2. The amount of the fuel (uraniumdioxide) and water per unit height in the IVO and TVO fuel bundles and canisters.

A) Fuel rod cell	**IVO**	**TVO**
Fuel (uraniumdioxide)		
- Volume (cm^3/cm)	0.4496	0.6518
- Mass (g/cm)	4.4628	6.6485
Water (density 1 $g/cm^{3)}$		
- Volume (cm^3/cm)	0.6357	1.1804
- Mass (g/cm)	0.6357	1.1804
Fuel-to-water mass ratio	7.020	5.632
B) Disposal canister	**IVO**	**TVO**
Fuel (uraniumdioxide)		
- Volume (cm^3/cm)	56.4	52.7
- Mass (g/cm)	562.3	538.5
Water (density 1 g/cm^3)		
- Volume (cm^3/cm)	137.4	151.5
- Mass (g/cm)	137.4	151.5
Fuel-to-water mass ratio	4.09	3.56

5 RESULTS

5.1 Parametric studies with CASMO-HEX/CASMO-4

5.1.1 General

The main goal of the two-dimensional unit cell calculations with the fuel assembly burnup codes CASMO-HEX (the IVO canister) and CASMO-4 (the TVO canister) was to study the impact of some important variables on the reactivity of the canisters in a simplified geometry.

First, the nuclide-wise composition of each fuel rod, as well as the average nuclide-wise composition of the fuel bundle were calculated as a function of burnup assuming the nominal full-power conditions of the reactor. Then the fresh/irradiated fuel bundle was placed at the centre of the unit cell defined to simulate the bundles loaded into the isolated holes of the canisters (see Fig. 1). The system analyzed in CASMO-4/CASMO-HEX calculations was always an infinite lattice of the identical unit cells.

The finite size of the bundle lattice can be taken into account in an approximate way as follows:

$$k_{eff} = k_{inf}/(1.-B^2M^2), \qquad (1)$$

where k_{inf} is the multiplication factor of the infinite lattice,
M^2 is the migration area of the lattice,
B_2 is the geometric buckling of the finite system and
k_{eff} is the multiplication factor of the finite lattice.

The exact value of the geometric buckling can be calculated only for the regular lattices without the reflectors. In practice, some approximations must be applied. The most common approximation for lattices, which have square geometry in the horizontal direction, may be the following formula:

$$B^2 = 2*(\pi/x')^2 + (\pi/h')^2 \qquad (2)$$

where $x' = x + 2d$,

$h' = h + 2d$,

x is the side of square, the size of which is equal to that of the finite lattice,

h is the height of the bundle and

d is the so-called reflector savings (a value of 7 cm used in this study).

A corresponding formula can be given for lattices, which are cylindrical in the radial direction.

5.1.2 TVO canister

A burnup calculation in the nominal full-power conditions with CASMO-4 was carried out for three types of the 9*9-1 fuel bundle:

- a real bundle with seven BA rods (content of gadolinia 3%),
- a bundle having the real enrichment distribution, but no BA rods and
- a bundle having a flat enrichment distribution and no BA rods.

The void content of coolant was assumed to be 40%, but the effect of void history on results reported below would be small, because only fuel bundles having a rather low burnup were studied.

For subsequent studies, the nuclide-wise material compositions and the geometry of the fuel bundle were read from the restart file of the relevant burnup calculation and were modified to correspond to the actual temperature and other state variables. The concentration of ^{135}Xe was set to zero and for the thickness of the channel box, a value of 0.01 cm was given (to simulate the fact that the TVO spent fuel are planned to be disposed without their flow channels).

In the TVO disposal canister eight of the fuel bundles are separated from other bundles by a layer of cast iron, the nominal thickness of which is 5 cm. This detail of the canister lattice was simulated by an infinite system of identical square unit cells. At the centre of each unit cell there was a fuel bundle surrounded by a ca. 1 cm thick layer of water and a 2.5 cm thick layer of cast iron.

First, the impact of the bundle type on the reactivity of the unit cell defined above was studied as a function of burnup. The results are given in Table 1. At the burnup of 10 MWd/kgU the effect of the BA rods is already quite small. The reactivity of the unit cell with the bundle having seven BA rods is at the highest somewhere at the range of 8.0 - 8.5 MWd/kgU (see Table 2). A bundle with the flat enrichment distribution has a higher reactivity than a bundle with a real enrichment distribution. The difference is at zero burnup almost 1 300 pcm and at the burnup of 15 MWd/kgU still about 900 pcm.

*Table 1. The infinite multiplication factor of three types of the 9*9-1 fuel bundles having an enrichment of 3.45% surrounded by a layer of water (1 cm thick) and cast iron (2.5 cm thick) at room temperature.*

	Type of the bundle		
	Real enrichment distribution		Flat enrichment distribution
Burnup (MWd/kgU)	With seven BA rods	Without BA rods	
0.0	0.82055	0.96544	0.97842
5.0	0.85739	0.92237	0.93393
10.0	0.87539	0.88031	0.89060
15.0	0.83641	0.83855	0.84758

The infinite multiplication factor of the unit cell decreases, if the temperature of water is increased as shown in Table 2 in case of the real fuel bundle with seven BA rods. In a finite system, the increased mobility of neutrons (the larger migration area) results in more leakage out of the lattice and in an even smaller effective multiplication factor of the system.

Table 2. *The infinite multiplication factor of a 9*9-1 fuel bundle with seven BA rods surrounded by a layer of water (1 cm thick) and cast iron (2.5 cm thick) at three temperatures.*

Burnup (MWd/kgU)	Temperature (°C) 20	50	80
7.5	0.87975	0.87612	0.87195
8.0	0.88114	0.87748	0.87322
8.5	0.88129	0.87755	0.87323
9.0	0.88029	0.87649	0.87214

An increased initial enrichment results in higher reactivities at all burnup points, as shown in Table 3 in case of the bundles with the flat enrichment distribution. In that case, the increase is 675 - 800 pcm per an increase of the average enrichment by one tenth of per cent.

By combining the data of Tables 1 and 3 one can conclude that to compensate the reactivity effect of an increase of enrichment by 0.1%, one should increase the burnup of the fuel by about 1 MWd/kgU.

Table 3. *The infinite multiplication factor (k_∞) of a 9*9-1 fuel bundle with the flat enrichment distribution surrounded by the layers of water (ca. 1 cm thick) and iron (2.5 cm thick).*

Burnup (MWD/kgU)	Enrichment (%) 3.45	3.80	Δk_∞ (pcm)
0.0	0.97842	1.00208	2366
5.0	0.93393	0.95854	2461
10.0	0.89030	0.91683	2653
15.0	0.84758	0.87563	2805

Finally, some series of CASMO-4 calculations were performed so that the number of fuel bundles surrounded by water needed to form a too reactive system ($k_{eff} > 0.95$) could be estimated. The main results of these studies are given in Tables 4 and 5.

The reactivity of an infinite lattice of 9*9-1 bundles increases, if each bundle is surrounded by a thin layer of water, but if the thickness of the water layer on each side is greater than about 0.6 cm, the extra water starts to decrease the reactivity of the system. Applying Eq. (2) with data of Table 4 one can estimate that six 9*9-1 fuel bundles with seven BA rods at the burnup of their highest reactivity are needed to increase the effective multiplication factor over the criticality safety limit of 0.95. With the fresh bundles without any BA rods the situation is, of course, far more critical. Only three or four bundles are needed to achieve the effective multiplication factor of 0.95.

Table 4. *The infinite multiplication factor and migration area of a 9*9-1 fuel bundle with seven BA rods surrounded by a layer of water at the burnup of 8 MWd/kgU at room temperature as a function of the bundle pitch.*

Bundle pitch (cm)	Infinite multi-plication factor	Migration area (cm^2)
13.22	1.28308	39.36
13.32	1.28394	39.15
13.52	1.28466	38.76
13.62	1.28506	38.58
13.82	1.28332	38.23
15.00	1.24199	36.60

Table 5. *The infinite multiplication factor and migration area of a homogenous 9*9-1 fuel bundle without BA rods surrounded by a layer of water at room temperature as a function of burnup (the pitch of the bundle lattice 13.62 cm).*

Burnup (MWd/kgU)	Infinite multi-plication factor	Migration area (cm^2)
0.0	1.42283	39.34
5.0	1.35493	39.01
10.0	1.29423	38.75
15.0	1.23482	38.53

5.1.3 IVO canister

A burnup calculation on the nominal full-power conditions were performed with CASMO-HEX for a VVER-440 fuel assembly of Russian origin assuming three initial enrichments: 3.2, 3.6 and 4.0%.

With CASMO-HEX it not possible to carry out so-called restart calculations as flexibly as with CASMO-4. Therefore, for each combination of the initial enrichment and discharge burnup studied an average nuclide-wise composition of the fuel bundle was read from the relevant CASMO-HEX output file and was then used for all fuel rods in subsequent criticality safety calculations.

The material regions outside fuel assembly must be described in a CASMO-HEX calculation as layers of hexagonal cells of equal size. The correct material thicknesses can be defined only in an approximate way by modifying material densities. The volume in an isolated hole of the IVO canister, but outside the fuel assembly placed there, was treated in this way. The nominal thickness of the cast iron layer between the holes of the IVO canister is 4 cm. In CASMO-HEX calculations two and a half unit cell layers of cast iron with its nominal density (7.1 g/cm^3) were specified to belong to the bundle cell, which corresponds to a about 5.3 thick layer of cast iron between the holes.

The infinite multiplication factor and migration area (cm^2) the IVO bundle cell described above is given in Table 6. The migration area is relatively constant depending more on the burnup than on the enrichment.

Table 6. The multiplication factor (k_∞) and the migration area (M^2; cm^2) of the infinite lattice of cells consisting of a VVER-440 fuel assembly surrounded by the layers of water and cast iron.

Burnup	Enrichment (%)					
(MWd/kgU)	3.2		3.6		4.0	
	k_∞	M^2	k_∞	M^2	k_∞	M^2
0.0	0.95566	49.89	0.98450	50.21	1.00938	50.46
5.0	0.91540	49.22	0.94398	49.56	0.96891	49.83
10.0	0.87806	48.65	0.90733	49.00	0.93307	49.30
20.0	0.81754	51.18	0.84797	51.62	0.87534	52.01

The impact of enrichment on the infinite multiplication factor of IVO canister cells studied is 720 - 760 pcm/0.1%, when the enrichment is changed from 3.2% to 3.6% and 620 - 680 pcm/0.1%, when the enrichment is increased from 3.6% to 4%. The impact seems to be increasing with the burnup. On the other hand, an increase of burnup by one MWd/kgU decreases the multiplication factor by about 800 pcm at low burnups and by about 600 pcm at moderate burnups (10-20 MWd/kgU).

5.2 Main results of MCNP4A calculations

With MCNP4A only canisters with fresh fuel were studied. In case of the TVO canister, the single water rod of the 9*9-1 bundles were replaced by a fuel rod. The fuel assemblies were assumed to be homogeneous, i.e. each fuel rod was of the same enrichment. They were always placed at the centre of their hole. The axial leakage from the canisters was always omitted.

If the MCNP4A results are combined with the burnup-dependent CASMO-4/CASMO-HEX results given above, the minimum discharge burnup of the spent fuel needed to guarantee the criticality safety of the canisters and its dependence on the (average) initial enrichment can be estimated reliably enough.

It was specified that in a MCNP4A calculation 75 cycles with 10 000 neutrons should have been carried out. Of these, the first 25 cycles were specified to be omitted in the calculation of the final multiplication factor. In practice, many calculations were stopped due to the limit set for the CPU time. However, also in these cases the standard deviation was considered to be small enough.

A dry disposal canister

Both canister types are deeply subcritical when dry. The MCNP4A calculations gave the following multiplication factors for the isolated canisters:

- IVO canister filled with eleven fresh VVER-440 fuel assemblies having the enrichment of 3.6%	0.224 ± 0.001
- TVO canister filled with 10 fresh 9*9-1 fuel bundles having the enrichment of 3.5% and four fresh 3.5% SVEA-64 subbundles	0.222 ± 0.001

The multiplication factor of an infinite lattice of dry TVO canisters is 0.310 ± 0.001.

An isolated disposal canister filled with water

The multiplication factor of both canister types filled with (pure) water was calculated for three enrichments in each case. Two sensitivity studies were carried out. First, the ring of eight holes was moved 1 cm inward, i.e. closer to the centre of the canister. Secondly, the canisters were surrounded by a water layer, the thickness of which was set to 5 cm.

The results are given in Table 8.

Table 8. The multiplication factor of an isolated IVO and TVO nuclear waste disposal canister when loaded with the fresh fuel bundles (without burnable absorbers) and filled with pure water at room temperature according to MCNP4A calculations.

I IVO canister

Enrichment (weight%)	Multiplication factor: Nominal geometry	The ring of eight holes 1cm inward	Water reflector (5 cm thick)
3.4	0.95164 ± 0.00165*		
3.6	0.96137 ± 0.00165*	0.96647 ± 0.00109	0.96149 ± 0.00111
4.0	0.98107 ± 0.00104		

* Only 27/28 active cycles of the 50 intended calculated

II TVO canister

Enrichment (weight%)	Multiplication factor: Nominal geometry	The ring of eight holes 1cm inward	Water reflector (5 cm thick)
3.2	0.98761 ± 0.00110		
3.5	1.00642 ± 0.00104	1.01378 ± 0.00091	1.00961 ± 0.00099
3.8	1.02610 ± 0.00093		

According to MCNP4A calculations the impact of enrichment on the reactivity of an isolated wet IVO canister is a little less than 500 pcm / 0.1%, i.e. somewhat smaller than in the CASMO-HEX calculations. In case of an isolated wet TVO canister the reactivity effect of enrichment is 650 - 700 pcm / 0.1%, which is in good agreement with the CASMO-4 results.

Moving the ring of eight holes one centimeter closer to the centre hole increases the reactivity of the canisters only a little (500 pcm for the IVO canister, about 700 pcm for the TVO canister). A 5 cm thick water reflector has an even smaller effect.

The effect of water density on reactivity of the isolated canisters were studied for a TVO canister filled with the fresh fuel bundles having enrichment of 3.5% and no BA rods. The results are given in Table 9. The multiplication factor decreases monotonously, when the density of water decreases. It is worth noting that when the fuel-to-water mass ratio in the TVO disposal canister is close to that of the IVO canister (at water density of about 87%), the difference between the multiplication factors of the canister types are rather small.

Table 9. The multiplication factor of a TVO disposal canister filled with the fresh fuel bundles having an enrichment of 3.5% as a function of water density.

Density of water (g/cm^3)	Multiplication factor
0.0	0.222 ± 0.001
0.2	0.552 ± 0.001
0.4	0.755 ± 0.001
0.6	0.875 ± 0.001
0.8	0.955 ± 0.001
0.95	0.996 ± 0.001
1.0	1.006 ± 0.001

Placing identical wet TVO canisters in an infinite lattice with square geometry increases the multiplication factor only a little, which is shown in Table 10. The multiplication factor of the infinite lattice seems to be about the same as that of a single canister having a 5 cm thick reflector of water.

Table 10. The multiplication factor of an infinite square lattice of TVO disposal canisters filled with water and with the fresh fuel bundles having an enrichment of 3.5% at room temperature.

Unit pitch (cm)	
98.1	1.009 ± 0.001
100	1.007 ± 0.001
108	1.008 ± 0.001
118	1.008 ± 0.001
128	0.996 ± 0.001

5.3 Minimum allowable burnup of the spent fuel

According to MCNP4A calculations the maximum multiplication factor of the IVO and TVO canisters are:

- IVO canister filled with eleven fresh VVER-440 fuel assemblies having the enrichment of 3.6%	0.970
- TVO canister filled with 10 fresh 9*9-1 fuel bundles having the enrichment of 3.5% and four fresh 3.5% SVEA-64 subbundles (no burnable absorbers)	1.010

The TVO canister is more reactive than the IVO canister due to its more optimum fuel-to-water mass ratio. If the presence of a rather heavy load of burnable absorbers in a typical TVO fuel bundle would be taken into account, the situation would be reversed.

If one assumes that an increase of burnup by one MWd/kgU decreases the reactivity of both canister types by 600 pcm, an IVO canister would fulfil the criticality safety criteria, if all its bundles have a higher than 4 MWD/kgU burnup (and the initial enrichment of 3.6% or less). The minimum burnup for the TVO fuel having an average initial enrichment of 3.5% would be about 10 MWd/kgU. As a practical rule of thumb one could say that both canister types are safe, if they are loaded with the fuel bundles having been in the reactor at least one normal annual cycle.

6 CONCLUSIONS

The criticality safety of the copper/iron canisters developed for the final disposal of the Finnish spent fuel have been studied with the MCNP4A code based on the Monte Carlo technique and with the fuel assembly burnup programs CASMO-HEX and CASMO-4.

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 has been designed for hexagonal VVER-440 fuel assemblies used at the Loviisa nuclear power plant (the IVO canister) and the other one for square BWR fuel bundles used at the Olkiluoto nuclear power plant (the TVO canister).

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 application of an even lower reactivity limit.

Based on the results of this study the IVO canister loaded with eleven similar VVER-440 assemblies with the initial enrichment of 3.6% fulfils the criticality safety criteria, if the discharge burnup of the assemblies is more than 4 MWd/kgU. The TVO canister loaded with eleven BWR assemblies with the initial enrichment of 3.5% and without burnable absorbers meets the same criteria, if the discharge burnup of the assemblies is more than 10 MWd/kgU. An increase of the average enrichment by 0.1 percentage might be compensated in both cases by increasing the minimum discharge burnup by one MWd/kgU.

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