BELGIAN SUPERCONTAINER LONG-TERM CRITICALITY CALCULATIONS

O. Wantz*, A. Dubus, R. Beauwens
Service de Métrologie Nucléaire
Université Libre de Bruxelles

ABSTRACT

We present a criticality risk assessment for one of the latest repository designs for spent nuclear fuel assemblies in Belgium. The supercontainer design consists in a 2-meter diameter cylindrical concrete container with a stainless steel liner holding four single spent fuel assembly canisters. The repository design foresees these supercontainers to be put in horizontal disposal galleries excavated in the Boom Clay at the reference site on the Mol/Dessel nuclear zone, near the SCK•CEN nuclear research center in Mol, Belgium.

We describe the techniques used to develop scenarios leading to criticality events, along with their application to the supercontainer case. We only consider in-package criticality scenarios. These are developed by using two different techniques: the bottom-up and the top-down approaches. The bottom-up approach consists in selecting and combining disruptive events in order to form scenarios. The top-down approach is based on the different states in which each component of the repository may be in the future. The scenarios are derived by taking combinations of the possible states of the different elements of the repository system.

We finally use the MCNP code in order to estimate the multiplication factor of the supercontainer system in several disrupted geometries and conditions. These geometries and conditions are directly derived from the scenarios development procedure. Different types of fuels and burn-ups have been studied. The major parameter has been found to be the moderation between the fuel rods of the fuel assemblies. In conclusion, we may say that the risks of an in-package criticality event in the supercontainer design appear to be extremely low.

SCOPE OF THIS WORK

In August 2000, NIRAS/ONDRAF (the Belgian Agency for Radioactive Waste and Enriched Fissile Materials) asked the Service de Métrologie Nucléaire to study the risks linked to the occurrence of a criticality event in the Belgian SAFIR2 (Safety Assessment and Feasibility Interim Report 2) high-level waste and spent fuels repository design [1]. This design foresees 4 canisters holding a single spent fuel assembly per disposal gallery section. The disposal galleries are horizontal galleries excavated in the Boom Clay layer at the reference site on the Mol/Dessel nuclear zone, near the SCK•CEN nuclear research center.

Our first goal was to determine the different ways in which such a criticality event could occur in a repository. We used two techniques in order to develop scenarios leading to a criticality event in the SAFIR2 repository design [2]: the bottom-up and the top down approaches. A distinction is made between criticality scenarios, according to the location the criticality event could occur:

in-package (inside the containers holding the waste), near-field, and far-field. For the moment, only the scenarios leading to an in-package criticality have been studied.

The second aim is to examine whether or not the identified long-term criticality scenarios could really lead to a criticality event. We have already presented criticality calculations for the SAFIR2 design [3]. These disrupted systems have been derived from the scenarios development step.

Now, NIRAS/ONDRAF is studying new repository designs, such as the supercontainer design, which may be seen as a variant of the SAFIR2 design. The supercontainer consists in a concrete container with a stainless steel liner holding four single spent fuel assembly canisters. The supercontainers are placed in horizontal disposal galleries excavated in the Boom Clay formation.

The last point we would like to study will be the determination of the consequences of a postulated criticality event in a repository system. This work will take place in further developments of this study.

BELGIAN NUCLEAR PROGRAM

About 60 percent of the electricity production in Belgium originates from nuclear power plants. Belgium owns 7 PWRs (Pressurized Water Reactors), which are located in two sites: 4 reactors in Doel and 3 reactors in Tihange. Together they have a capacity of approximately 5,900 MWe. All these reactors use classical UOX (Uranium OXide) fuel assemblies. Two of them (Doel 3, Tihange 2) have also accepted a limited number of MOX (Mixed OXide) fuel assemblies (see Table I). These MOX fuel assemblies came from the reprocessing of spent UOX fuels in Cogema - La Hague (France).

Since 1993, the Belgian government has promulgated a moratorium on the reprocessing of spent UOX fuels in Cogema – La Hague. An estimation of the total amounts of radioactive waste expected in the present Belgian program based on a 40-year life time for the 7 Belgian reactors is given in Table II, according to two scenarios (total reprocessing, no more reprocessing). The production column takes into account the waste produced during the operational life of the reactors. The dismantling column corresponds to the amounts of waste expected during the dismantling phase of the reactors.

The reprocessing option would largely decrease the total amount of category C (HLW) waste but with a small increase of the category B (LILW-LL) waste. For the moment, no decision has been made on the continuation of reprocessing, nor on the final destination of the radioactive waste in Belgium. The Boom Clay layer is currently being studied as a possible -'reference'- host formation for disposal of category B and C waste. Boom Clay at the nuclear zone of Mol/Dessel is also studied as a possible host formation for deep disposal of category A (LILW-SL) waste, besides the option of surface disposal of category A waste.

Table I Belgian Nuclear Reactors Overview [4]

unit	gross capacity [MWe]	beginning of commercial operation	fuel type	fuel assembly type
Doel 1	412	1975	UOX	14x14
Doel 2	412	1975	UOX	14x14
Doel 3	1020	1982	UOX+MOX	17x17
Doel 4	1049	1985	UOX	17x17
Tihange 1	976	1975	UOX	15x15
Tihange 2	970	1983	UOX+MOX	15x15
Tihange 3	1070	1985	UOX	17x17

In Belgium, the nuclear waste are classified as [1]:

Category A waste consist in conditioned waste containing radionuclides of a sufficiently low activity level and with a sufficiently short life span to allow surface disposal (LILW-SL).

Category B waste are conditioned low and intermediate-level waste contaminated by long-lived alpha emitters in quantities that are too great for these waste to be classified as category A, but which emit too little heat to belong to category C (LILW-LL).

Category C waste include all conditioned high-level waste containing significant amounts of beta and gamma emitters with a short life span and large quantities of long-lived alpha emitters. Because of the high activity level, the waste in this category emits considerable amounts of heat (more than 20 W/m^3) (HLW).

Table II Estimation of the expected radioactive waste production for the Belgian PWRS based on a 40-year life time [5], based on data from 1998

waste type	production [m^3]	dismantling [m^3]	total [m^3]
	reprocessing / no reprocessing		reprocessing/ no reprocessing
A	21,300	35,400	56,700
B	6,200 / 5,200	2,600	8,800 / 7,800
C	900 / 6,700	0	900 / 6,700
total	28,400 / 33,200	38,000	66,400 / 71,200

BELGIAN NULEAR WASTE DISPOSAL DESIGNS

In this section, we only consider category C waste.

The first repository design for category C waste has been developed in the late '80s in SAFIR [6]. This repository design was mainly intended for vitrified waste resulting from the reprocessing of spent fuel assemblies. The Boom Clay layer has been selected as a possible host rock according to its particular properties (stability, low hydraulic gradient, radionuclide retention capacity …).

The SAFIR design consists in horizontal disposal galleries (about 800 m long) excavated in the Boom Clay at a depth of about 230 m beneath the Mol/Dessel nuclear zone. The galleries are about 2 m in diameter and the waste packages are placed at the center of the galleries in disposal tubes, surrounded by bentonite blocks

Due to the 1993 moratorium on the reprocessing of spent fuel, a new repository design has been studied: in the SAFIR2 design [1] one also considers the direct disposal of spent fuel assemblies. The design remains almost the same for the glass waste packages. The spent fuel assemblies are foreseen to be put in canisters. These stainless steel canisters hold a single fuel assembly. They are put in four disposal tubes per gallery section surrounded by bentonite blocks.

The supercontainer design (see Fig. 1.) is largely inspired by the SAFIR2 design. The current thinking is that fuel assemblies (1) will be put in single place canisters (2) filled afterwards with sand as in SAFIR2. Four canisters would then be inserted in a concrete core supercontainer (3) surrounded by a thin stainless steel layer (4). The diameter of the supercontainer is about 2 m and its length 5 m. A supercontainer only holds 4 single assemblies canisters in order to limit thermal constraints on the host rock. The disposal gallery lining is made of concrete blocks (5). Each disposal gallery is 800 m long and will hold about 160 supercontainers. Other new designs exist but are not described here. The new designs have not been fully finalized yet, and that for e.g. the studies on technical feasibility and on criticality can still lead to changes in the designs.

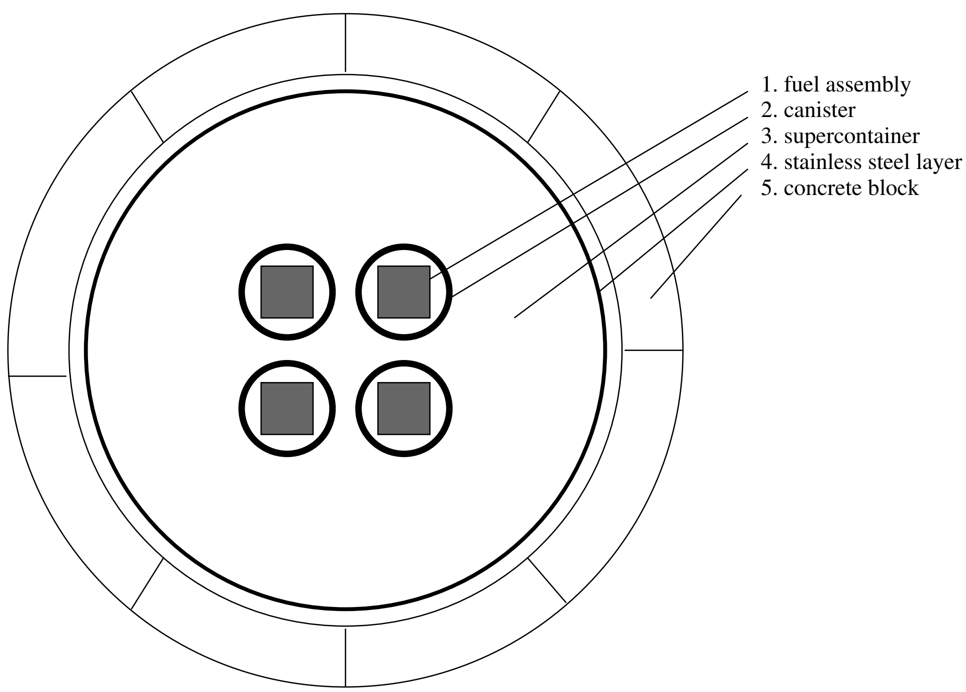

Fig. 1 The supercontainer design: schematic cross section in a disposal gallery as used in the current studies on the criticality risk

CRITICALITY IN NUCLEAR WASTE REPOSITORIES

Criticality

Criticality is the self-sustained nuclear fission reaction, which could occur in systems containing fissile materials in particular conditions. A thermal (slow) neutron collides with a fissile element, giving birth to 2 fission reaction products, about 200 MeV of energy, and 2 to 3 fast neutrons, which could be able (after moderation) to fission other fissile elements in the system.

Criticality is measured by means of the multiplication factor, k_{eff}. This factor is defined as the ratio between the numbers of neutrons in a fission reaction generation to the previous one.

According to the value of the multiplication factor, a system is called:

- Subcritical: $k_{eff} < 1$. In this case, the fission reaction dies out. This is the safe situation.
- Critical: $k_{eff} = 1$. The fission reaction is self-sustaining, as in a nuclear reactor.
- Supercritical: $k_{eff} > 1$. The reaction is explosive, the number of neutrons in successive generations increases exponentially.

The main parameters influencing the multiplication factor of a system are the moderation, the geometry, and the presence of absorbing species. Moderation consists in decreasing the speed of the neutrons (which will enhance their chance to create a fission reaction when they collide with fissile materials). Most often moderation is assumed by water. So the presence of water is a very important factor. The geometry influence on the multiplication factor resides in the neutron system escape probability. If a neutron leaks out of the system, it will not be able to give a fission reaction. Absorbing species absorb neutron without leading to a fission reaction or new neutrons.

A safety limit of 0.95 has been selected for the multiplication factor: the system is thus considered as being subcritical when the value of the $k_{eff}+2\sigma$ remains below this safety limit.

How to deal with criticality risks?

Long-term criticality safety in radioactive waste repositories can be assessed by using a three steps approach:

- Criticality scenarios development: determination of the potential ways a criticality event could occur in the future history of the repository, with an eventual determination of the occurrence probability for each scenario;
- Criticality calculations: determination of the multiplication factor of the considered repository system according to the final states reached in the scenarios development step;
- Determination of the consequences of criticality events. These events could either be postulated or derived from the scenarios development and criticality calculations procedures.

LONG-TERM CRITICALITY SCENARIOS DEVELOPMENT

The aim of any scenarios development procedure is to obtain a set of scenarios (future possible evolutions of a repository system), which reflect the most probable future evolutions of the considered repository. In our case, we focus on the scenarios thought to lead to a criticality event inside the packages containing the waste (in-package criticality scenarios).

Bottom-Up Approach

The bottom-up approach is derived from the Sandia methodology [7], and consists in the following steps:

- An initial comprehensive identification of all the FEPs (Features, Events, and Processes) felt to be important to the long-term isolation of radioactive waste in deep geologic formations;
- A classification of these FEPs to aid in completeness arguments;
- A screening of these FEPs based on well defined criteria;
- The formation of scenarios by taking specific combinations of the FEPs, which remain after the screening procedure;
- The final screening of these scenarios.

Top-Down Approach

The top-down approach considers combinations of the different states of the elements of the repository system, the detailed phenomena and their couplings are disregarded. This approach could be divided as follows [8]:

- An initial identification of all the elements of the considered system (the barriers of the system, natural or man-made);
- The identification of all the possible states in which each barrier could be in the future evolution of the repository;
- The combination of the compatible states, which gives a first scenarios set;
- The final screening of these scenarios.

Application to the Belgian Supercontainer Repository Design

The system is defined as being: the spent fuel assemblies, the canisters holding these assemblies, the canisters filling material, the supercontainer containing the canisters, the disposal gallery, and the host rock (the Boom Clay layer).

We now successively present the results obtained with both the bottom-up and the top-down approaches to long-term in-package scenarios development for the Belgian supercontainer repository design.

In the bottom-up approach, the disruptive FEPs remaining after screening have been identified as being:

FEP1: water intrusion inside the disposal galleries. According to the properties of the Boom Clay layer, this FEP is certain to occur in the future history of the repository. The only remaining question is when water will enter the disposal galleries.

FEP2: water infiltration inside the supercontainer. Once water is present in the disposal galleries, it will infiltrate the supercontainer (after corrosion of the thin stainless steel protective layer) according to the properties of the concrete.

FEP3: water intrusion inside the canisters. This FEP happens after corrosion of the canisters (the most probable corrosion type is pitting corrosion of the stainless steel canisters).

FEP4: sand filling presence. Canisters could be bad-filled or present sand filling leakage if the canister is corroded and the supercontainer disrupted. This FEP has a very low probability of occurrence, but it could be interesting to study the influence of the presence of the sand filling inside the canisters.

FEP5: spent fuel assemblies geometry alteration. If water is present in the canisters, it could corrode the structures of the assemblies, leading to changes in their geometry.

The combination (occurrence or non-occurrence) of these remaining FEPs gives after scenarios screening the final bottom-up scenarios set:

B-U Scenario1: the five disruptive FEPs occur. Water is present inside the galleries, has infiltrated the supercontainer, corroded the canisters, the sand filling is absent or leaking and the geometry of the spent fuel assemblies is altered.
B-U Scenario2: same scenario as the first one but here the fuel assemblies geometry is preserved.
B-U Scenario3: same scenario as the first one but here the sand filling is present.
B-U Scenario4: same as the second scenario but the sand filling is present.

All the scenarios without water moderation have been skipped because water presence is required since a moderator is necessary in order to reach criticality [3].

For the top-down approach the system elements and their states are:

Element1: the spent fuel assemblies. Their geometry could either be intact (E1.1) or disrupted (E1.2).
Element2: water. Water is absent (E2.1) or present (E2.2) in the canisters according to the state of the canisters (intact or corroded).
Element3: sand filling. The sand filling is in place (E3.1) or leaking or absent (E3.2). The distinction between sand filling leakage or absence is not made because the sand filling absence is the worst case of sand filling leakage.

We assume water presence inside the disposal galleries and water infiltration inside the supercontainer. The degradation of the supercontainer geometry is not taken into account, this point is studied as geometry effects in the criticality calculations part of this work.

The combination of the system element states gives after scenarios screening, the final top-down scenarios set:

> T-D Scenario1: the fuel assemblies geometry is preserved, water is present in the canisters, and the sand filling is in place.
> T-D Scenario2: same as the first scenario but the geometry of the fuel assemblies is no more preserved.
> T-D Scenario3: same as the first scenario but here the sand filling is either leaking or missing.
> T-D Scenario4: same as the second scenario but the sand filling is either leaking or missing.

Here again we need water moderation: all the combinations with system element E2.1 have been rejected.

Conclusion

In a previous paper on the SAFIR2 design criticality scenarios development [2], we have shown that the top-down approach was quite better than the bottom-up one. The bottom-up approach is a binary approach (occurrence or non-occurrence of disruptive FEPs). This was due to the fact that the system elements could present more than 2 states. Here we only consider two states for all the system elements and the two approaches give the same final scenarios.

LONG-TERM CRITICALITY CALCULATIONS

Modeling

Our model is based on a typical 17x17 nuclear fuel assembly. The fuel pellets are modeled as being 4.267 m long cylinders with a 0.819 cm diameter. The densities of the fuel pellets are 10.450 for UOX and 11.000 for MOX. The fuel pellets are surrounded by Zircaloy-4 fuel rods with a 0.819 cm internal diameter and a 0.950 cm external diameter. Thus, the model assumes no He gas filled gap between the fuel pellets and the fuel rods internal face.

The control or instrument tubes have been modeled as having the same diameter as the fuel rods for the sake of simplicity. The actual diameter of the tubes is a bit larger than the one of the fuel rods. These are filled with the same material as the canister: either pure sand, or pure water, or a mix of sand and water. The height of the rods (fuel rods and control or instrument tubes) is 4.885 m.

The fuel assembly consists in a square lattice of 289 rods: 264 fuel rods and 25 control or instrument tubes. The distance between the rods is a variable parameter. The nominal distance between the rods centers is 1.260 cm. The structures (top and bottom nozzles, spacing grids …) of the fuel assemblies have been neglected in the present modeling.

Different burn-ups have been considered for the UOX fuel (initial enrichment of 4.5%): UOX-0 (0 MWd/tHM), UOX-1 (9,333 MWd/tHM), UOX-2 (18,666 MWd/tHM), UOX-3 (28,000 MWd/tHM), UOX-4 (37,333 MWd/tHM). The MOX fuel is supposed to be fresh fuel (MOX-0). We ignore the fission products in the composition of the spent fuels (UOX-1, UOX-2, UOX-3, UOX4), which is a conservative assumption. The compositions of the spent fuels are not official ones, and the results gained with them are only given as qualitative quantities. The isotopic evolution of the different fuels with time has not been considered in the present calculations.

The canister filling material can be modeled as being either pure sand, or pure water, or a mix of sand and water. The canisters are made of stainless steel. The canisters are 5.0 m long with a 33.70 cm internal diameter, their thickness being 5.0 cm. A single fuel assembly fills in each canister.

The supercontainer is a cylinder, which holds four single assembly canisters in a specific concrete core. The distance between the canisters in this concrete core is a variable parameter (the nominal value being 10.0 cm). The supercontainer concrete core is surrounded by a 1.0 cm thick stainless steel layer. The radius of the supercontainer is 102.0 cm and it height is 5.80 m.

The internal radius of the disposal gallery is 112.0 cm, the gap between the supercontainer and the gallery walls is filled with pure water. The gallery walls consist in concrete blocks with a 25.0 cm thickness, the Boom Clay layer is modeled as an outer cylinder with a 1.0 m thickness surrounding the gallery walls. We only model a section of a disposal gallery holding one supercontainer. We assume that there is no interaction between adjacent supercontainers.

All the calculations have been performed with the MCNP-4C2 code [10]. This Monte Carlo code calculates the multiplication factor of 3D systems. The results are given along with their 95% confidence intervals ($k_{eff} \pm 2\sigma$). The variance, σ, is in all our calculations quite small (about maximum 0.00080), so the results are presented as being the k_{eff}. The confidence intervals are not represented in the figures.

Moderation effects

Water intrusion inside the canisters is one of the major disruptive events, which could influence criticality of the supercontainer system. No water is expected inside the canisters in the early times after repository closure, but after a given time, water could enter inside the canisters.

As the canisters are filled with sand, the maximum water content inside a canister is limited to the void fraction in sand (between 30 and 40 % volume). We have varied the water fraction inside the canisters from 0 to 100% volume by 10% steps for the different types of fuels and burn-ups.

Fig. 2. shows no criticality risks in the case of canisters with a water content of 40% volume fraction, for each of the studied fuels. In the case of canisters filled with sand there is no criticality risks even in the case of a water intrusion.

To take into account the possible leakage of the sand outside the canisters or possible bad-filled or even un-filled canisters, we also computed larger water fractions (up to 100%) in the canisters. The system remains below the 0.95 safety limit for all but one of the studied cases. Only the fresh uranium oxide fuel (UOX-0) is above the 0.95 limit when the canisters are completely filled with water. If a burn-up is assumed (UOX-1, UOX-2, UOX-3, UOX-4), the multiplication factor remains below the limit.

The MOX fuel (MOX-0) does not present criticality risks even in the case of canisters completely filled with water.

The 100% volume cases could be viewed as a variant supercontainer design, where the canisters are not foreseen to be filled with sand.

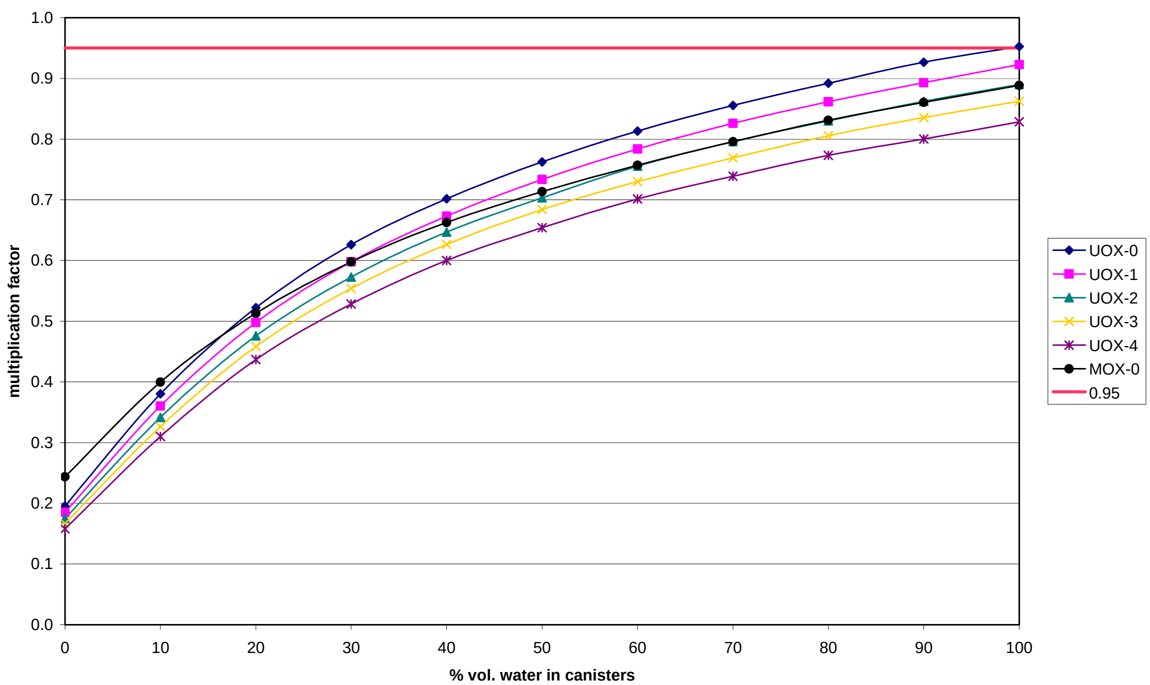

Fig. 2 Moderation influence on the multiplication factor

In the next calculations sets, we will compute systems with:

No water, index "(0)": cases where no moderation takes place, the canisters has not already been corroded, water is not present inside the canisters;
A 40% volume water fraction, index "(40)": cases where the canisters are filled with sand, but water fills in all the void spaces between the sand grains;
A 100% volume water fraction, index "(100)": cases where a sand leakage occurred or where no sand filling is foreseen in the design.

Supercontainer geometry influence

In this calculations set, we would like to study the influence of the geometry of the supercontainer on the multiplication factor. The chosen parameter is the distance between the canisters inside the super container. The nominal distance is 10 cm. We vary this distance from 0 to 60 cm by 10 cm steps.

The shape of the curves in Fig. 3 is always the same for all the studied cases. The multiplication factor slightly decreases for distances between 0 to 20 cm and is almost constant for values above 20 cm. If no moderation takes place, the system never shows criticality risks for the studied geometries. The same conclusion may be drawn for systems where the canisters are corroded and water enters them and fills in all the void spaces between the sand grains. If there is no sand filling, the 0.95 multiplication factor safety limit is reached for fresh UOX fuel (UOX-0) for the smallest distances between the canisters (0, 10, and 20 cm).

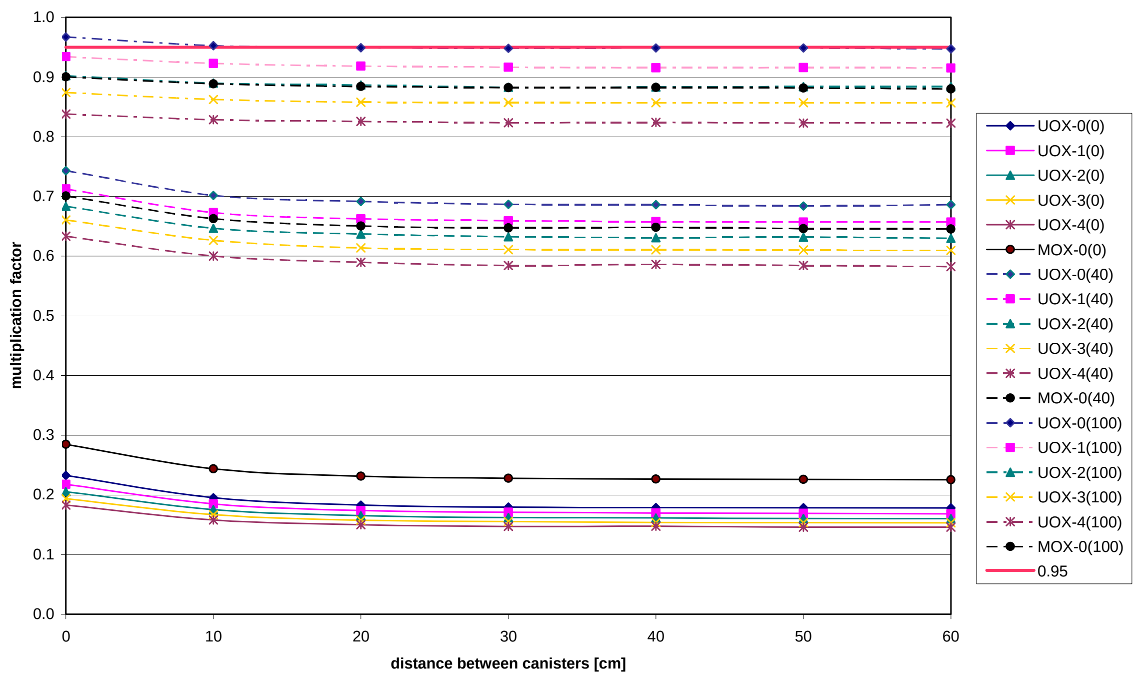

Fig. 3 Impact of supercontainer geometry changes on the multiplication factor

The distance between the canisters is thus not a key parameter for criticality risks. This parameter could then be fixed by other constraints (thermal output, activity, costs …). We would recommend either to change the nominal distance in order to stay below the safety limit when the canisters are completely filled with water even in the most conservative case (fresh UOX fuel, UOX-0), or to ensure the presence of the sand filling inside the canisters in order to limit the water fraction. The presence of the sand filling cannot be guaranteed over very long time scales, but the supercontainer design largely decreases the risk of a sand leakage outside the canisters when compared to the previous SAFIR2 design [2,3].

Fuel assemblies geometry variations effects

Fig. 4 shows the effects of a geometry variation of the fuel assemblies on the multiplication factor. The geometry variation considered consists in varying the distance between the fuel rods centers from 0.96 to 1.36 cm, the nominal distance being 1.26 cm (the centers of the fuel assemblies stay at the center of the canisters).

The shape of the results varies according to the water contents in the canisters due to two opposing effects. The geometry effect can be viewed when no water is present inside the canisters. In this case, decreasing the distance between the fuel rods leads to a smaller leaking factor and thus a bigger multiplication factor. The second effect is the moderation of the system: for a given geometry a higher water contents gives a higher multiplication factor, as already derived from Fig. 2. We can also see in Fig. 4 the importance of moderation: if the distance between the fuel rods decreases, the leaking factor decreases too, but there are fewer places for inter-rods moderation.

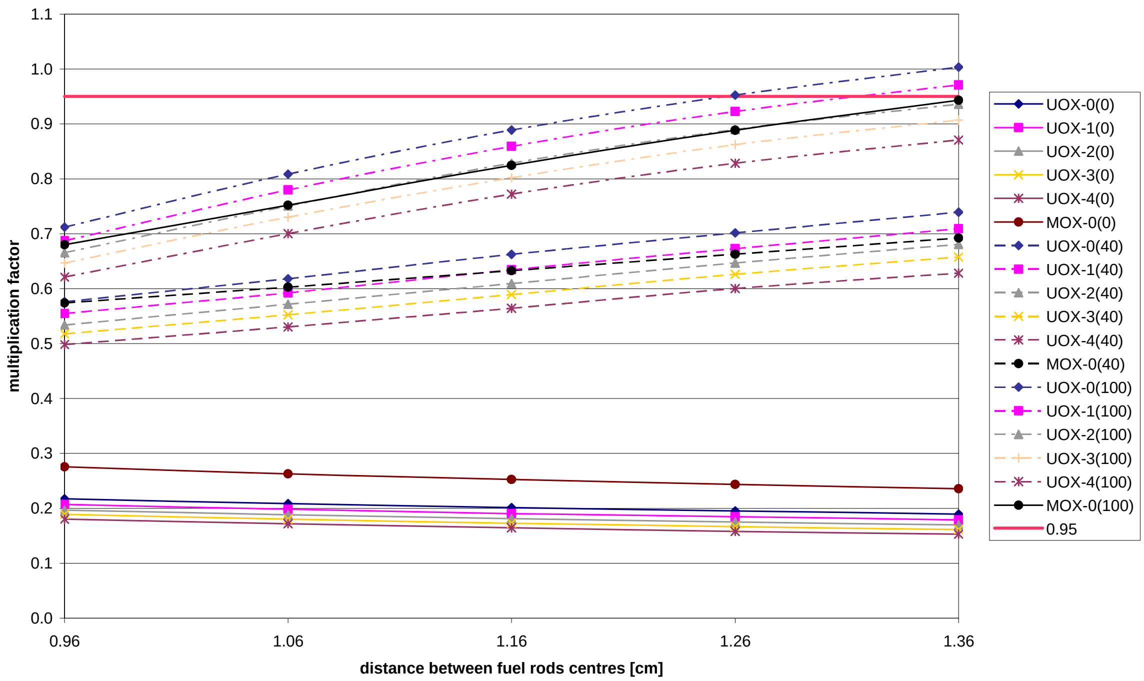

Fig. 4 Fuel assemblies geometry variations impact on the multiplication factor.

So, the most important effect is inter-rods moderation as the angular coefficient of the straight lines changes as soon as moderation takes place. When water is present, the decrease of the distance between the fuel rods leads to a decrease of the multiplication factor. The angular coefficient increases with the water contents showing again the importance of the inter-rods moderation on the multiplication factor.

If there is no water inside the canister, or if the water fraction is limited to 40% volume, the multiplication factor remains largely below the 0.95 safety limit when the fuel assemblies geometry is varied. If the canisters are completely filled with water, there could be high values of the multiplication factor (even larger than the unity) when the distance between the fuel rods is larger than the nominal distance. In this case (distance of 1.36 cm between fuel rods centers), we need a burn-up of minimum 18,666 MWd/tHM (UOX-2) in order to stay below the safety limit. We would like to mention that these configurations (100% volume water, 1.36 cm between fuel rods centers) are impossible to reach: if there is no sand filling, the degradation of the fuel assemblies structures will bring the rods together rather than take them apart.

As already mentioned, the configuration UOX-0 with 100% water, nominal distance between the fuel rods (1.26 cm) also reaches the 0.95 safety limit. So, in the case of fresh fuel disposal, sand filling is required.

CONCLUSION

The scenarios development procedures have enabled us to determine the potential situations where a long-term criticality event could occur in the Belgian supercontainer repository design. We have also identified the major parameters influencing long-term in-package criticality (moderation and geometry variations).

The criticality calculations have shown that the main parameter influencing long-term in-package criticality is moderation (more precisely moderation between the fuel rods of the assemblies). The natural variation of the geometry of the fuel assemblies (decrease of the distance between the rods) in presence of water leads to safe situations (decrease of the multiplication factor). The distance between the canisters in the supercontainer is a second order parameter, which will not influence long-term criticality.

The supercontainer design remains safe in all cases if the sand filling inside the canisters is intact. If the sand filling is absent (by design or leakage), criticality risks could be encountered for the zero or low burn-up assemblies. To ensure presence of the sand filling inside the canisters during long time periods will thus decrease criticality risks.

For the moment we can conclude that the risk of a long-term in-package criticality event in the supercontainer repository design is lower than the one of the previous SAFIR2 design. Furthermore, the SAFIR2 calculations were performed for lower UOX initial enrichment (3.5 %, instead of 4.5 % for the supercontainer calculations).

We still have to take into account the effects of time on the fuel pellets inventory over long timescales. But our results are conservative as they do not take into account these effects, which will decrease the fissile materials contents of the fuel pellets. Sensitivity studies on the concrete core composition are also planned for the year 2004.

ACKNOWLEDGMENTS

This work is funded by NIRAS/ONDRAF, the Belgian Agency for Radioactive Waste and Enriched Fissile Materials.

REFERENCES

1 NIRAS/ONDRAF "Safety Assessment and Feasibility Interim Report 2 (SAFIR2)", Brussels (2001).

2 O. Wantz, O.F. Smidts, A. Dubus, R. Beauwens "In-Package Criticality Scenarios Development for the Belgian Spent Fuel Repository" In Proc. of The International High-Level Radioactive Waste Management Conference (IHLRWM'03), Las Vegas, NV, USA, March 30 - April 3 2003.

3 O. Wantz, O.F. Smidts, A. Dubus, R. Beauwens "Long-term In-Package Spent Fuel Criticality Calculations" In Proc. of The 9th International Conference on Radioactive Waste Management and Environmental remediation (ICEM'03), Oxford, UK, September 21-25 2003.

4 Association Vinçotte Nuclear "National Report established for the second meeting of the Contracting Parties in the framework of the Nuclear Safety Convention", Brussels (2001).

5 F. Decamps "La gestion des déchets radioactifs belges: aspects techniques, écologiques, radiologiques, économiques et techniques", Brussels (2001)

6 NIRAS/ONDRAF "Safety Assessment and Feasibility Interim Report (SAFIR)", Brussels (1989).

7 R.M. Cranwell, R.W. Guzowsli, J.E. Campbell, N.R. Ortiz "Risk Methodology for Geologic Disposal of Radioactive Waste: Scenario Selection Procedures", Technical Report SAND80-1429, Sandia National Laboratories, Albuquerque (1990)

8 J. Anderson, T. Carlsson, T. Eng, F. Kautsky, E. Soderman, S. Wingerforgs "The Joint SKI/SKB Scenario Development Project", SKI, Stockholm (1989).

9 G. Evrard "Evaluation du niveau de sous-criticité du stockage souterrain d'assemblages irradiés de combustibles UO2 4,5% et MOX 9,3%", Brussels (1996).

10 J.F. Briesmester "MCNP – A General Monte Carlo N-Particle Transport Code". Manual LA-13709-M, Los Alamos (2000).

* Corresponding author: oliwantz@ulb.ac.be, Service de Métrologie Nucléaire Université Libre de Bruxelles CP 165/84 B-1050 Brussels, Belgium