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Criticality analysis of canned MOX fuel rods in the TN 7-2 cask

Maik Hennebach
DAHER NUCLEAR TECHNOLOGIES GmbH

Abstract

To assess the feasibility of using the TN 7-2 cask for the transport of MOX fuel rods from a prototype fast reactor, a criticality analysis has been conducted with Monte Carlo simulation calculations. The fuel rods are placed loosely within steel cans, which poses a unique challenge with regards to criticality safety due to the wide variety of possible configurations.

The basic design approach for the transport basket is a solid aluminum body with six separated drilled holes for loading the steel cans. A borated steel tube surrounds each position to decrease the neutronic coupling between the can inventories. The solid aluminum basket protects the inventory from the mechanical effects during all transport conditions.

The fuel rods have been stored for more than a decade, so the radiation and thermal source strengths are not problematic, and the welded steel cans in combination with the fuel rod cladding and the TN 7-2 cask provide ample protection against any release of radioactive material. Accordingly, criticality safety is a crucial part of the overall safety analysis.

A default approach to assess the criticality risk of loose fuel rods is to assume a regular hexagonal lattice and to determine the rod-to-rod pitch that defines the point of optimal moderation. In this case, however, this approach severely underestimates the potential of this inventory: by placing most of the fuel rods in a tight ring near the wall of the can and optimizing the lattice distance of the remaining rods in the center of the can, the effective neutron multiplication factor k_{eff} can be increased by about 10%.

To counteract this effect from extremely unfavorable fuel configurations, we capitalize on the fact that the cask is intended solely for transport and not for storage. This allows us to use moderator material like polyethylene to increase the neutron absorption in the borated steel walls and thereby decouple the seven cask positions from each other. The presentation will show the special design features of the basket which ensure safe subcriticality.

Introduction

The transport cask TN 7-2 provides a very effective way to transport MOX fuel rods from a prototype fast reactor. The fuel rods are placed loosely within steel cans, which poses a unique challenge with regards to criticality safety due to the wide variety of possible configurations. The fuel rods have been stored for more than a decade, so the radiation and thermal source strengths are not problematic, and the welded steel cans in combination with the fuel rod cladding and the TN 7-2 cask provide ample protection against any release of radioactive material. Accordingly, criticality safety is a crucial part of the overall safety analysis.

The outer body of the TN 7-2 cask consists of a steel structure with lead shielding and a thermal isolation layer. During transport, the top and bottom are protected by wooden shock absorbers. For criticality safety, the inner components are far more relevant: The basic design approach for the transport basket is a solid aluminum body with seven separated drilled holes for loading the steel cans. A borated steel tube surrounds each position to decrease the neutronic coupling between the can inventories. The solid aluminum basket protects the inventory from the mechanical effects during all transport conditions.

This paper will describe the approach for the criticality safety analysis, especially regarding the treatment of the possible configurations of the loose fuel rods, and the design optimizations of the transport basket that will ensure safe subcriticality.

Description of the calculation model

Criticality calculation code and cask model

The investigation of criticality safety is done with three-dimensional Monte Carlo simulation calculations, performed with the SCALE 6.1 code package [1]. Apart from the Monte Carlo module KENO VI, the module CENTRM is used to process neutron cross sections, which are derived from a 44 group library based on ENDF/B-V data and condensed for water moderated LWR fuel. Calculations were performed with 1000 generations of 1000 neutrons per generation, which decreases the statistical uncertainty to $\sigma < 0.001$ for all k_{eff} calculation results.

The TN 7-2 cask is modeled as a cylindrical container with inner and outer steel walls and the lead shielding in between (see **Figure 1**). The thermal insulation is neglected and replaced with void. Since the outer cask has no significant influence on the neutron multiplication factor k_{eff}, this rough geometrical model is sufficient. The transport basket is modeled as a solid aluminum block with tubular holes for the seven can positions. The borated steel tubes surrounding each position are modeled with a boron content of 1.5 wt.-% B_{nat}.

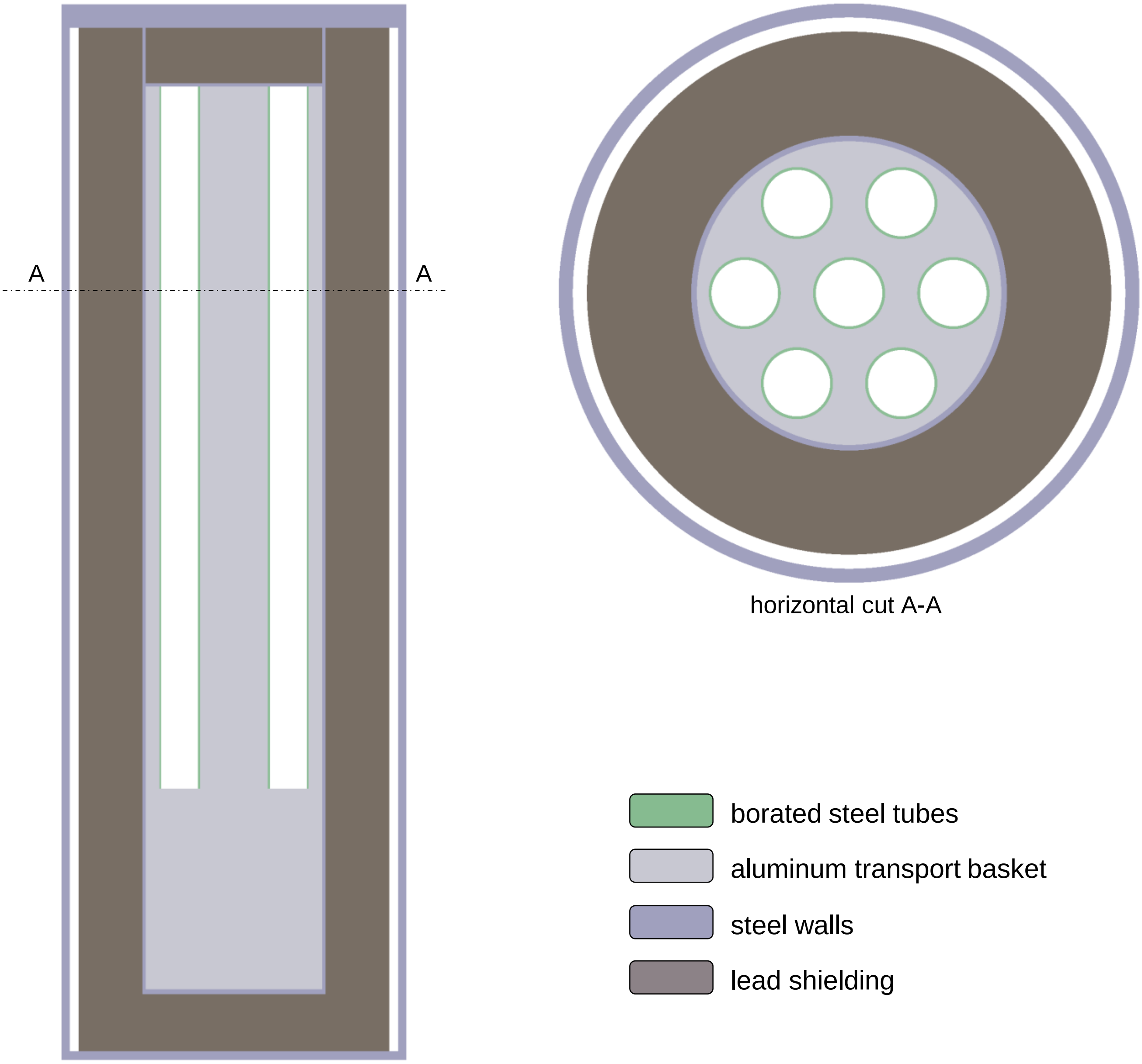


Figure 1 Calculation model for the TN 7-2 cask

Calculation model for the fuel rods within the cans

For the canned fuel rods, a maximal number of 111 fuel rods per can is assumed. The rods only fill a small part of the can cross section and can be moved around within the can by outside forces, for example vibrations or even a drop of the cask during transport. The cans are not represented in the calculation model. For the fuel rods, only the fuel of the fissile zone is taken into account, since most other details of the fuel rod geometry have no significant effects on k_{eff}. The cladding of the fuel rods is conservatively neglected. The fissile zone of the rods is assumed with a length of roughly 207 cm and a composition of 30% plutonium in a matrix of natural uranium. This reproduces all of the important characteristics of the fuel rods and the cans.

For the basic calculation model, a hexagonal lattice of the fuel rods is used (see **Figure 2**) for all seven positions in the transport basket. This kind of lattice is often used as the default approach for similar loose collections of fissile material. However, previous experience with a similar inventory in dual purpose (transport and storage) casks [2] shows that this approach severely underestimates the potential k_{eff} of this inventory. The derivation of a significantly more reactive configuration is described below.

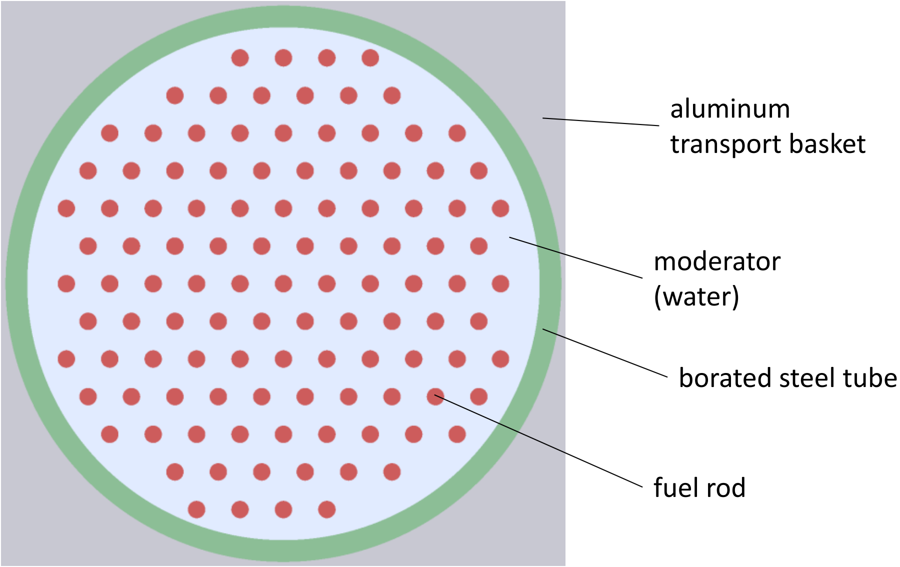


Figure 2 Cross section of the fuel rods within the transport basket position

Derivation of the most reactive configuration

Optimal moderation

Regarding the optimal moderation of this system, flooding of the fuel cans with water is considered. Comparing the result for seven flooded cans ($k_{eff} = 0.953$) with the result for a completely dry system ($k_{eff} = 0.308$) shows that the moderating effect of water in the vicinity of the fuel drastically increases the reactivity.

For the hexagonal fuel rod grid assumed in the basic calculation model, the spacing between the fuel rods is a pitch of 10 mm. As can be seen in **Figure 2**, the outer fuel rods are very close to the borated steel tubes with this pitch. The results in **Table 1** show that a closer placement of the fuel rods causes a strong decrease in k_{eff}. This indicates that the hexagonal grid is still undermoderated at maximal pitch.

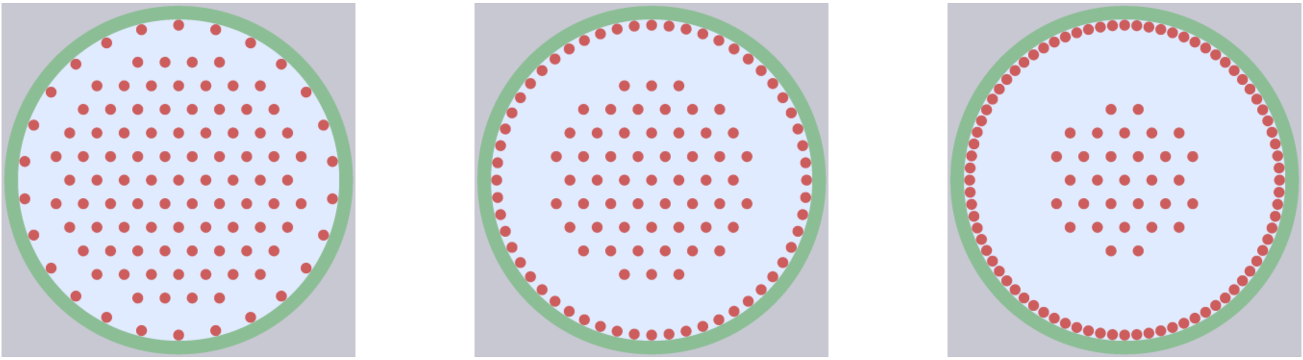
Table 1 Results for varied hexagonal lattice pitch

hex lattice pitch	k_{eff}
6 mm	0.6759
7 mm	0.7469
8 mm	0.8186
9 mm	0.8899
10 mm	0.9526

Ring/lattice configuration

Repositioning some of the fuel rods in a ring around the wall of the can allows a widening of the lattice for the remaining rods to achieve optimal moderation. Furthermore, a sufficiently tight fuel rod ring around the lattice rods also prevents moderated neutrons from leaving a can and thus decreases the chance of absorption in the borated tubes around each can. Fission neutrons originating within the fuel rod ring, however, do not cross a lot of moderating water on their way out of the can and so have good chances to get past the borated tubes to reach another can.

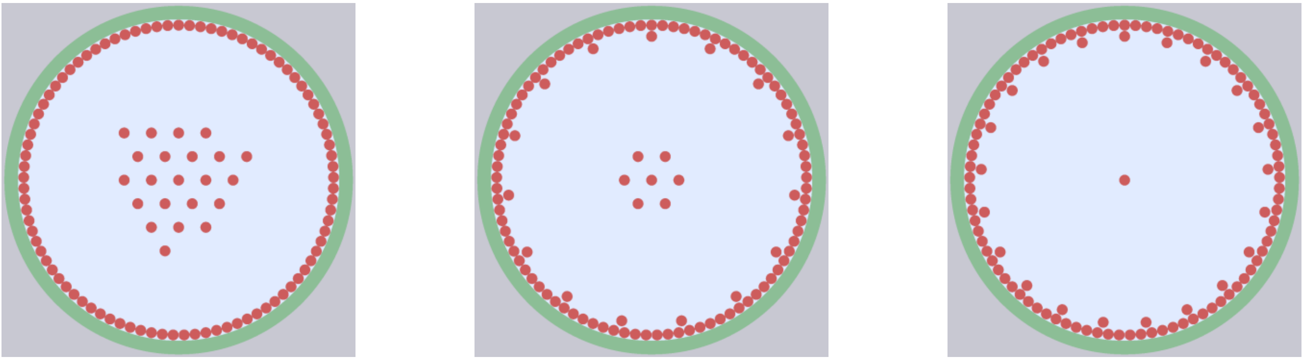
As the k_{eff} results for some configurations with varying numbers of ring and lattice fuel rods show (see **Figure 3**), this rearrangement causes a steep increase in k_{eff} even before the lattice is widened. The results also show that removing all rods from the lattice causes k_{eff} to drop again, so the system is still driven by the remaining lattice fuel rods. From the configurations that were studied, the distribution with 80 fuel rods in the outer ring and 31 fuel rods in the lattice is the most unfavorable one. The k_{eff} result for this configuration (k_{eff} = 1.041) is about 0.09 higher than for the basic calculation model.



26 ring rods
k_{eff} = 0.974

56 ring rods
k_{eff} = 1.024

80 ring rods
k_{eff} = 1.041



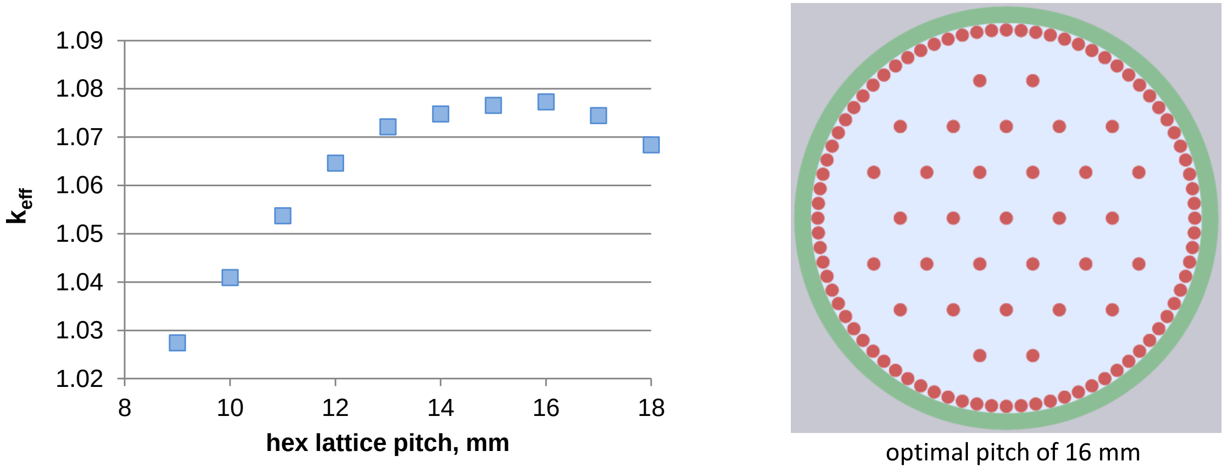
89 ring rods
k_{eff} = 1.039

89+15 ring rods
k_{eff} = 0.973

89+21 ring rods
k_{eff} = 0.895

Figure 3 Examples of ring/lattice configurations of the fuel rods

Widening the pitch of the rods remaining in the central lattice further increases k_{eff}, as the results plotted in Figure 4 show. The optimal moderation is reached for a pitch of 16 mm, increasing the k_{eff} result by 0.04 compared to the starting pitch of 10 mm.



optimal pitch of 16 mm

Figure 4 Ring/lattice pitch optimization with 80 fuel rods in the outer ring and 31 lattice rods

Reactivity of other configurations

For intact fuel rods, the configuration described above (80 fuel rods in the ring and a pitch of 16 mm for the remaining 31 lattice rods) is very likely to be the most reactive one. A tight rod cluster anywhere else than near the can wall would be undermoderated and would not prevent the escape and subsequent absorption of neutrons as effectively.

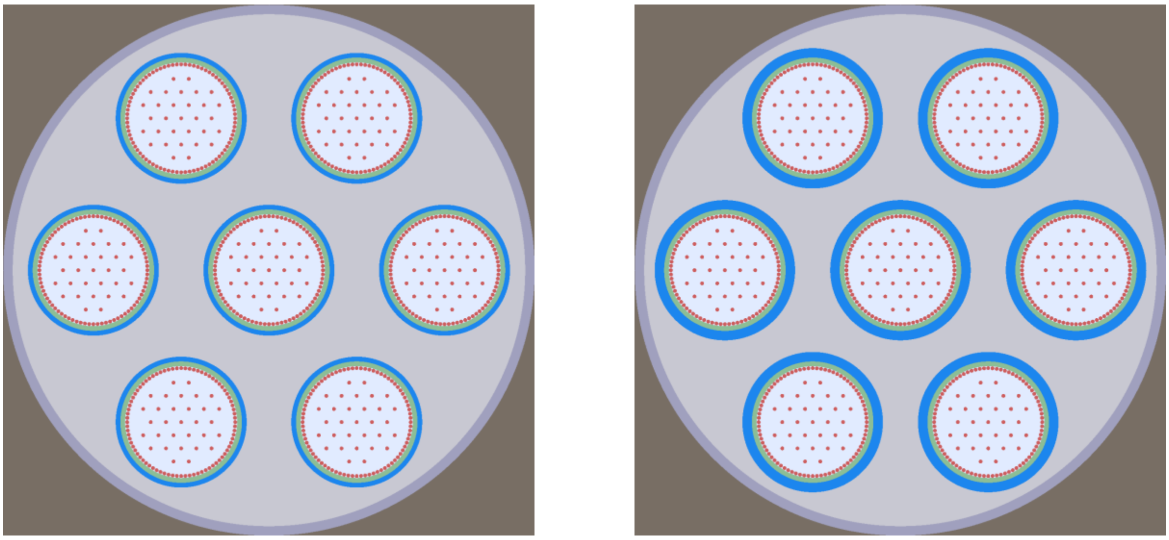
To gauge the possible effects of a hypothetical loss of cladding integrity, homogeneous mixtures of water and the fuel zone heavy metal of all rods within a can are examined. Structural material of the fuel rods and especially the non-enriched UO_2 of the breeder zones are neglected. Distributing this mixture over the whole can, corresponding to a hydrogen to fissile ratio of H/X = 71.4, results in the highest k_{eff} of 0.925 – both lower (when neglecting part of the fuel) and higher fuel concentrations (attained by not filling the whole can volume) lead to lower values for k_{eff}. This result is significantly lower than for the ring/lattice configuration.

Optimization of the transport basket

To ensure safe subcriticality even when taking the ring/lattice configuration into account, the only approach that does not involve conditioning of the fuel rods within the cans is to increase the neutronic decoupling of the basket positions. As described in [2], a newly developed highly borated aluminum material was used to achieve this in the dual purpose cask.

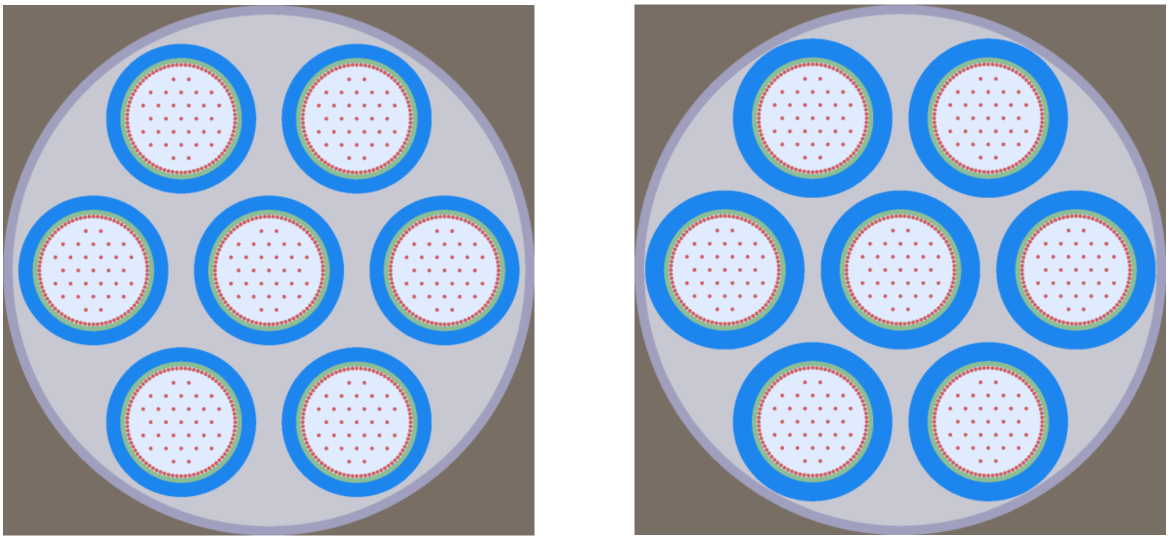
For the TN 7-2, we capitalize on the fact that the cask is intended solely for transport, and not for storage. This allows us to use moderator material like polyethylene (PE) to increase the neutron absorption in the borated steel walls, since the risk of a hydrogen build-up due to radiolysis is far smaller when the radioactive inventory only remains in the cask for a short time.

For the criticality assessment of this design optimization, we assume simple PE sheaths around the positions. As the calculation results given in **Figure 5** show, k_{eff} decreases to safely subcritical values for a thickness of these PE sheaths of 10 mm or greater.



5 mm PE • k_{eff} = 0.979

10 mm PE • k_{eff} = 0.878



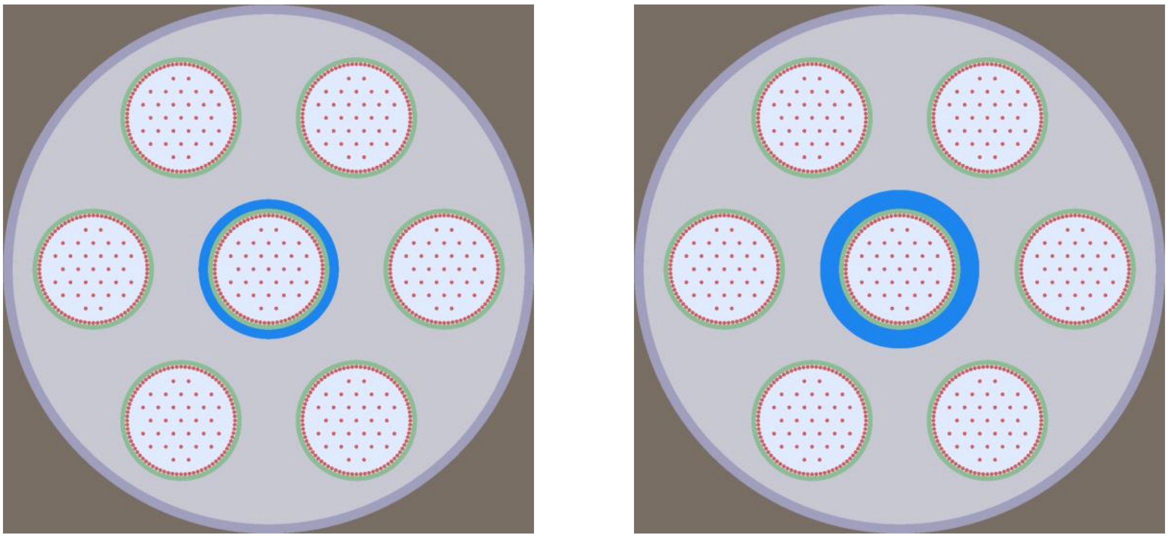
15 mm PE • k_{eff} = 0.796

20 mm PE • k_{eff} = 0.734

Figure 5 PE sheaths with varying thickness around all basket positions

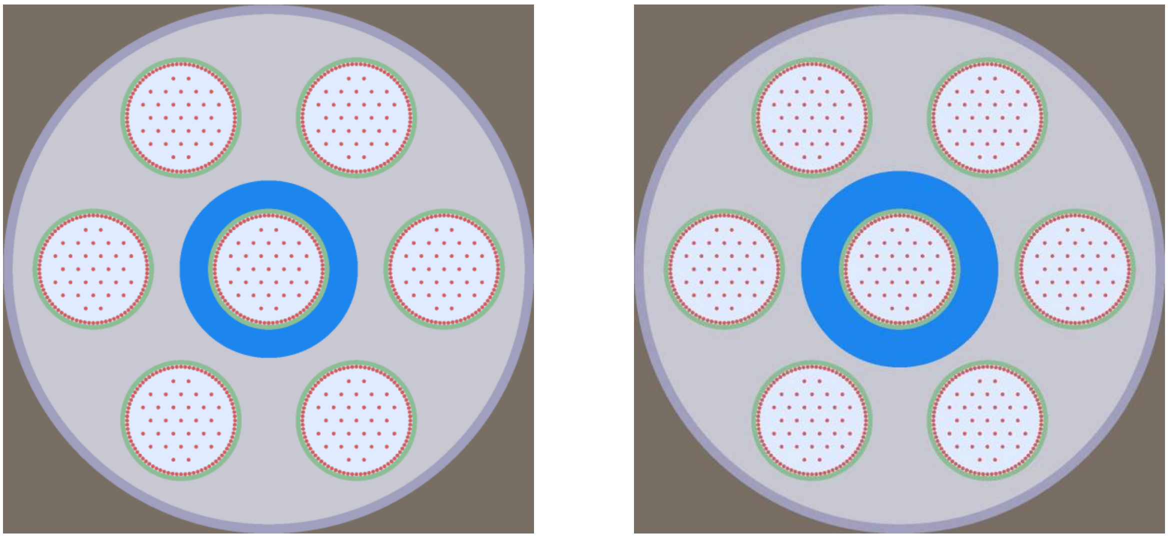
This basket design would be sufficient regarding safe subcriticality, but using a PE sheath for all seven positions is a somewhat inelegant solution regarding construction and assembly of the basket. To further optimize the design, we concentrate on the central basket position, which is adjacent to all other positions and will therefore be crucial regarding the k_{eff} of the whole system.

This is clearly demonstrated by calculation models where only the central position is equipped with a PE sheath: even though there is no modification of the outer six basket positions, a PE thickness of at least 30 mm for the central position is sufficient to achieve safe subcriticality (see **Figure 6**).



10 mm PE • k_{eff} = 1.034

20 mm PE • k_{eff} = 0.985



30 mm PE • k_{eff} = 0.947

40 mm PE • k_{eff} = 0.912

Figure 6 PE sheaths with varying thickness around the center position

Conclusions

Our criticality assessment of the transport cask TN 7-2 with an inventory of MOX fuel rods placed loosely within steel cans has two main results:

- the default approach of assuming a regular hexagonal fuel rod lattice significantly underestimates the potential k_{eff} of arrangements of loose fuel rods
- the increase in k_{eff} from taking the most reactive ring/lattice fuel rod configuration into account can be counteracted by the use of a PE sheath of at least 30 mm thickness around the central basket position

With this feasibility study, using state of the art methods and a thorough investigation of possible fuel rod configurations, DAHER NT has demonstrated that safe subcriticality can be ensured when using the TN 7-2 cask for the transport of MOX fuel rods loosely arranged in steel cans.

References

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