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Exclusion of Criticality for a Final Repository in a Saline Host Rock based on the Neutron Absorbing Properties of ^{35}Cl

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Outline

- Introduction and background
- Methods and assumptions
- Calculation results
  - Intact cask models
  - Exemplary long term degradation cases (selection)
  - Research- and prototype reactor fuels
- Code validation issues
- Summary and conclusions

Introduction and Background

- Studies in the context of the **"Preliminary Safety Analysis of the Gorleben Site"**
  - Proposed repository in a stable, deep geological **salt dome**
  - Existing pilot mine within a large, in other respects unworked salt formation
  - Depth of proposed emplacement area about 850 m below ground level
  - Emplacement area mainly consists of solid **Magnesium Chloride $MgCl_2$**
  - Disposal cask concepts BSK-3 and POLLUX-10
  - Concept study for the feasibility of direct disposal of transport/storage casks ("DIREGT" concept)

- German *"Safety Requirements Governing the Final Disposal of Heat–Generating Radioactive Waste"* stipulate **Exclusion of Criticality** for the whole reference period of one million years

Remark: The salt dome at Gorleben in Lower Saxony, Germany, was the primarily investigated repository site since the 1970s, until the federal *Repository Site Selection Act* („Standortauswahlgesetz, StandAG") entered into force end of Juli 2013, in order to restart a country-wide, consensual and open-ended site search without preselection.

Methods and Assumptions

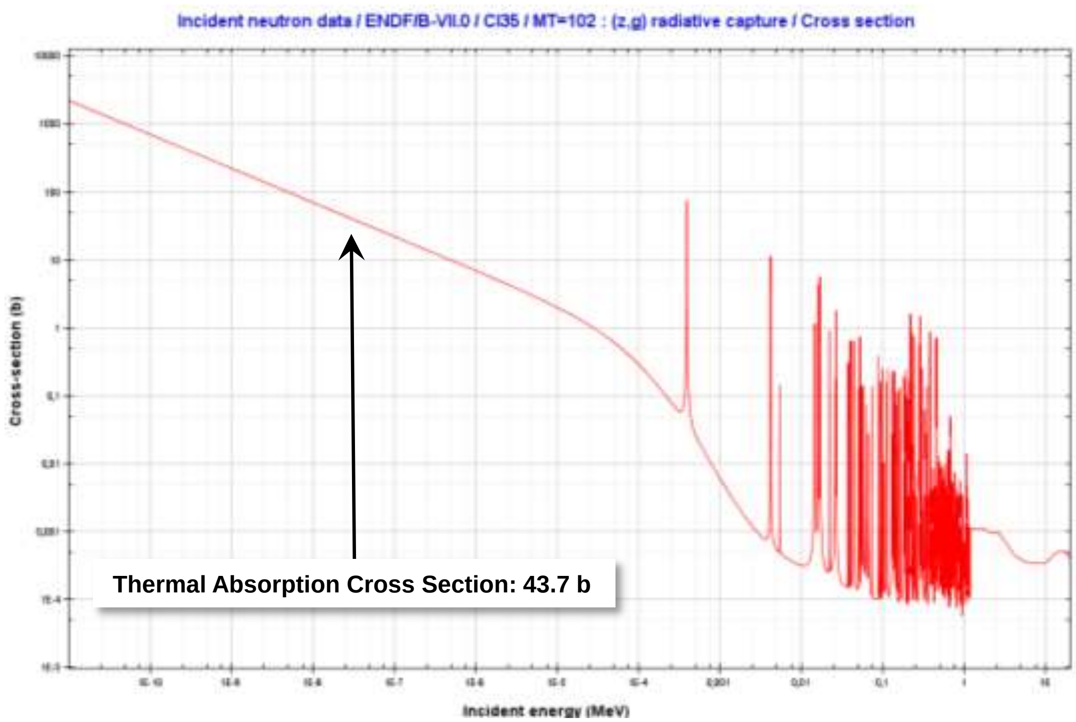
- **Calculation Methods**
  - Generic cask models
  - PWR UO_2 fuel 4,0%, fresh fuel assumption (no burn-up credit)
  - Different research and prototype reactor fuels

- **Deterministic Analysis**
  - **Intrusion of brine** is considered very unlikely, hence **postulated**
  - As a consequence, also **degradation cases** are **postulated**
  - No assessment of point in time or probability of occurrence
  - Analyses based on the inventory of a single cask, respectively
  - No accumulation of inventories of multiple casks assumed

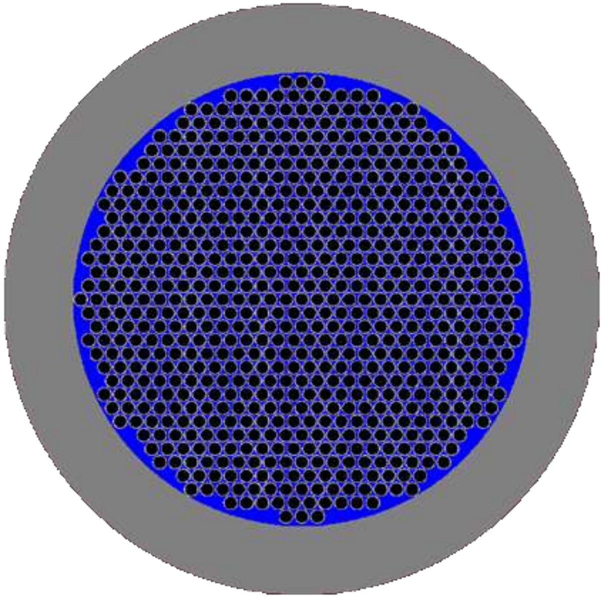
- **Applied Calculation Tools**
  - KENO VI from SCALE 6.0
  - MCNP5 Version 1.51
  - ENDF/B-VII cross sections as supplied with the codes

Relevant Properties of ^{35}Cl and Saturated Brine

- Any solution possibly intruding the emplacement area within the large salt dome can be credibly assumed as **saturated brine**, based on the host rock composition
- Properties of ^{35}Cl
  - Thermal absorption cross section **43.7 barn**
  - Natural abundance 75.76 %
- Representative solution sample from the Gorleben salt dome as basis for "saturated brine"
  - $MgCl_2$ concentration 466 g per liter, comprising 356 g Cl per liter, or **270 g ^{35}Cl per liter**
  - Brine density 1.345 g per liter

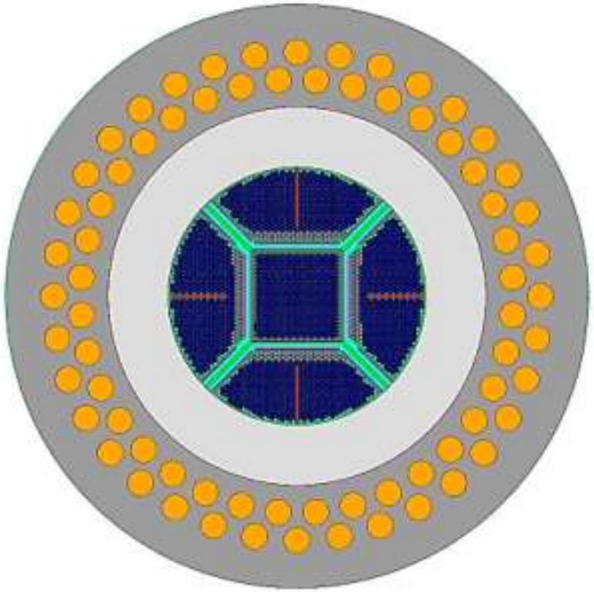


Cask Models under Scope (cross section views, not to scale)



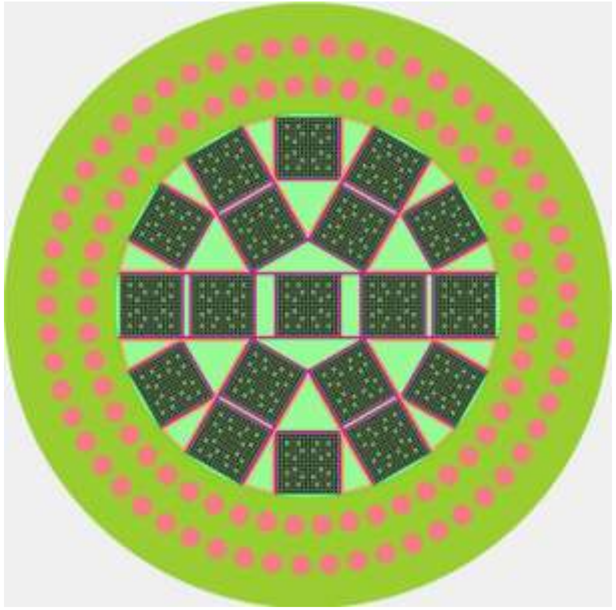
BSK-3

(comprises compacted fuel rods from three PWR assemblies)



POLLUX-10

(comprises compacted fuel rods from ten PWR assemblies)



DBB19

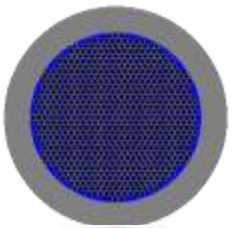
(generic, CASTOR®-based cask model; comprises complete PWR assemblies)

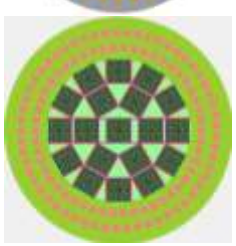
Consecutive Degradation Cases under Scope

- The following **postulated degradation cases** are investigated
  - **Ingress of water/brine** to the emplacement area, providing
    - Moderator
    - Corrosive agent
  - **Flooding of** in other respects intact **casks** (reference case)
  - **Loss of implemented neutron absorbers** due to chemical reactions with the brine (only applicable for DBB19 model)
  - Loss of internal basket structures and **collapse of fuel structures** due to corrosive reactions (especially pronounced for DBB19 model)
  - Degradation of uranium dioxide due to chemical processes and **formation of non-stochiometric uranium-based mineral phases** (relevant for all cask models)

- **No claim for completeness** is made!

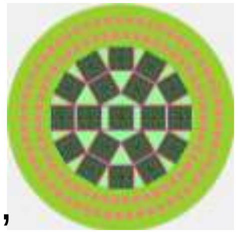
Results: Intact but flooded PWR Fuel Casks





	k ± σ Reference Case subcritical by design	k ± σ Reduced k_{eff} due to ^{35}Cl
Moderator	Pure Water	Saturated Brine
BSK–3	0,77492 ± 0,00054	0,66680 ± 0,00047
POLLUX–10	0,71177 ± 0,00019	0,62997 ± 0,00017
DBB19	0,92742 ± 0,00014	0,56452 ± 0,00010

Exemplary Degradation Cases (1): DBB19, Postulated Loss of Fixed Boron



- **Loss of implemented fixed boron** due to chemical processes after flooding of the cask interior with brine assumed
- Model: Boron removed from in-cask borated stainless steel components, the remainder being unchanged

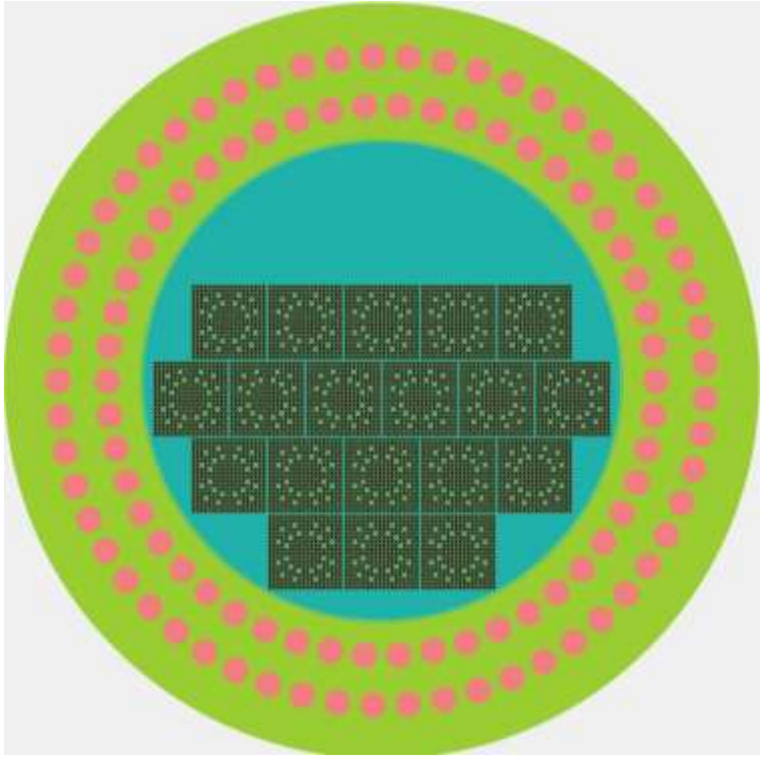
Moderator	$k_{eff} \pm \sigma$
Pure Water	1,04386 ± 0,00025
Saturated Brine	0,63139 ± 0,00016

- Model essentially **subcritical when taking into account ^{35}Cl**

- Note: This degradation case does not apply for BSK-3 and POLLUX-10 casks, as they do not rely on implemented neutron absorbers

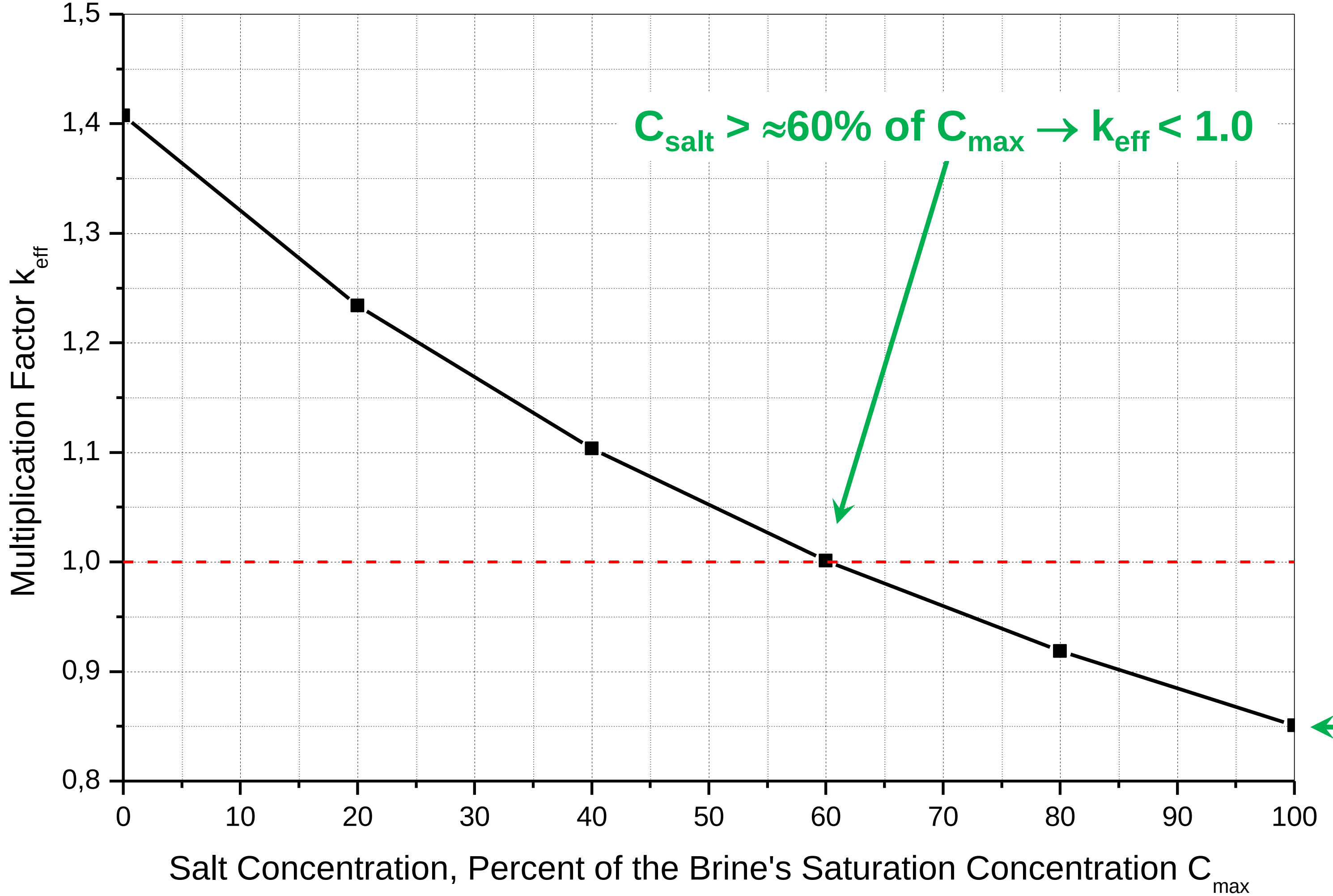
Exemplary Degradation Cases (2): Degradation of DBB19 Basket Structure

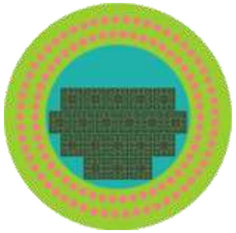
- After loss of boron, consecutive **collapse of basket structures** assumed
- Conservative assumption of regulary fuel assembly configuration



DBB19 calculation model comprising degraded basket structure

Exemplary Degradation Cases (2): Degradation of DBB19 Basket Structure – Parameter Study





Exemplary Degradation Cases (3): Formation of Mineral Phases inside POLLUX-10 Cask

- **POLLUX-10**
  - Long term: interior cask structure fully degraded (removed from the model)
  - UO_2 degraded to U_3O_8, porously filling inner cask volume
  - Residual pore volume filled with moderator, homogenized

Moderator	$k_{eff} \pm \sigma$
Pure Water	1,25774 ± 0,00031
Saturated Brine	0,83166 ± 0,00024

- Model essentially **subcritical when taking into account ^{35}Cl**

Research and Prototype Reactor Fuels

- Recent and legacy fuels from **research and prototype reactors**
  - Currently stored, not foreseen for further use; probably cannot be repatriated
  - Mainly small amounts of
    - Uranium-based fuels from 20% up to 93% enrichment
    - Fuels based on mixtures of HEU and Plutonium (e.g. breeder driver fuels)
    - Fuels bearing Plutonium, Thorium and ^{233}U
    - Others

- **No dedicated disposal concept** exists up to now
  - Feasibility of direct disposal of the respective storage casks is investigated

- For the fuels of highest reactivity, also with regard for ^{35}Cl criticality cannot be excluded by simple assessment, based on the inventory of a single cask
  - **Further conditioning measures** may become necessary

Code Validation and Qualification Issues

- **No evaluated criticality benchmark experiments** available which significantly involve ^{35}Cl
  - Currently, no such experiments are planned worldwide
  - A few polyvinyl chloride bearing experiments with insignificant reactivity contribution of ^{35}Cl are published; benefits are limited
  - First investigations on potential experimental configurations probably being useful have started, probably to be discussed in the future

- Thus at the moment, appropriate **code validation remains a major challenge**

- To mitigate this situation it can be useful to apply
  - Sophisticated **sensitivity and uncertainty analysis tools** in order to gain deeper understanding of the negative reactivity contribution of ^{35}Cl in the systems under scope
    - TSUNAMI (ORNL), neutron induced reaction cross sections
    - XSUSA, SUnCISTT (GRS), neutron induced reaction cross sections; technical parameters
  - **Sufficiently large safety margins**
    - Max. calculated k_{eff} including saturated brine is about 0.85 (LWR fuel) in this study

Summary and Conclusions

- Work has been conducted in the context of **"Preliminary Safety Analysis of the Gorleben Site"** in Germany, comprising a deep geological salt dome

- Criticality in the post-closure phase of a repository is excluded without intrusion of moderator; hence i**ntrusion of brine** was **postulated** → deterministic approach

- **Exclusion of criticality** for single casks loaded with PWR fuel without burn-up credit is **feasible** in case of full regard for **neutron absorbing properties of ^{35}Cl**
  - Exclusion of criticality […] **without regard for ^{35}Cl not feasible** for all types of casks and degradation cases
  - Further analyses involving **BWR and MOX fuels** (not presented here) yield similar results

- Exclusion of criticality for **research and prototype reactor fuels** more demanding, probably requiring further conditioning

- **Code validation** remains an issue; proper code validation requires additional evaluated benchmark experiments; conceivable alternatives are under investigation

Thank you very much for your attention!

Any questions?