Criticality effects of long term changes in materials and geometry in a damaged disposal canister.

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The Swedish back-end system



④ Possible alternative for very low-level decommissioning waste. A decision has not yet been made on this.

Background



- In March 2011 SKB applied for permit to build a final repository for spent fuel in Forsmark and an encapsulation plant (Clink) in Oskarshamn.
- This application have been reviewed by the Swedish radiation authority (SSM) and as we speak, hearing in the environmental court is ongoing.
- The application included a criticality safety analysis for the final repository for spent fuel. After review comments from SSM the criticality safety analysis have been revised/redone.
- SSM consider it good enough for this stage of the project but have pointed out a few improvement suggestions, which we will address in the future PSAR for the final repository.

SKB

Background - Reactivity evolution during the first million years



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Assumptions/results in the criticality analysis



- The criticality analysis assumed water filled canister but intact geometry within the canister.
- The analysis used BUC for PWR and Burnable Absorber Credit for BWR.
- Cooling time of 1 year assumed in all calculations.
- For 5 % U-235 enriched PWR fuel a burnup of 34 MWd/kgU is needed to meet the 0.95 criteria.
- For BWR it was shown that 3.2 % U-235 enriched fuel can be stored with sufficient margins. For an enrichment of 5 % U-235 14 Gd-rods with 5.5 % Gd is required.

Initial state





Canister evolution analysis



- The scenarios leading to water filled canister after a copper shell breach are those of SR-Site:
 - Canister failure due to corrosion (preceded by bentonite erosion)
 - Canister failure due to shear load (large earthquake in vicinity).

Choice of scenarios



After water contact, all materials start to corrode with their specific corrosion rates. However for several parameters and properties there are no data in the literature or they are difficult to evaluate because of the large time span.

Three possible strategies to deal with this are:

- 1. Assume the most pessimistic evolution of the repository, independent of likelihood.
- 2. Analyze all possible combinations of corrosion rates within a given interval for each material.
- 3. Evaluate the most probable evolution of the system, using realistic corrosion rates for all the components. Analyze less probable system evolutions, if they seems not entirely unrealistic and they result in increased reactivity.

Main evolution scenario – Corrosion of cast iron insert



- Cast iron have the highest corrosion rate of the materials in the canister.
- Corrosion of carbon steel and cast iron will form magnetite. Base case 1 μm/year, interval 0.1 μm-10μm, based on relevant experimental and archaeological data.

 $3Fe(s) + 4 H_2O = Fe_3O_4 + 4 H_2$

• The general assumption here was that the magnetite formed e.g. between cast iron and copper will extrude in the free space of the canister instead of causing its deformation.

Properties of magnetite



- Hydrated magnetite was analyzed with various water content (0-30%) and different densities (5.17-2.3 g/cm3)
- Magnetite is the most probable corrosion product, but siderite (Fe(II)carbonate) and iron sulfides cannot be excluded. Mackinawite (Fe_{1-x}S) assume to form initially during sulfide corrosion.

Cross sections of BWR and PWR canisters when the gap is filled with magnetite.





Situation ~ 9000 years after breach, 9 mm steel corroded to give a ~19 mm thick magnetite layer. Shorter times and thicker corrosion product layers for hydrated magnetite. Reactivity increase higher with siderite

All free volume in the container filled with magnetite





Situation after ~13 500 years (left) or 19 500 years (right), all free volume in the canister filled with crystalline magnetite-shorter times for hydrated magnetite

Completely corroded insert.





Corrosion of zircalloy, stainless steel and spent fuel.



- Under repository conditions, only passive corrosion of Zircaloy expected, i.e. very low corrosion rates.
- Possibility of ZrO₂(s) corrosion layer thickness decrease or its absence ruled out.
- Stainless steel and Inconel assumed to corrode 1 to two orders of magnitude slower than carbon steel. Grid spacers may corrode before filling of the space between fuel rods with magnetite, but not top and bottom plate.
- Corrosion of spent fuel assumed to occur with 10⁻⁷/y, corresponding to ~3 kg U dissolved during the ~15 000 years needed to fill all free space in the canister with iron corrosion products. Uranium assumed to be deposited on the magnetite layer, causing reactivity increase.
- The influence of dissolved hydrogen in the groundwater, as well as that of the carbon content in the carbon steel or cast iron also accounted for.

Criticality calculations



- Criticality calculations were performed using Scale 5.1 with the Scale 44-group ENDF/B-V library (SCALE 2006). Comparisons have been made with Scale 6.1 and Scale 6.2 with ENDF/B-VII. The results deviates slightly but doesn't effect the conclusions.
- Most reactive fuel types in the Swedish system are used:
 - PWR: W15x15UPGRADE, BWR: SVEA 96 Optima 3
- In the calculations 5 % U-235 enrichment is assumed for PWR.
- For BWR 3.2 % enrichment is used which corresponds to 5 % U-235 with 14 BArods with 5.5 % Gd2O3.

Nominal cases



- Dry canister
 - PWR: keff = 0.2900
 - BWR: keff = 0.2322
- Water filled canister
 - PWR: keff = 1.0993, keff is less than <0.95 if the average fuel assembly burnup is higher than 34 MWd/kgU
 - BWR: keff = 0.9142

Influence of Magnetite



	Insert material	
Fuel type	Cast iron	Magnetite
PWR	1.0993	1.1039
BWR	0.9142	0.9266



BWR - Influence of gap size on k_{eff}







PWR - Influence of gap size on k_{eff}



Influence of magnetite water content on k_{eff}



Other evolutions leading to higher reactivity



- Moving of part length rods in an unfavorable direction.
- Hydrogen dissolved in groundwater.
- Fuel material is uniformly distributed on the inner surface of the magnetite layer. The fuel pellet diameter has been reduced corresponding to the lost amount of fuel material. In this case, only uranium and plutonium are assumed to be deposited on the surface of the magnetite.
- Faster corrosion of BA-rods consider not likely.

Other evolutions – leading to lower reactivity



- The magnetite layer is assumed stiff, i.e. it grows resulting in that the fuel rods are pushed closer to each other.
- In the PWR case the magnetite layer will fall down at the bottom of the fuel channel into the fuel assembly. The space between fuel rods in the bottom part of the fuel assembly will be filled by magnetite and the top part will be surrounded by a larger water gap.
- In the BWR case box walls will prevent the magnetite to fall into the fuel assembly, so only the magnetite above the box will fall into the fuel assembly.
- Fuel pellets fall down in the bottom of the fuel channel.

Future considerations



- Pure water used conservatively in all calculations instead of groundwater. Can we take credit for salt?
- Long term stability of BA.
- Long term stability of FP.

Conclusion



- In the next criticality safety analysis for the final repository SKB will take long material and geometry changes inside the canister into account.
- The main process is the formation of magnetite from cast iron which will increase the reactivity through closing the gap between the fuel and the insert.