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Regulatory Issues for Final Disposal

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Overview and Introduction

- **DIN working committee NA 062-07-045 AA ("Criticality Safety") of the German Institute of Standardization (DIN = "Deutsches Institut für Normung") has worked out a Draft Criticality Safety Standard entitled "Criticality safety of disposition of nuclear fuel to be discarded".**
- **Draft is still under internal discussion and review.**
- **Publication expected end of next year**

- **Risk-informed approach for both pre-closure and post-closure phase → rationales**
- **Requirements for BUC**

Introduction

Nuclear fuels to be discarded (Germany):

- **LWR fuels (unirradiated and irradiated): Western UOX and MOX fuel designs, UOX VVER**
- **FBR (Fast Breeding Reactor) fuels**
- **HTR (High Temperature Reactor) and Thorium-HTR fuels**
- **RR (Research Reactor) and MTR (Material Test Reactor) fuels (HEU)**
- **other types …**

? Time periods to be analyzed (w.r.t. criticality/criticality safety) ?

Disposal of fissile materials: Time period issues

Pre-closure phase (Mining and loading without any observation phase afterwards) :

- Disposition in salt (e.g., Gorleben salt diapir): Approx. 40 years (for loading)
- Disposition in clay: More than 100 years (for loading) (due to required miner's activities)

! Criticality safety standard for operating a repository required !

Post-closure phase:

Time period to be analyzed: 10 000 years ? 1 000 000 years? …any other fixed period?

Remember some simple facts:

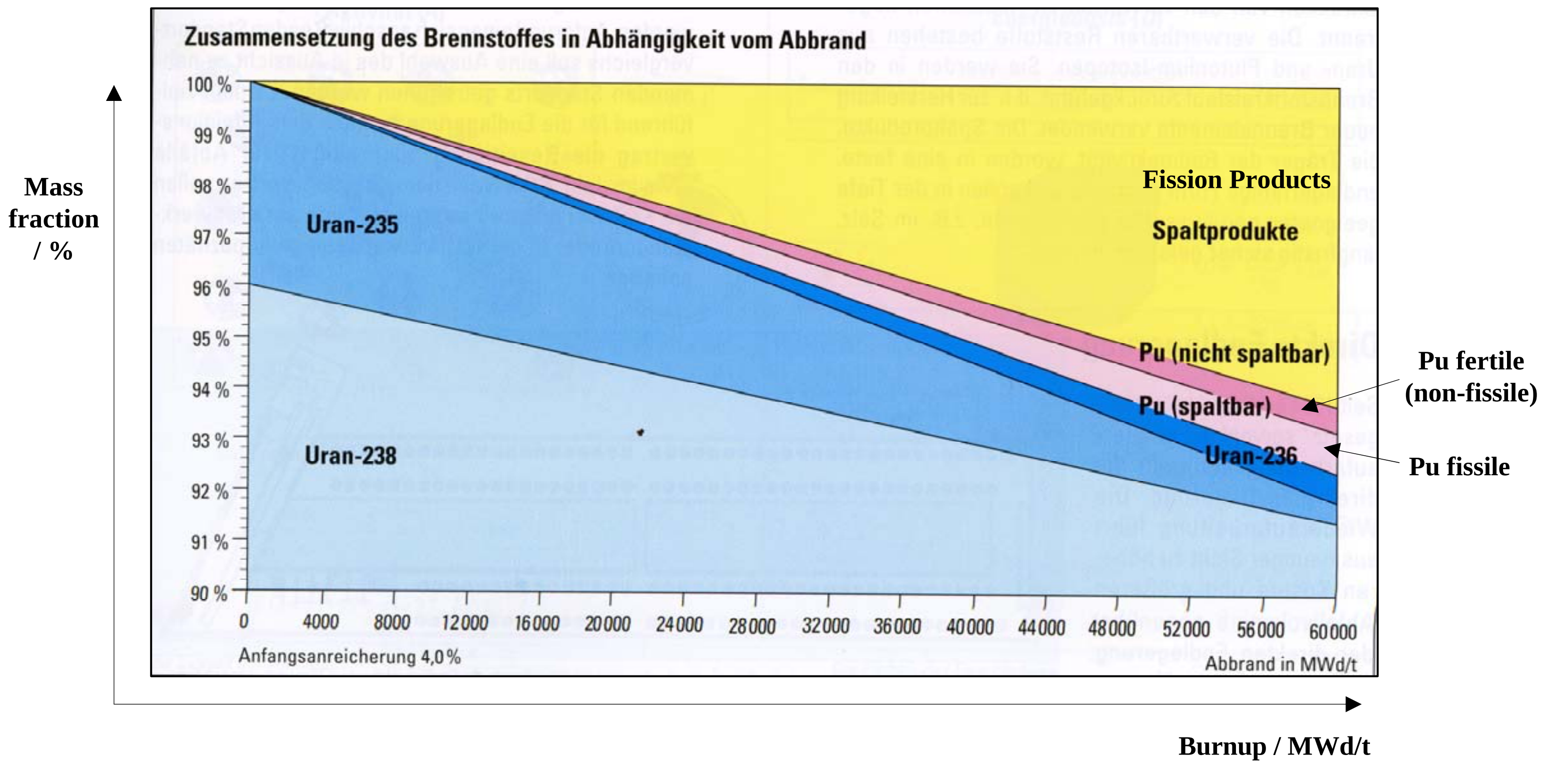
- Burn-up and build-up of fissile nuclides
- Radioactive decay properties: Half-life values, branching ratios,…

Disposal of fissile materials: Time period issues

Remember some simple facts:

- **Build-up of actinides**

Example: Change in isotopic composition of Convoy Series UOX Fuel with 4.0 wt.-% initial enrichment (18x18-24 fuel assemblies, NPP Neckarwestheim II)



Disposal of fissile materials: Time period issues

Remember some simple facts:

- **Radioactive decay properties**

$$Pu-239 \xrightarrow{2.411\cdot10^4\,a} U-235 \xrightarrow{7.038\cdot10^8\,a} Th-131 \xrightarrow{25.5h} \cdots$$

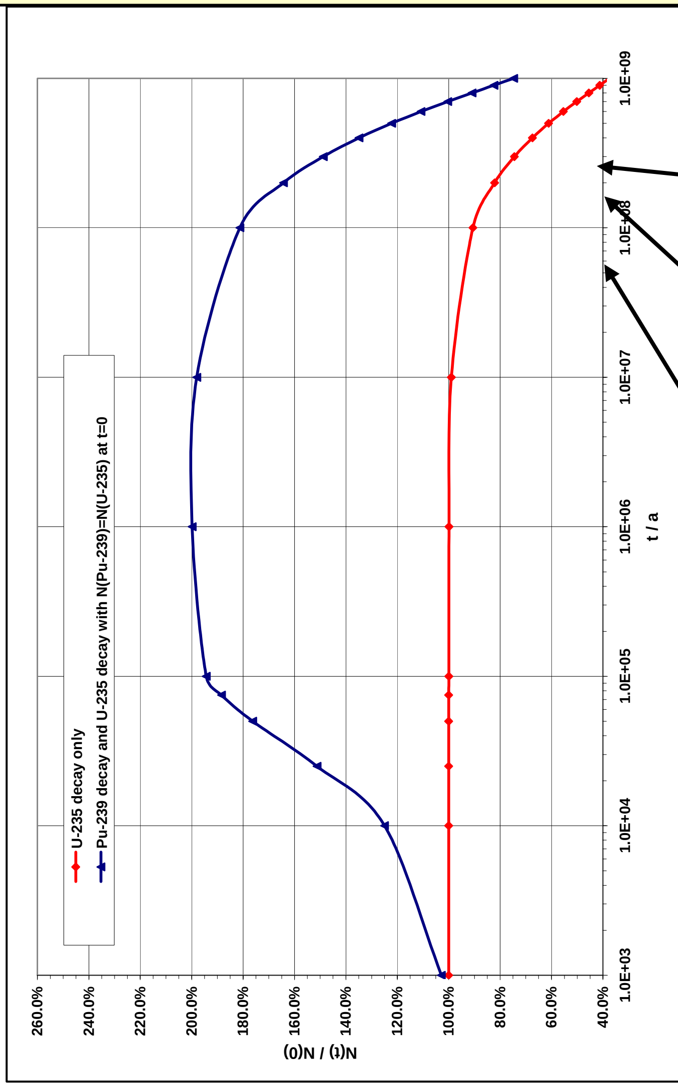
$$Pu-241 \xrightarrow{14.35a} Am-241 \xrightarrow{432.2a} Np-237 \xrightarrow{2.144\cdot10^6\,a} Pa-233 \xrightarrow{27.0d} U-233 \xrightarrow{1.592\cdot10^5\,a} \cdots$$

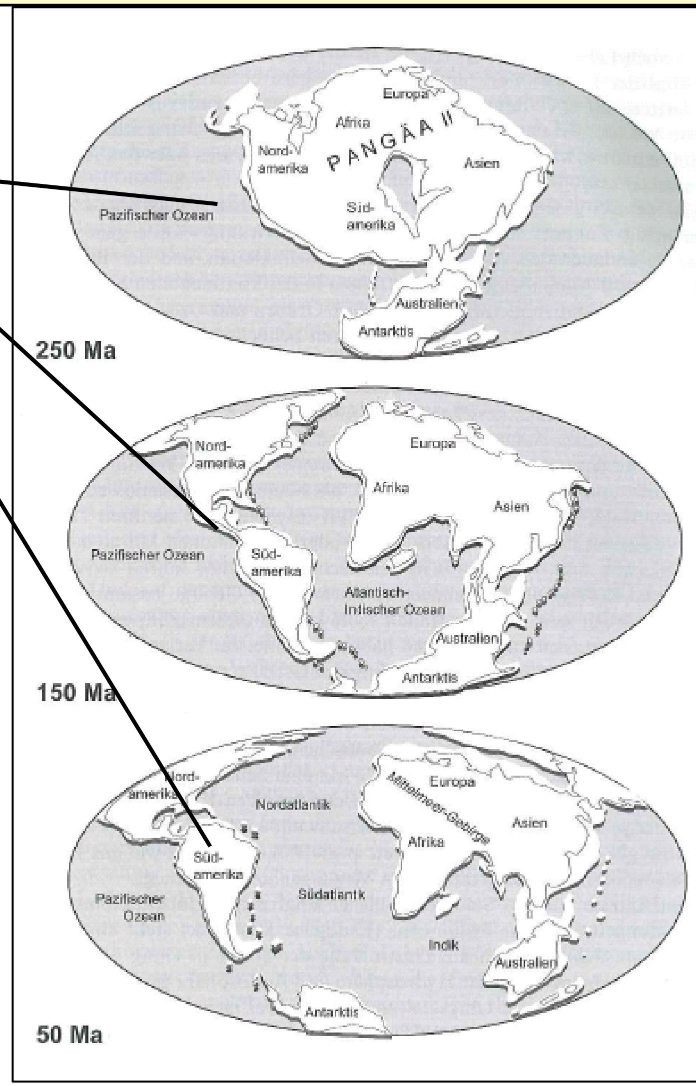
$$Pu-240 \xrightarrow{6563a} U-236 \xrightarrow{2.342\cdot10^7\,a} \cdots$$

$$Pu-242 \xrightarrow{3.75\cdot10^5\,a} U-238 \xrightarrow{4.468\cdot10^9\,a} \cdots$$

Disposal of fissile materials: Time period issues

Disposal of U-235 (e.g., HEU from RR or MTR) and U-235+Pu-239 (e.g., spent LWR fuel)

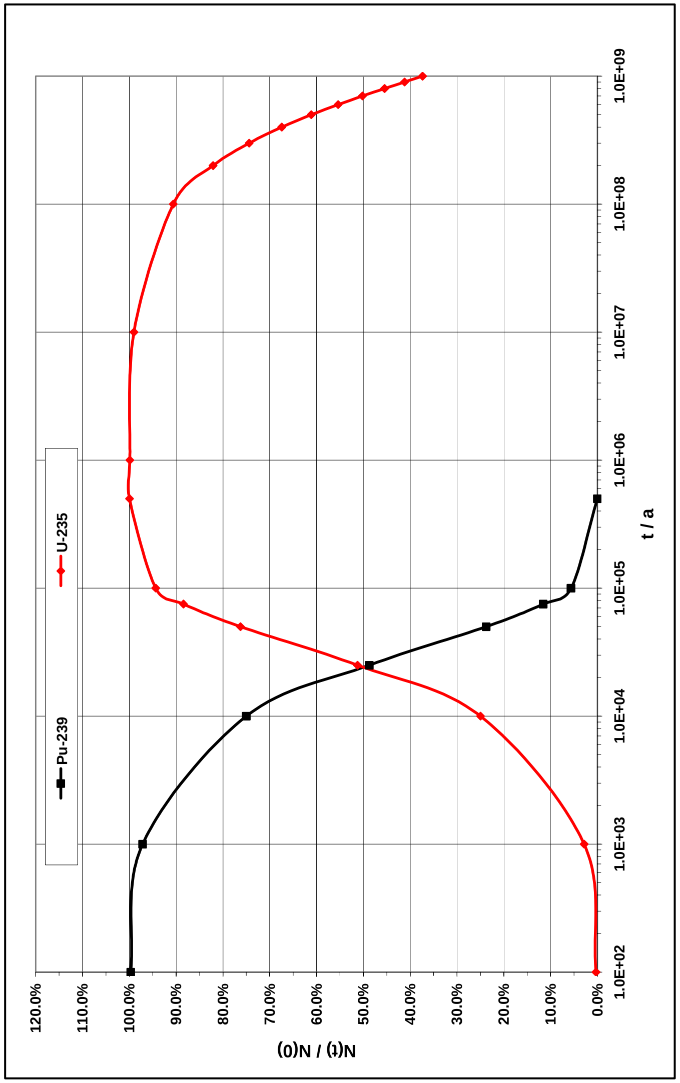


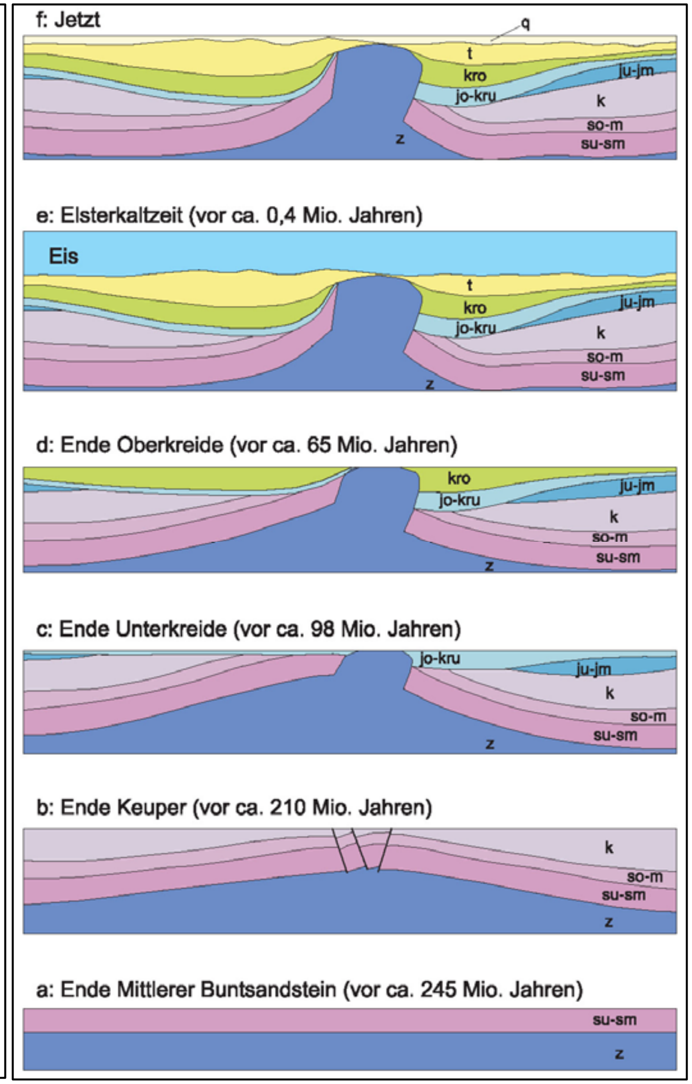


Models of future worlds (due to continental plate drifts) (www.scotese.com)

Disposal of fissile materials: Time period issues

Disposal of Pu-239



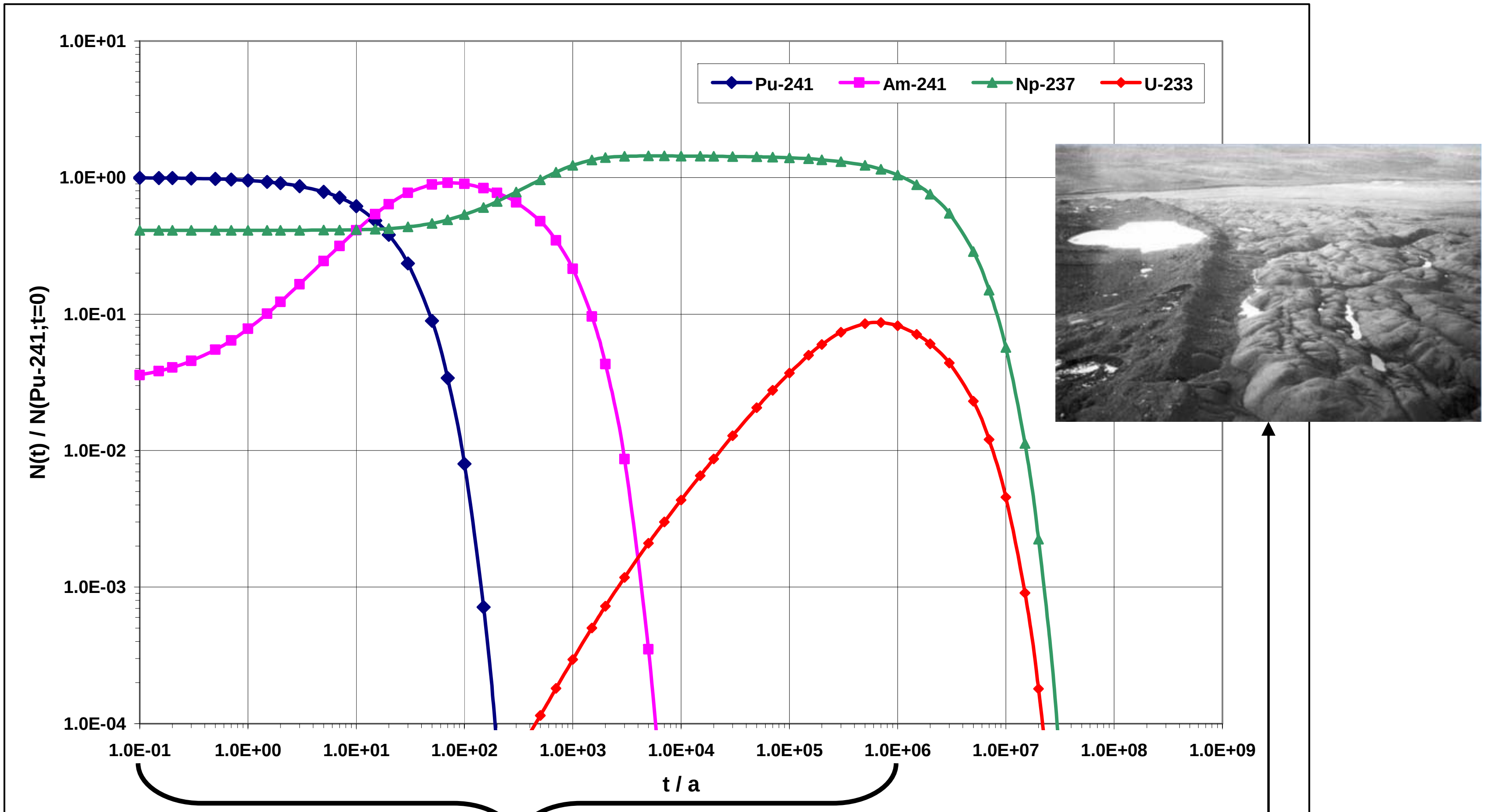


Before 250 Million years → Evolution of the Gorleben salt diapir → today (BGR Hannover, Germany)

Disposal of fissile materials: Time period issues

Example for U-233 production:

17x17-25 Fuel Assembly, e=4.-wt.-% U-235, B=50 MWd/kg U (no CR insertion during depletion, no outages)

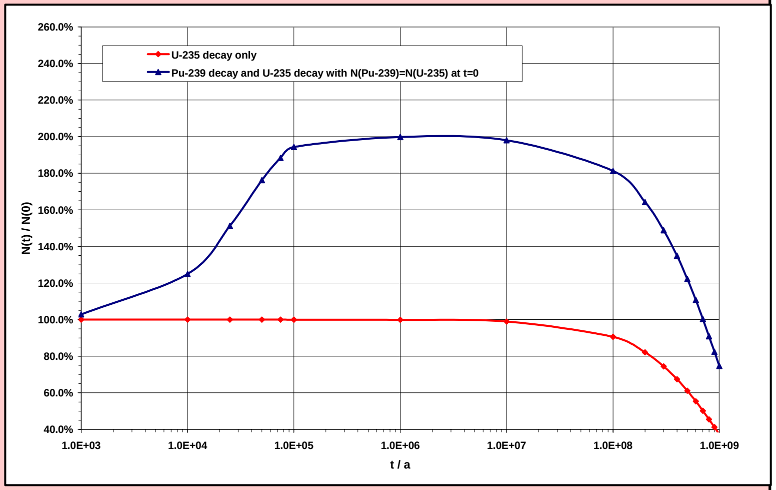


approx. 10 glacial epochs to be expected (Milankovitch)

Disposal of fissile materials: Time period issues

Conclusion: Time period to be analyzed w.r.t. criticality / criticality safety:

- **Depends of the isotopic inventory of the fuel storage units:**
  - ☞ U-235 content per unit,
  - ☞ accumulation of U-235 through Pu-239 decay,
  - ☞ admixture of neutron absorbing nuclides



- **Different for different fuel storage units, therefore**
- **Is impacted by the evolution of the storage units (← tectonics, climate, …)**
  - ☞ corrosion/degradation of structural materials and barriers
  - ☞ intrusion of water
  - ☞ separation of actinides and fission products
  - ☞ migration of materials from the storage units, accumulation in near-fields or the far-field of the disposal
- **Depends of the site of the disposal (i.e., salt, clay or granite)**

↕

? Exclusion of criticality events possible ?

↕

? Criterion ?

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Disposal of fissile materials: Criticality safety acceptance criterion

Basic criticality safety principle: Single Failure Criterion (SFC)

- **Single failure must not result in a criticality event**

SFC generally valid for all fuel management system outside reactor cores

In case of non-compliance with the SFC: **DIN25403-1**

- **Consideration of the probability and the consequences of a criticality event**

Compliance with the SCF is achieved by applying safety measures:

- **Passive measures**
- **Active engineered measures automatically initiated**
- **Active engineered measures manually brought into action**
- **Administrative measures**

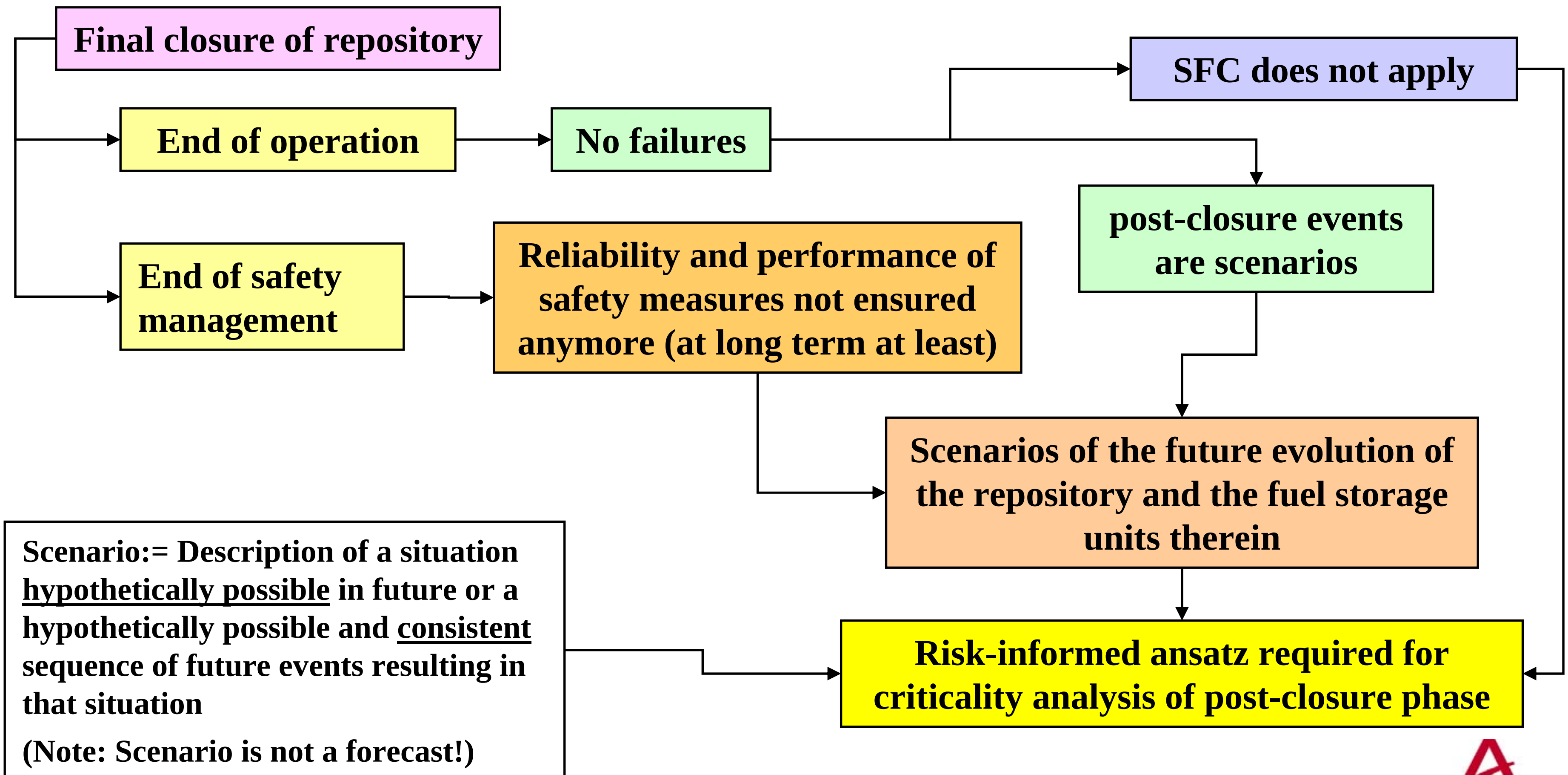
↑

Reliability and performance of safety measures

- **ensured by a safety managment system establishing controls and checks of parameters important for ensuring criticality safety**

Disposal of fissile materials: Criticality safety acceptance criterion

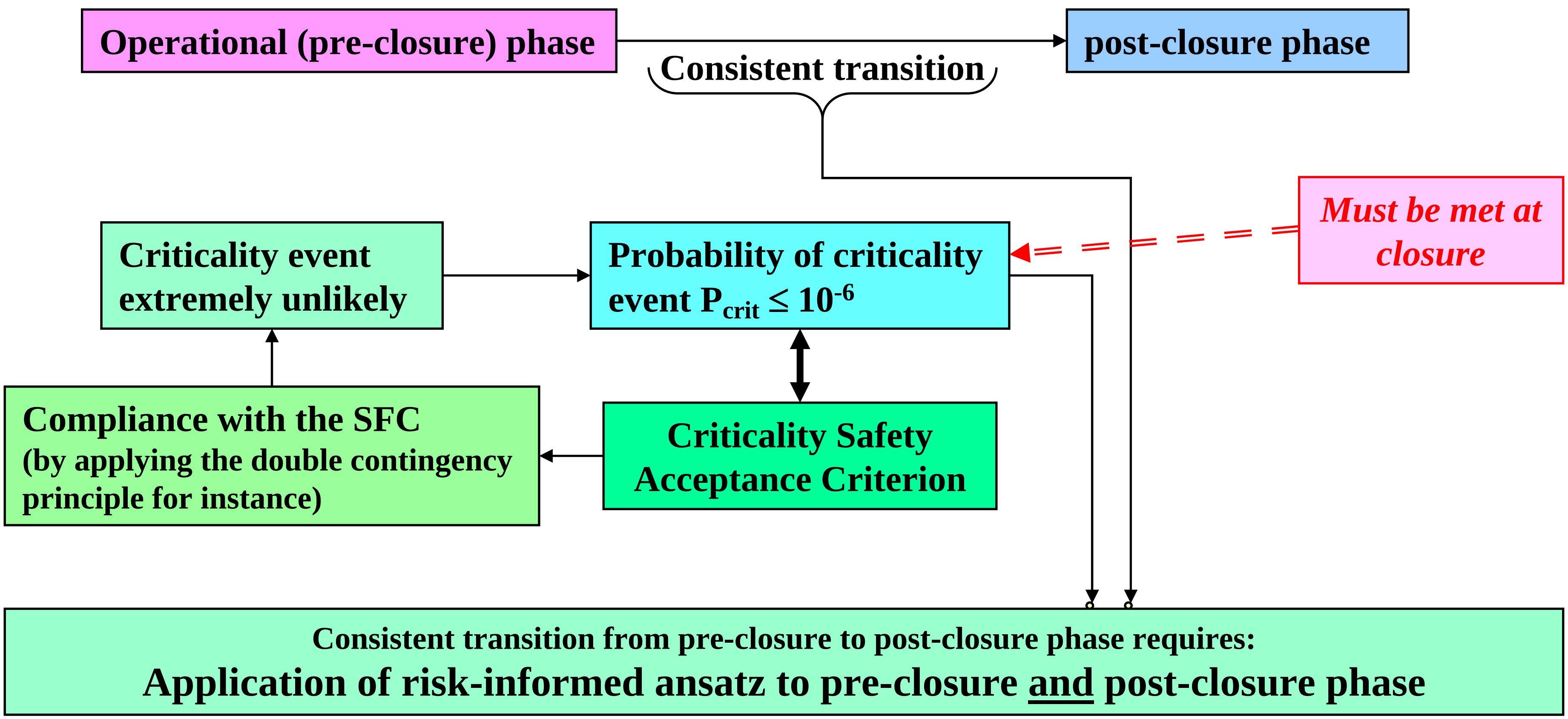
However generally valid the definition of the SFC is, the principle applies to the OPERATION of fuel managment systems outside reactor cores.



Disposal of fissile materials: Criticality safety acceptance criterion

Non-compliance with the SFC
- **Consideration of the probability and the consequences of a criticality event**

Non-applicability of the SFC
- **Consideration of the probability and the consequences of a criticality event**



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Probability of criticality for a fuel storage unit under some scenario S

Parameters describing the storage unit under S

Nuclear data

$$P_{crit} = P\left(k_{eff}(\vec{x},\vec{\xi}) \geq (1-\delta k_M) \,\middle|\, S\right)\cdot P(S)$$

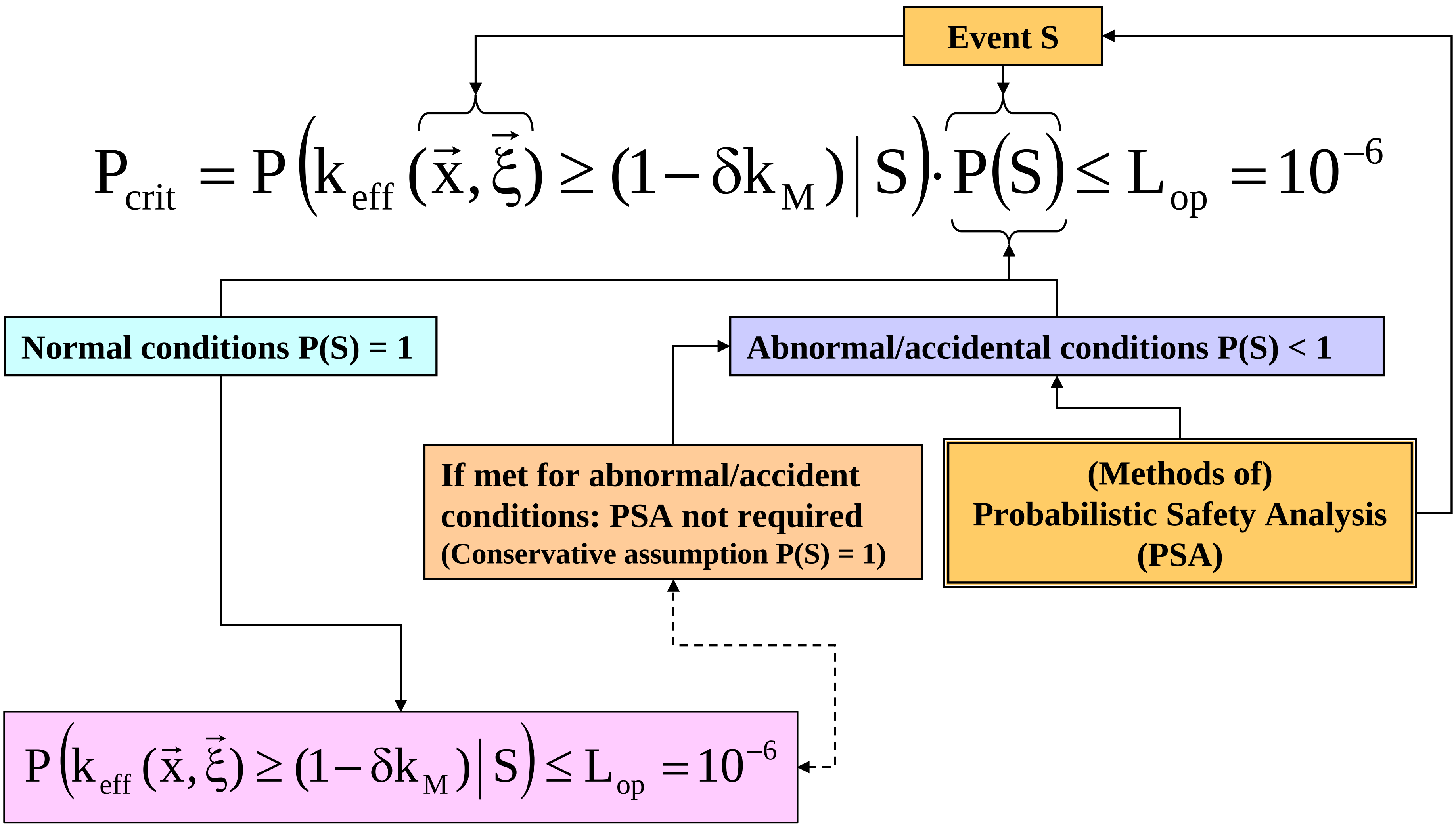
Probability that $k_{eff} \geq (1-\delta k_M)$ **under the condition that S is given**

Probability that S occurs

Administrative safety margin:

- δk_M **= 0 if uncertainties in** ξ **are considered by means of a fully hierarchical Bayesian evaluation procedure (← see Presentation 2.10 of the workshop)**
- δk_M **= 0.01 if cov(** ξ**) is considered by means of a first order perturbation evaluation (e.g. application of TSUNAMI ← see Presentation 2.11 of the workshop)**
- δk_M **= 0.02 if uncertainties in** ξ **are not explicitly considered**

Criticality safety acceptance criterion for pre-closure phase



Criticality safety acceptance criterion for pre-closure phase

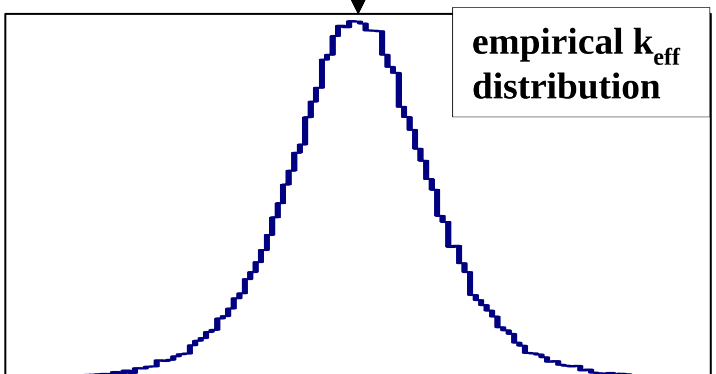
$$P\left(k_{eff}(\vec{x},\vec{\xi}) \geq (1-\delta k_M) \,\middle|\, S\right) \leq L_{op} = 10^{-6}$$

P(S) = 1

$$\int_{1-\delta k_M}^{\infty} dk_{eff}\; f(k_{eff} \mid S)$$

Monte Carlo sampling on $f(k_{eff}|S)$

(cf. presentations 2.10 and 2.11 of the Workshop)



(Free-of-binning)-Fit of the distibution, (using a Johnson empirical distribution e.g.)

Monte Carlo Sampling (MCS) on the fit parameters and their covariance matrix

MCS k_{eff}-distribution

Smirnov-Cramér-von Mieses Test

fit rejected

fit not rejected

MCS sample

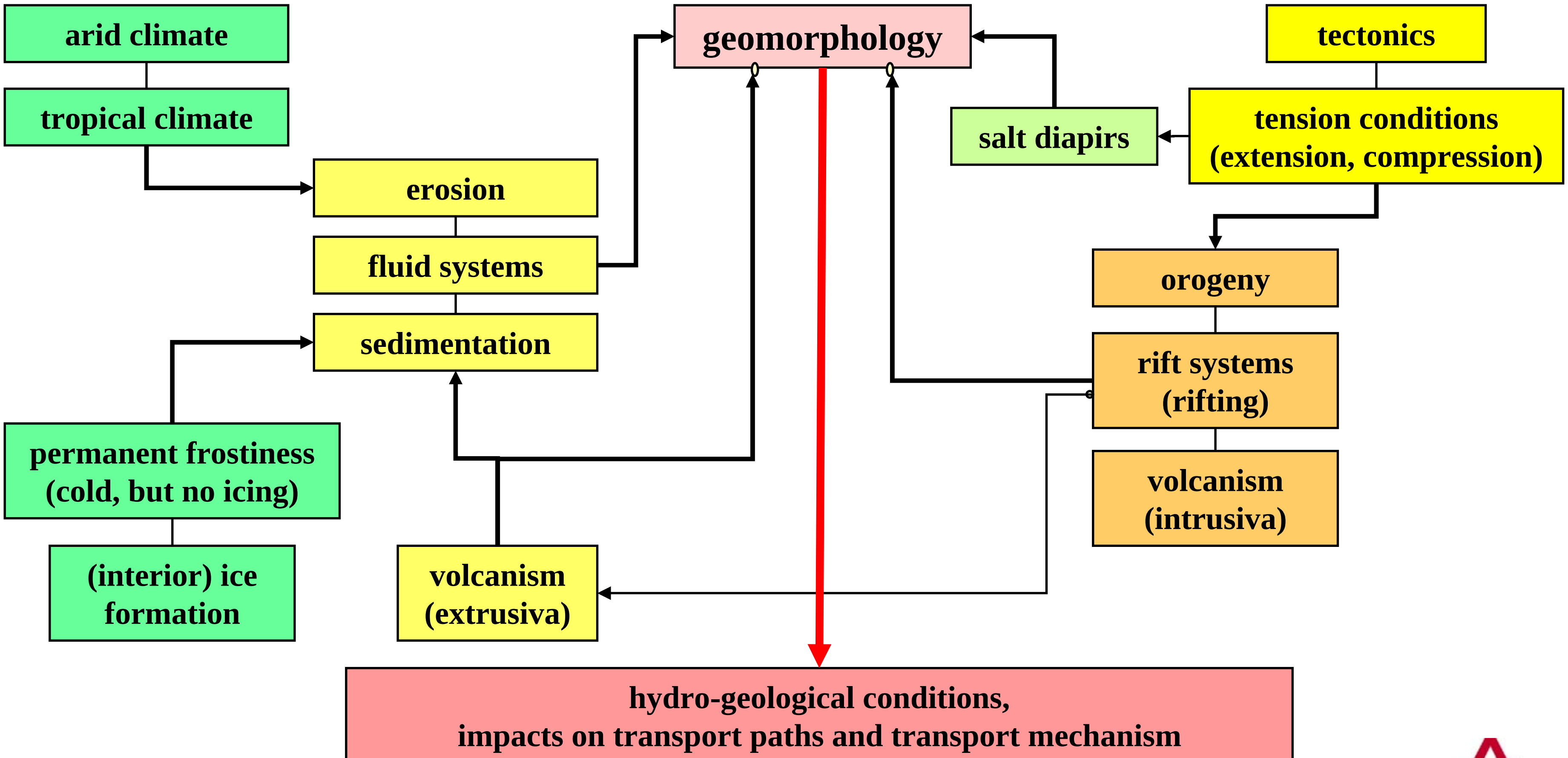
$$\gamma_{MCS} \equiv \int_{1-\delta k_M}^{\infty} dk_{eff}\; f_{MCS-fit}(k_{eff} \mid S)$$

Evaluation of the order statistics on γ_{MCS}

Criticality safety acceptance criterion for post-closure phase

$$P_{crit} = P\left(k_{eff}(\vec{x},\vec{\xi}) \geq (1-\delta k_M) \middle| S\right) \cdot P(S) \leq L_{clos}(t - t_{clos})$$

Evolution of scenarios S for t > t_{clos}



Criticality safety acceptance criterion for post-closure phase

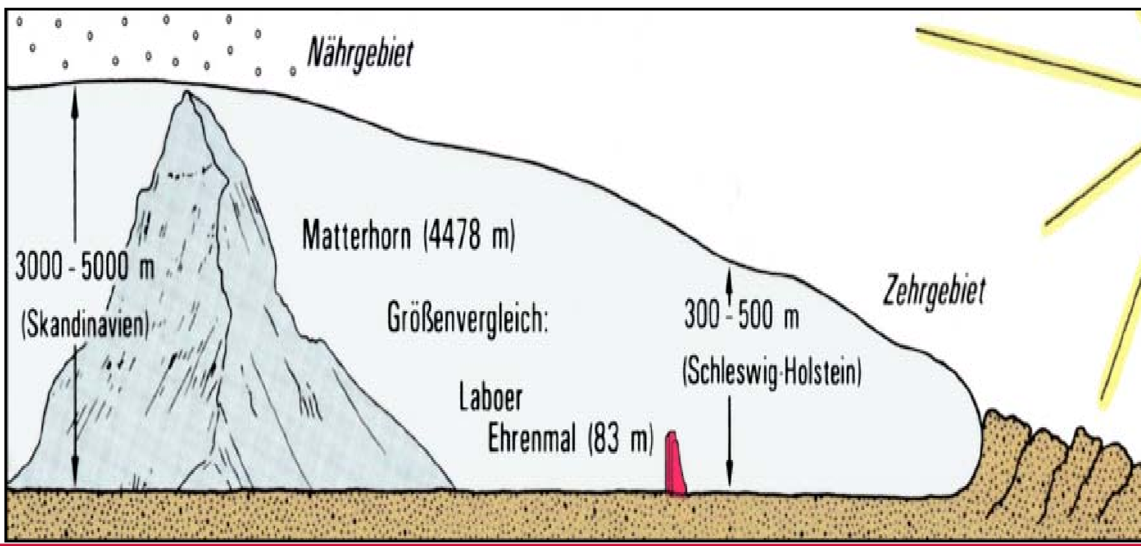
$$P_{crit} = \underbrace{P\left(k_{eff}(\vec{x},\vec{\xi}) \geq (1-\delta k_M) \,\middle|\, S\right)} \cdot \underbrace{P(S)} \leq L_{clos}(t - t_{clos})$$

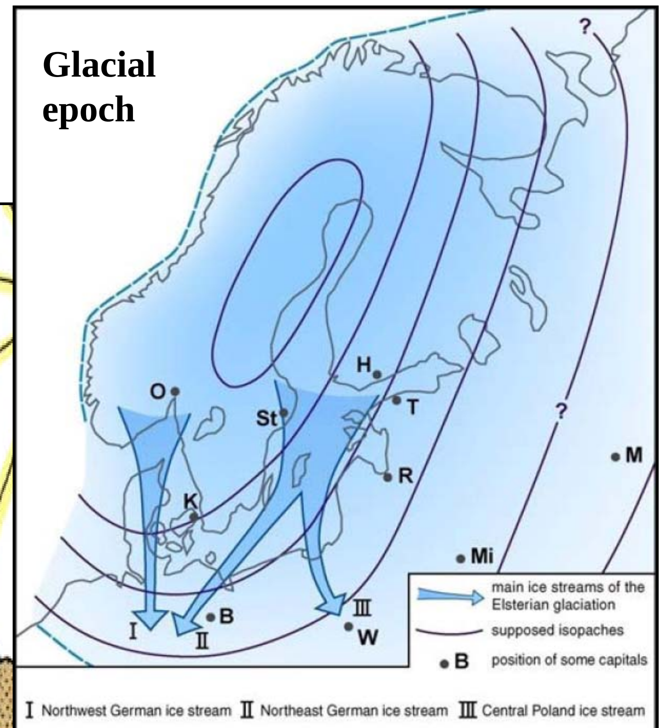
Can be calculated for given S

For some cases: may virtually become 1 with increasing time, e.g. sinking for prospecting

Uncertainty P(S) increases with increasing time ($t-t_{clos}$)

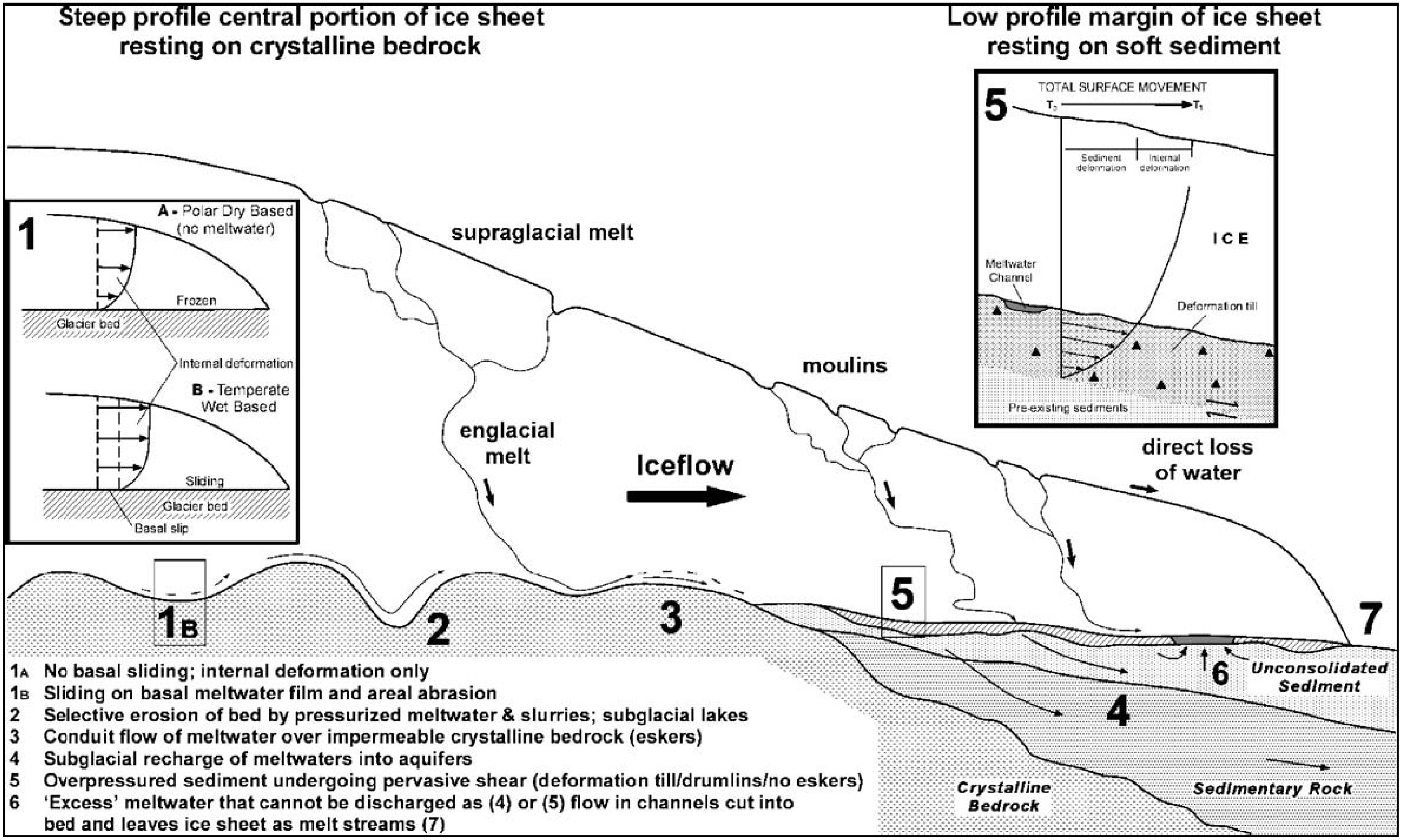
For $t > t_S$ it won't be possible to give a reasonable estimate for P(S)



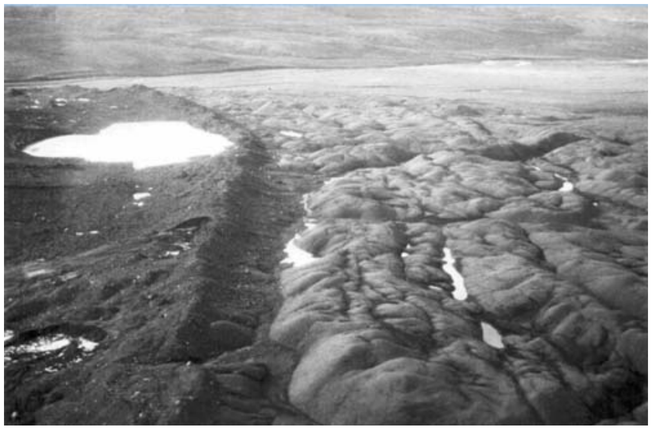


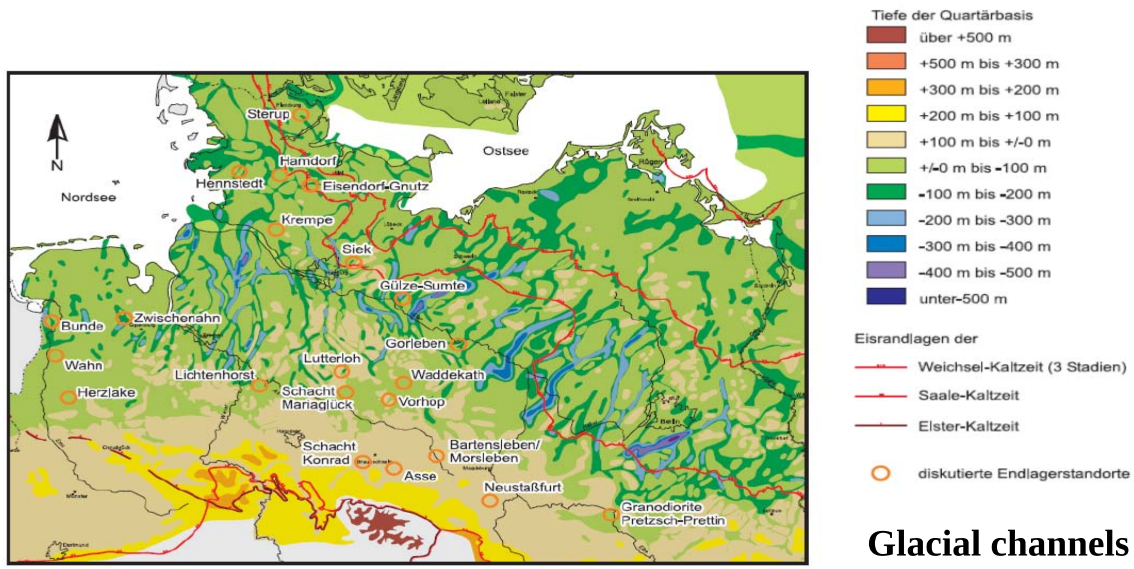
CSN / IAEA Workshop on Advances in Applications of Burnup Credit for Spent Fuel Storage, Transport, Reprocessing, and Disposition
Cordoba, Spain, 27 – 30 October, 2009

Criticality safety acceptance criterion for post-closure phase

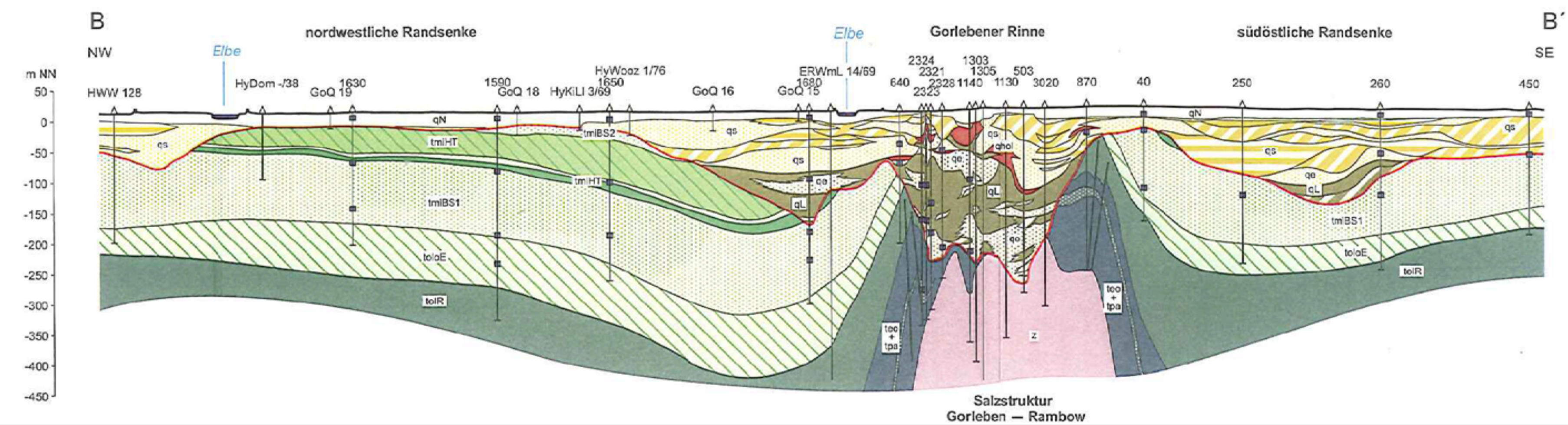


Criticality safety acceptance criterion for post-closure phase





Glacial channels



Criticality safety acceptance criterion for post-closure phase

$$P_{crit} = P\left(k_{eff}(\vec{x},\vec{\xi}) \geq (1-\delta k_M) \middle| S\right) \cdot \underbrace{P(S)} \leq \underbrace{L_{clos}(t-t_{clos})}$$

Uncertainty P(S) increases with increasing time (t-t_{clos})

For $t > t_S$ it won't be possible to give a reasonable estimate for P(S)

To avoid compensation for increasing uncertainty, e.g.

- **smaller storage capacities → increase of handling processes and transports**
- **decrease of fissile content → increase of total mass to be stored**

$$L_{clos}(t-t_{clos}) = 1-\left(1-L(t_{clos})\right)\cdot \exp\left(-\varphi_S \cdot (t-t_{clos})\right),\ t_{clos} \leq t \leq t_S$$

$$\text{with } \varphi_S \Leftrightarrow L_{clos}(t_S - t_{clos}) = 10^{-4}, \text{ and } L(t_{clos}) = L_{op} = 10^{-6}$$

Note: Probability > 10^{-4} → credible event

Criticality safety analysis for pre-closure phase

$$P_{crit} = P\left(k_{eff}(\vec{x},\vec{\xi}) \geq (1-\delta k_M) \,\middle|\, S\right) \cdot P(S) \leq L_{op} = 10^{-6}$$

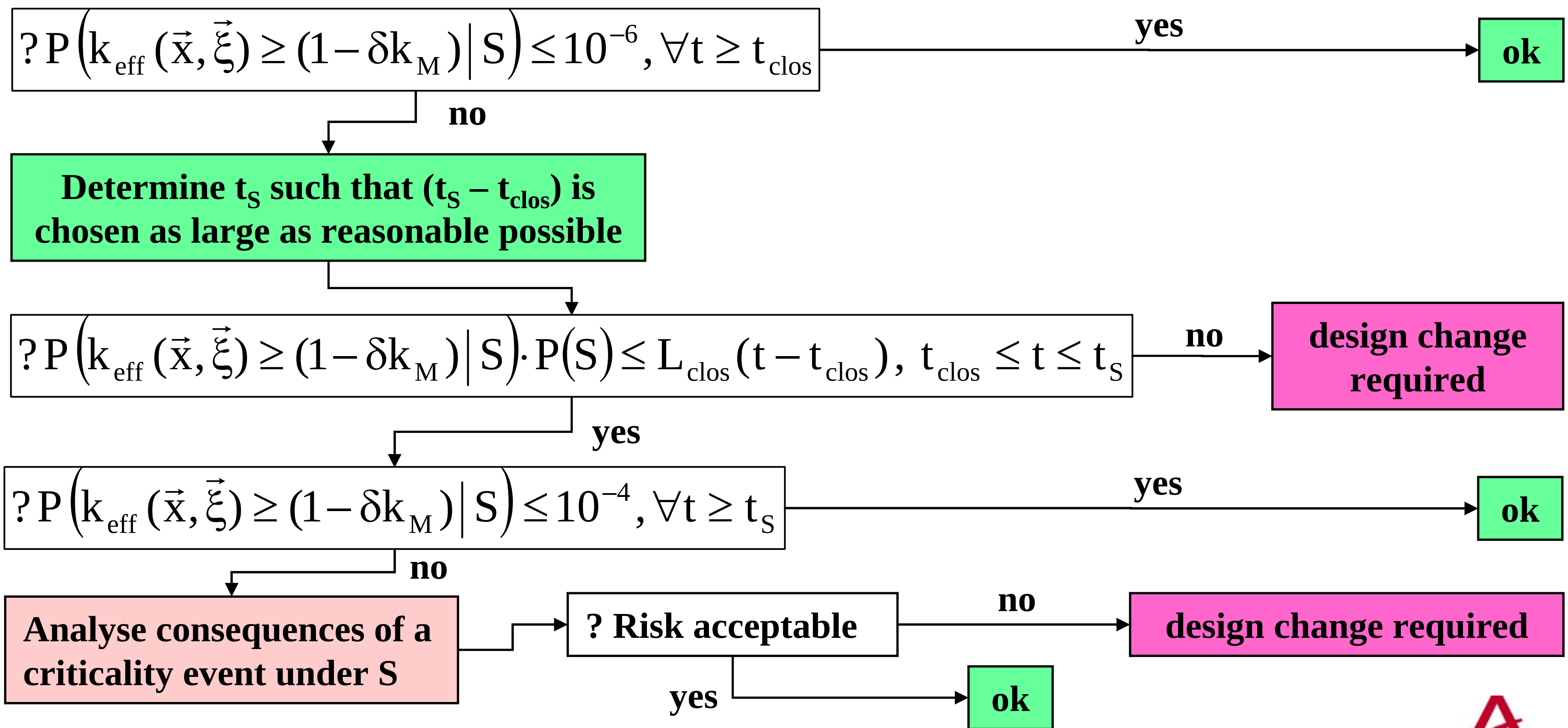
with P(S) = 1 for normal operation conditions, P(S) < 1 abnormal/accident conditions

Criticality safety analysis for post-closure phase

$$P_{crit} = P\left(k_{eff}(\vec{x},\vec{\xi}) \geq (1-\delta k_M) \middle| S\right) \cdot P(S) \leq L_{clos}(t-t_{clos})$$

$$L_{clos}(t-t_{clos}) = 1-\left(1-L(t_{clos})\right)\cdot \exp\left(-\varphi_S \cdot (t-t_{clos})\right),\ t_{clos} \leq t \leq t_S$$

$$\text{with } \varphi_S \Leftrightarrow L_{clos}(t_S - t_{clos}) = 10^{-4},\ \text{and } L(t_{clos}) = L_{op} = 10^{-6}$$



Some remarks on the use of burn-up credit

Loading Curve (LC) based on reactivity equivalence at t = t_{LC}

$$k_{\gamma} = (1 - \delta k_M),\ \gamma = P\big(k = (1 - \delta k_M) \,\big|\, S\big) = \begin{cases} 10^{-6}, t_{LC} < t_{clos} \\ L_{clos}(t_{LC} - t_{clos}),\ t_{clos} \le t_{LC} \le t_S \\ 10^{-4}, t_{LC} > t_S \end{cases}$$

Note:

- **Reactivity equivalence only holds for t = t_{LC} (in general) !**
- **It has to be demonstrated that LC meets the criticality safety requirements at all t different from t_{LC} taking into consideration the following issues:**
- **Change of isotopic content/spatial distribution due to radioactive decay**
- **Change of isotopic content/spatial distribution due to the impacts of the scenarios to be considered**

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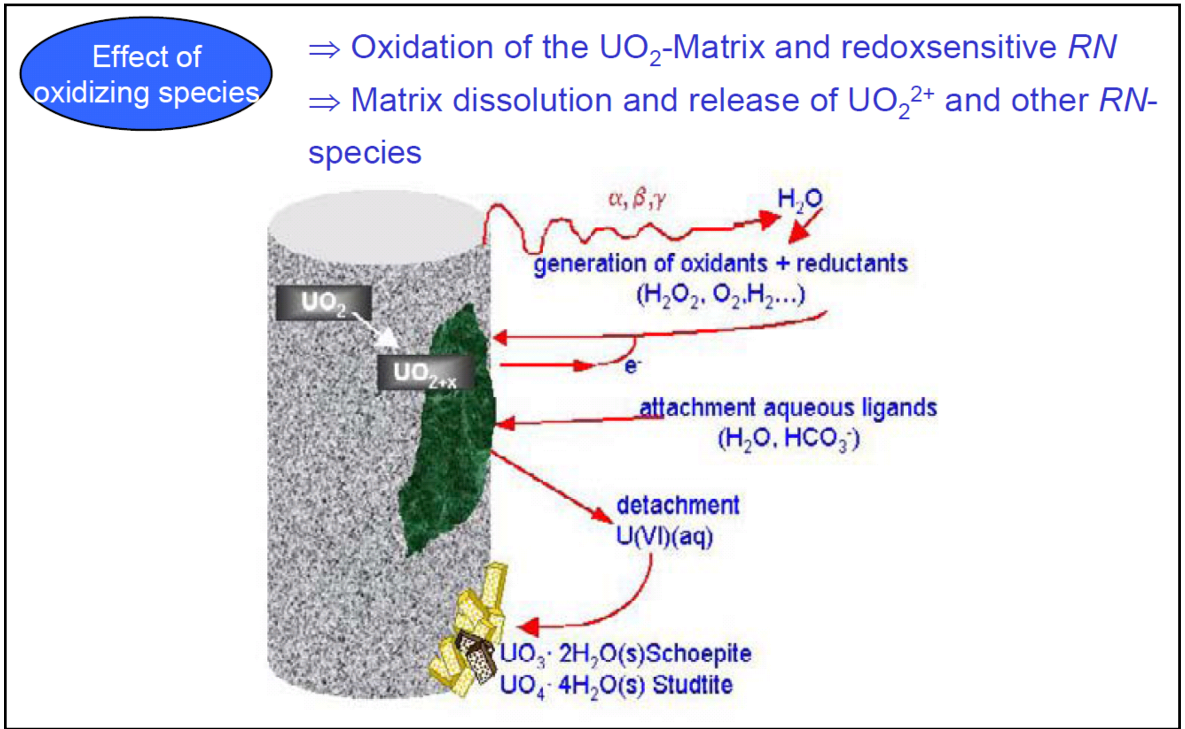
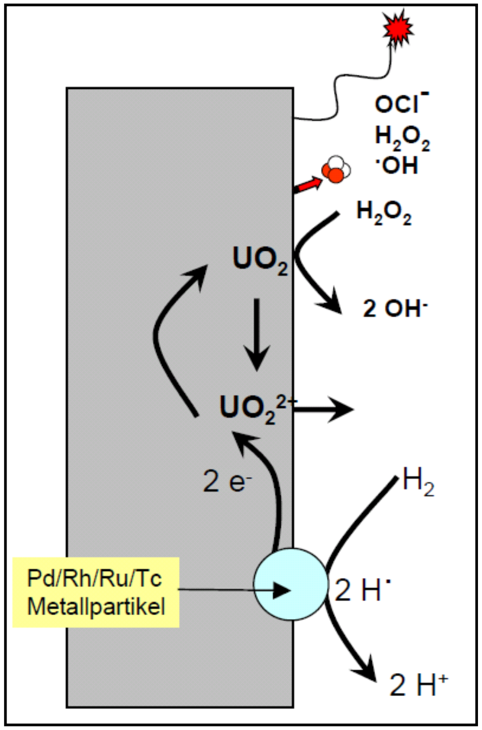
Some remarks on the use of burn-up credit

Impacts of some scenarios may include evaluation of corrosion and dissolution processes:

- **Corrosion processes can be directly induced by chemical reactions or can be indirectly induced by (e.g. anaerobe) organism (bacteria)**
- **Corrosion and dissolution rates are impacted by**
  - activity and decay modes of radioactive isotopes
  - radiolysis
  - catalytic effects of some fission products (Pd, Rh, Ru, and TC in metallic form) ….





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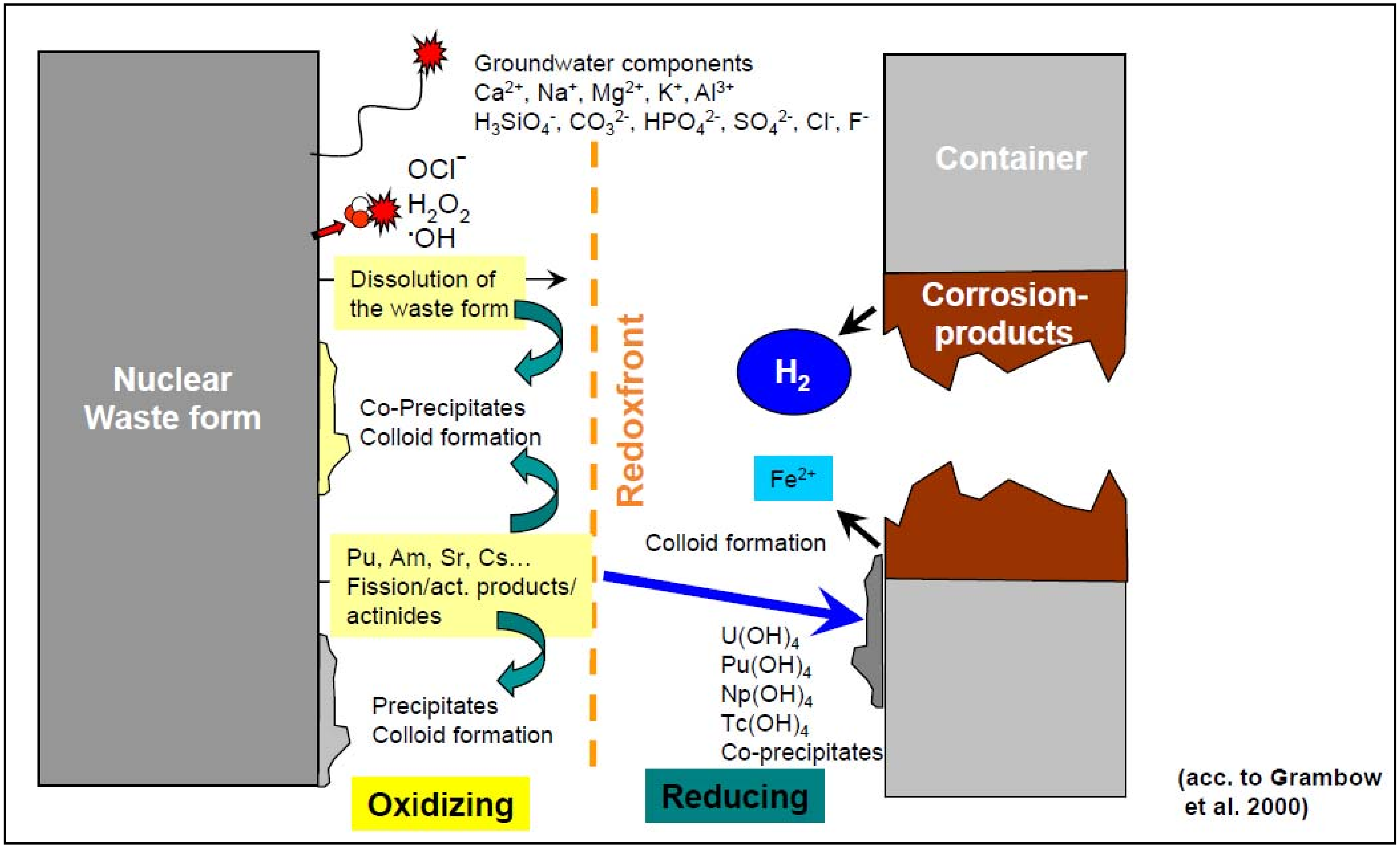
Some remarks on the use of burn-up credit

- **Corrosion and dissolution rates are impacted by**
  - **…**
  - **presence of structural materials**



Some remarks on the use of burn-up credit

Some scenarios may result in

- **a separation of actinides and fission products because of the very different geochemical properties**
- **accumulation of actinides in the near-fields or the far-field of the repository or**
- **a taking-away of fission products out of the storage units**

However, all the above-mentioned impacts of scenarios on the spent fuel behavior are not due to the use of burn-up credit, but to the fact that the (irradiated) fuel is exposed to final disposal.

→ These impacts have also to be taken into account (at least to some extent), if no burn-up credit is taken.