# Present Status of Criteria to Prove Functionality of the Geological Barrier in Order to Demonstrate Safe Confinement of HLW/SF- Radioactive Waste

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# Motivation – Regulatory Demands

**Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive waste (BMU 2010)**

- Safe confinement of radioactive waste in an isolating rock zone
- Long-term statement on the integrity of the isolating rock zone
- For probable developments, evidence must be provided on the basis of a long-term geoscientific prognosis verifying that the integrity of the isolating rock zone is guaranteed throughout the reference period of 1 million years

… should demonstrate that …

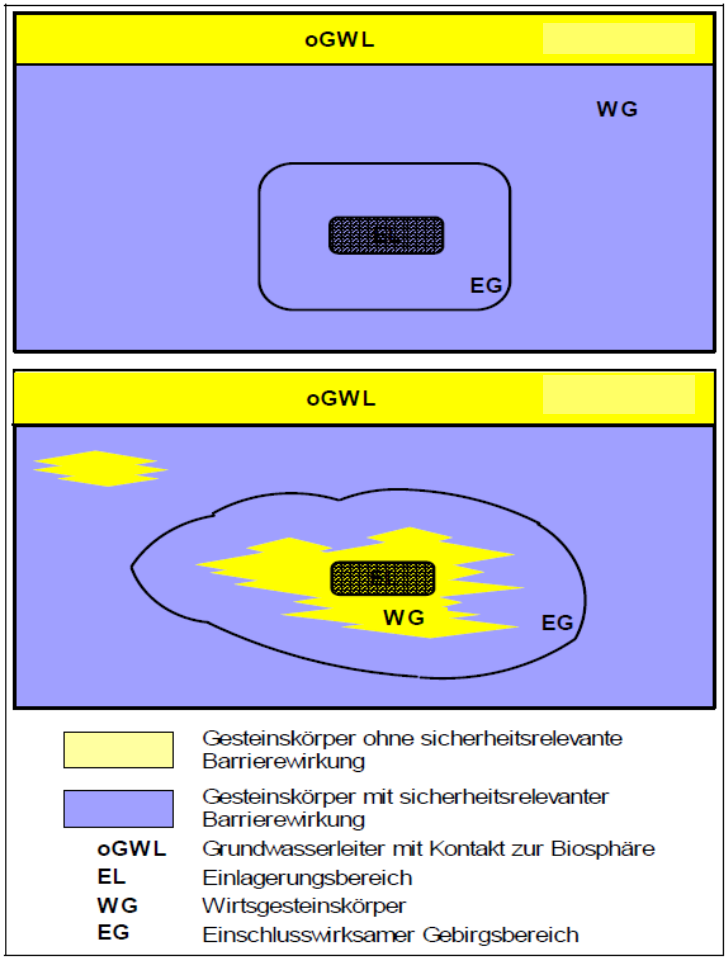
(1) The formation of secondary water pathways within the isolating rock zone* which could lead to the ingress or escape of potentially contaminated aqueous solutions can be excluded, and that

(2) Any pore water that may be present in the isolating rock zone does not participate in the hydrogeological cycle outside of the isolationg rock zone as defined by water legislation. This requirement shall be considered to have been met if the dispersion of pollutants within the isolating rock zone by advective transport processes is at best comparable with dispersion by diffusive transport processes.

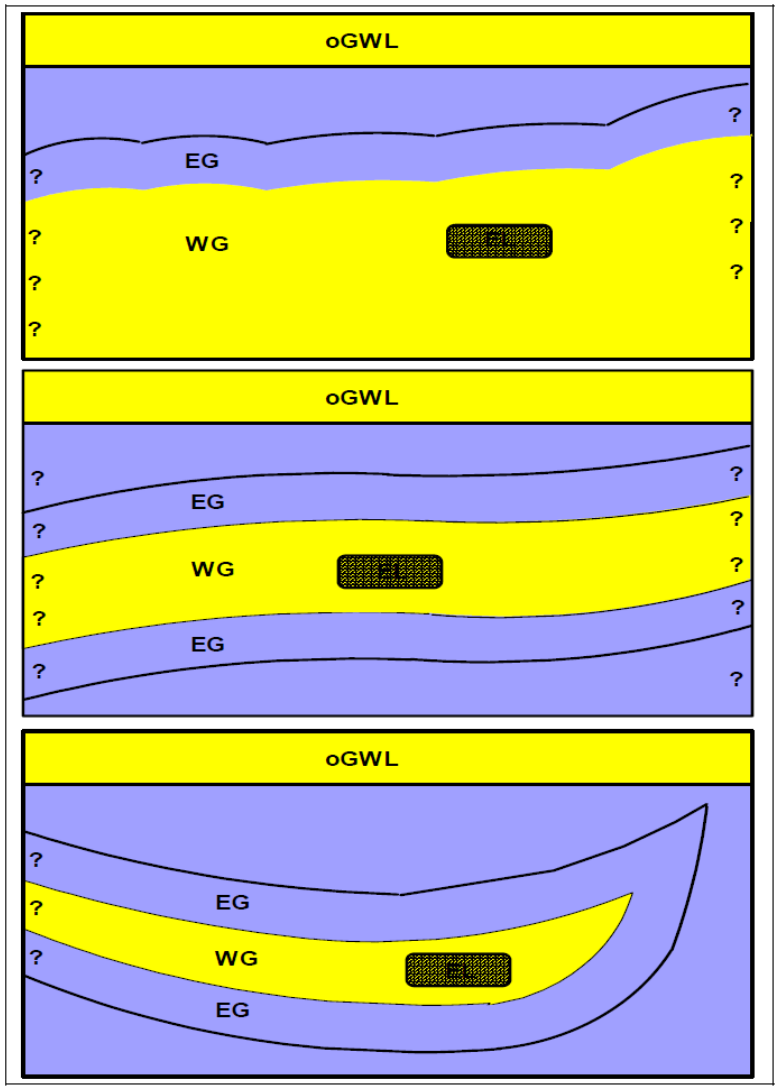
* Instead of „isolating rock zone“ the term „containment providing rock zone“ (CRZ) is common

# Background – AkEnd Definition of CRZ

AkEnd:
Focus on salt and argillaceous rock




**Type Aa (above) and type Ba (below)**



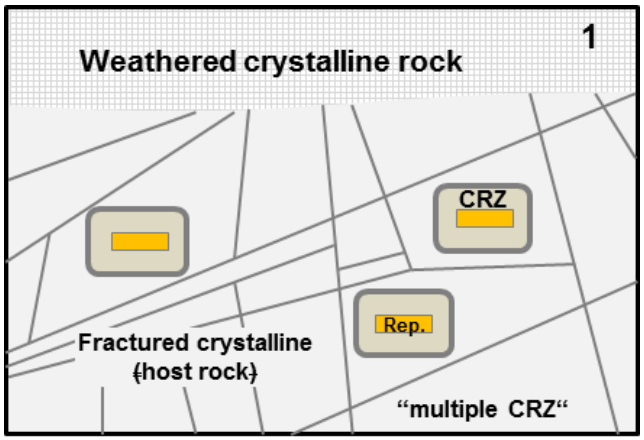

**Types Bb**

# Motivation – Regulatory Demands

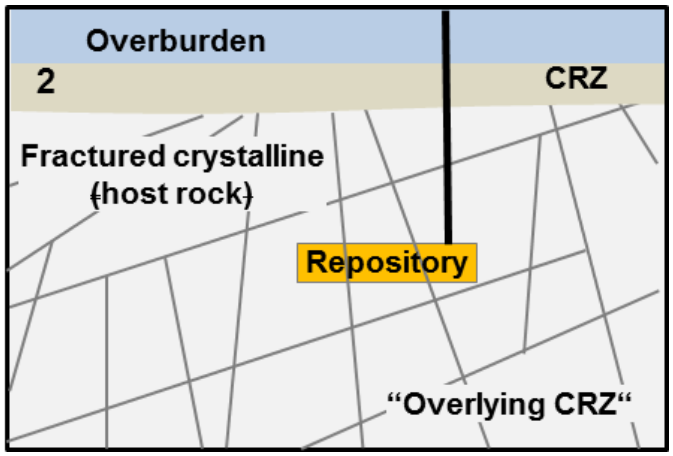
## Repository Site Selection Act (StandAG 2016)

- Includes crystalline rock as a potential host rock in addition to salt and argillaceous rock

- In crystalline rock CRZ- type Aa and Ba is not expected
- An additional type – consisting of multiple CRZ´s (type M) - may exist within crystalline rock (Finnish experience)




Type M




Type Bb

- **All types of CRZ require criteria to verify the integrity of the geological barrier in order to exclude the formation of secondary water pathways**

# Criteria to assess integrity of a rock salt barrier

## Integrity-relevant processes and evidence criteria to demonstrate integrity

- Process: Generation and growth of (interconnected) cracks due to shear stress induced damage (deviatoric loading)

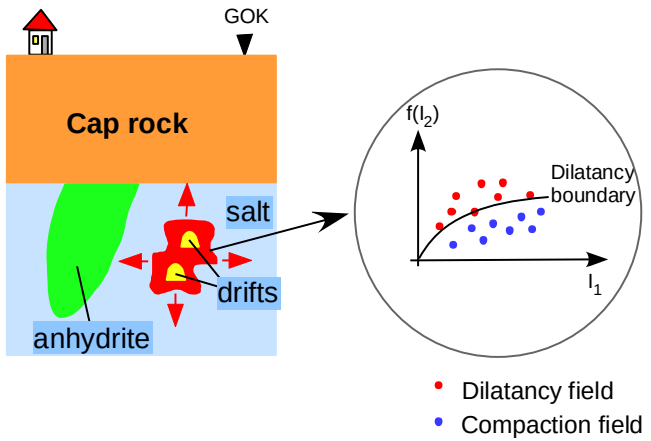
- Dilatancy-criterion: Dilatancy boundary or boundary of microstructural damage

$$\tau_{Oct} / \tau_{Dil} \leq 1 \quad \text{if } \tau_{Oct} / \tau_{Dil} > 0$$

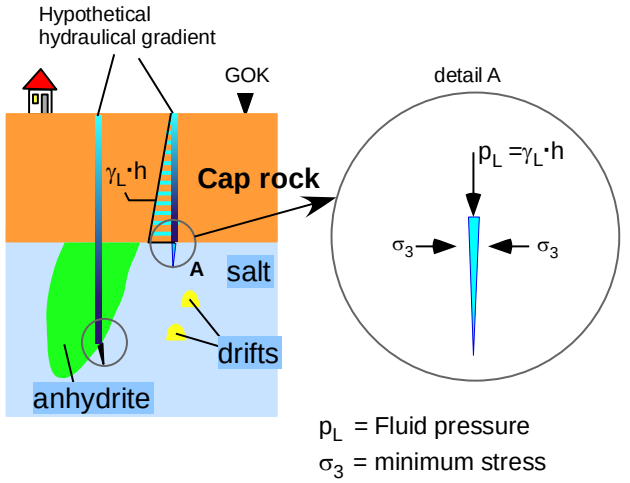
- Process: Fluid-pressure-driven opening of grain boundaries if the fluid pressure exceeds the normal stress and adhesive forces at the boundaries

- Fluid-pressure-criterion, e.g. simplified approach neglecting tensile strength
- Comparison of $\sigma_3$ and depth dependend theoretical brine pressure

$$\sigma_3 > p_L$$




Source: BGR



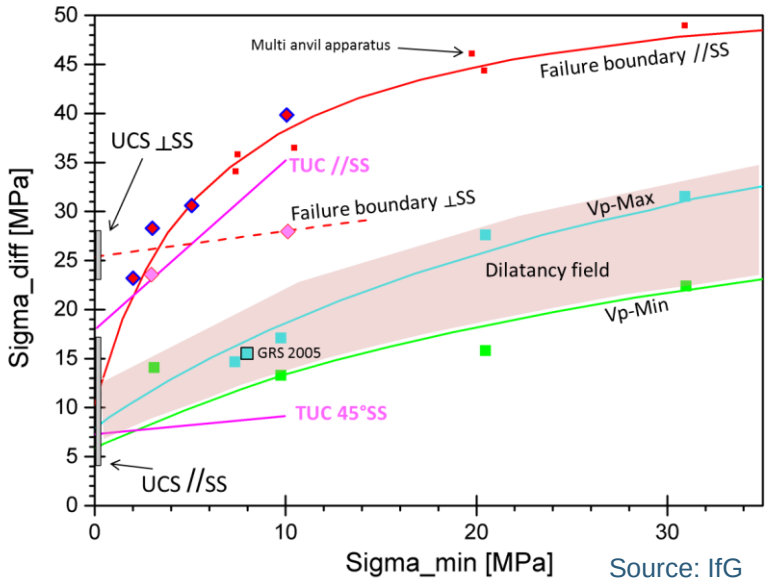
# Criteria to assess integrity of argillaceous rock

## Integrity-relevant processes and evidence criteria to demonstrate integrity

- Process: Generation and growth of (interconnected) cracks due to stress induced damage
- Conservative approach of the dilatancy criterion based on the failure boundary $\sigma_F$

$$\sigma_{Dil} = 0.5 \cdot \sigma_F \rightarrow \sigma / \sigma_{Dil} \leq 1$$

$\sigma_F$: (Anisotropic) failure boundary of argillaceous rock
Different failure criteria are applied, e.g. several variations of Mohr-Coulomb, Hoek-Brown

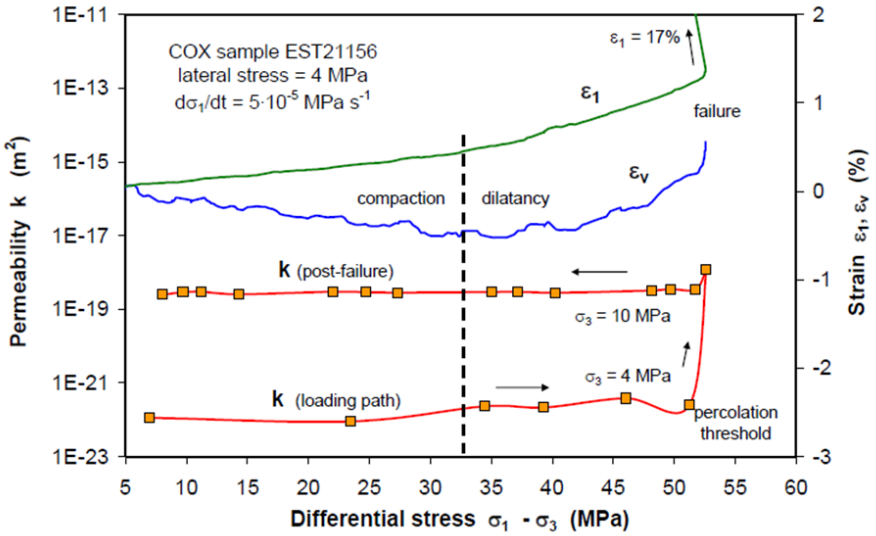



Source: IfG

- Process: Fluid-pressure-driven induced pathways if fluid pressure eliminates particle-to-particle contacts
- Fluid-pressure criterion takes into account hydro-mechanical coupling $\boldsymbol{\sigma' = \sigma - \alpha \cdot p \cdot 1}$

$$\sigma'_3 \leq 0$$

$\sigma'_3$: Minimum effective stress




Source: GRS

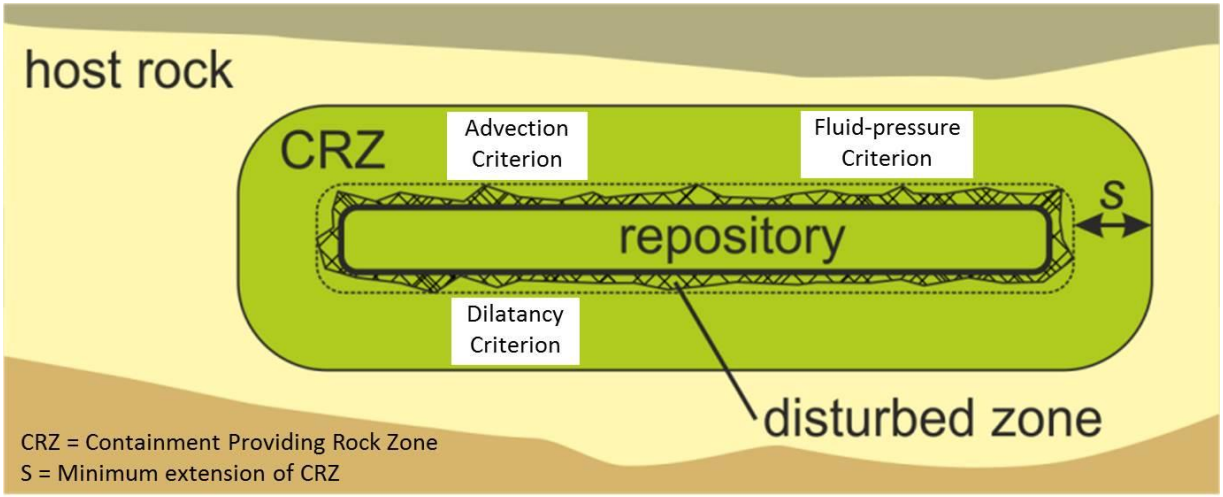
# Criterion to assess tightness of argillaceous rock

**Porewater present in the CRZ must not transport any pollutant to the hydrological cycle outside the CRZ, advectively**

- This requirement defines the CRZ in argillaceous rock
- Conservative approach: If a dissolved conservative tracer does not flow from the disposal area to the boundary of the CRZ by movement of the porewater in the reference period of 1 million years any pollutant is confined in the CRZ as well
- Advection criterion (on potential flow paths):

$$Øv \,/\, v_{limit}$$

$Øv$: Average filter rate
$v_{limit}$: Filter rate limit

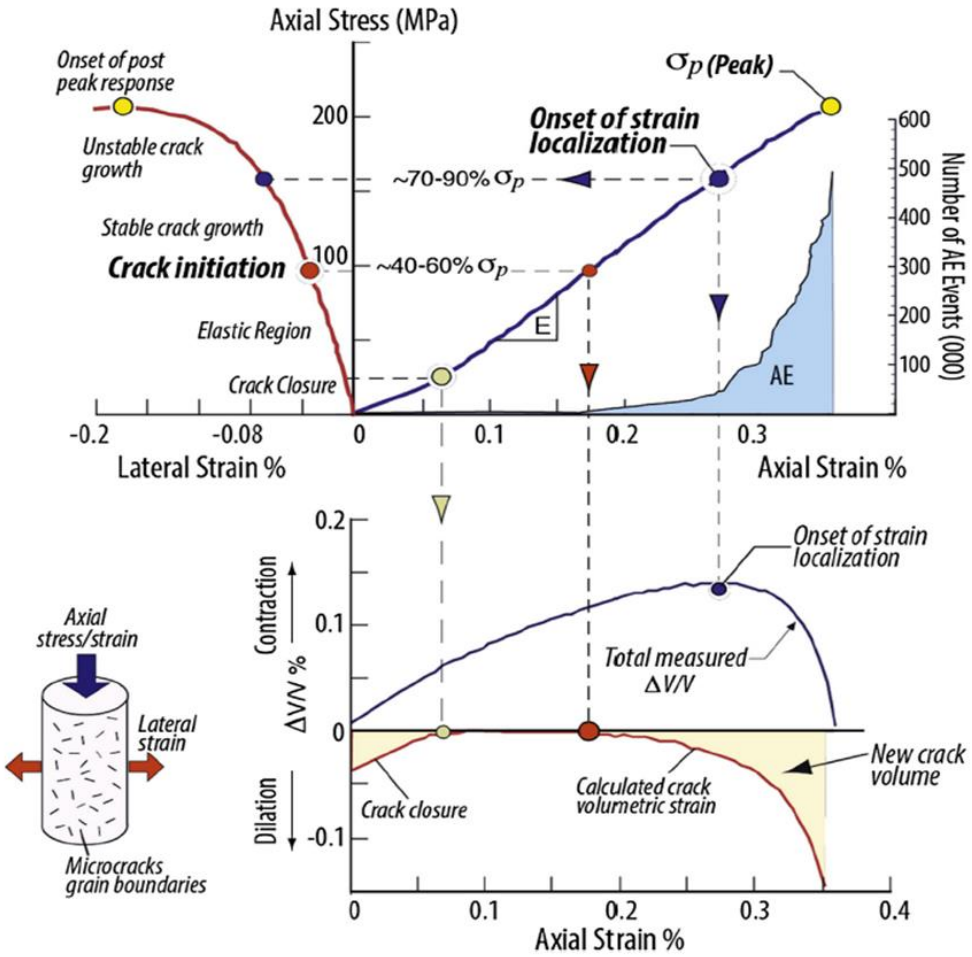



➢ A statement on the required barrier thickness can be derived!

# Criteria to assess integrity of crystalline rock

## Integrity-relevant processes and evidence criteria to demonstrate integrity

- Process: Generation, growth and (re-)opening of (interconnected) cracks due to stress induced damage characterized by brittle failure
- Applicable failure boundaries of Mohr-Coulomb-type are available but a dilatancy boundary cannot be identified, reliably




Source: Hoek & Martin

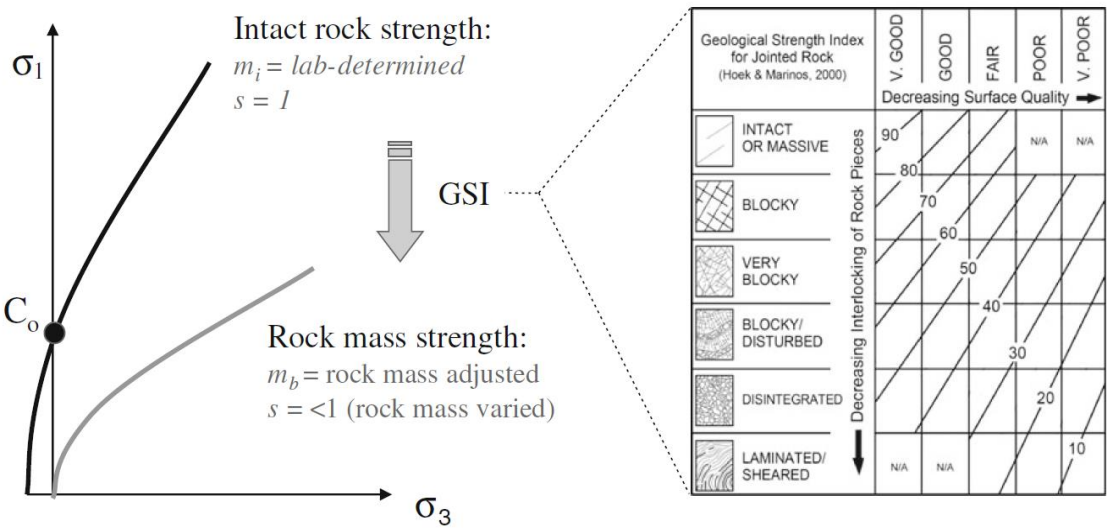
# Criteria to assess integrity and tightness of crystalline rock

## First step: Investigation of an adequate failure boundary

- Some experimental results indicate that the dependence of failure boundary on $\sigma_2$ can be neglected → working hypothesis
- The failure boundary depends on the geological joint index GSI and a disintegration/damage factor

➢ Hoek- Brown

$$\frac{(\sigma_1-\sigma_3)}{(m_b\cdot\frac{\sigma_3}{\sigma_1}+s)^a} \leq \sigma_{c0}$$




$\sigma_{co}$: Uniaxial compression strength
$m_b$, s, a: materialfunctions depending on GSI and D

Source: Eberhardt

# Criteria to assess integrity of crystalline rock

- Crack-damage-criterion describes the onset of strain localization (evolution of interconnected cracks) instead of the dilatancy criterion by reducing the peak failure boundary by a factor of 0.7

$$\frac{(\sigma_1-\sigma_3)}{(m_b\cdot\frac{\sigma_3}{\sigma_1}+s)^a} \leq 0.7 \cdot \sigma_{c0}$$

- When considering the influence of fluid pressure within in a hydro-mechanical coupling the crack-damage-criterion is formulated in terms of effective stress

$$\frac{(\sigma_1'-\sigma_3')}{(m_b\cdot\frac{\sigma_3'}{\sigma_1'}+s)^a} \leq 0.7 \cdot \sigma_{c0}$$

# Criterion to assess tightness of crystalline rock

**Porewater present in the CRZ must not transport any pollutant to the hydrological cycle outside the CRZ, advectively**

- Similar to agillaceous rock this requirement also defines the CRZ in crystalline rock
- Again the conservative approach can be applied: If a dissolved conservative tracer does not flow from the disposal area to the boundary of the CRZ by movement of the porewater in the reference period of 1 million years any pollutant is confined in the CRZ as well
- The advection criterion can also be applied
- The quantification of the advection criterion for crystalline rock, however, is still under consideration as potential approaches to handle the influence of fracture networks are investigated, presently

# Temperature limits in salt, argilleaceous and crystalline rock

**Regarding heat generating radioactive waste (HLW, SF) the temperature rise in the repository has also to be taken into account**

- The temperature limit acts as a design parameter for repository layout
- Temperature limits are quantified in several international repository projects
- Presently, the temperature limit of 100 °C constitutes the lower limit of all international approaches in well developed repository projects

**StandAG:**

**Preliminary, the temperature limit at the container surface is restricted to 100 °C.**

- **However, if research results show that a higher temperature limit is more adequate regarding the whole repository system a modification is not excluded**

# Summary

**In order to provide criteria to assess intgrity and tightness of geological barriers in different rock formations - potentially suitable to dispose radioactive waste - prior to site selection the follwing procedure is applied**

Integrity

(1) The (thermo)mechanical behaviour is considered in order to establish reliable conservative criteria to demonstrate that stress induced creation of interconnected cracks is excluded

(2) The influence of hydro-mechanical coupling on the criteria is investigated

Tightness

(3) The filter rate of a conservative tracer is limited on potential flow paths to avoid that the tracer crosses the outer boundary of the CRZ

- Presently, criteria to assess integrity and tightness of salt and argillaceous rock are well developed
- Criteria to assess integrity and tightness of crystalline rock are still under investigation ... but progress is evident

**Many thanks …**

**… to all colleagues working in different organizations for their contributions to the development of the integrity and tightness criteria**

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# Thank you very much for your attention!

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