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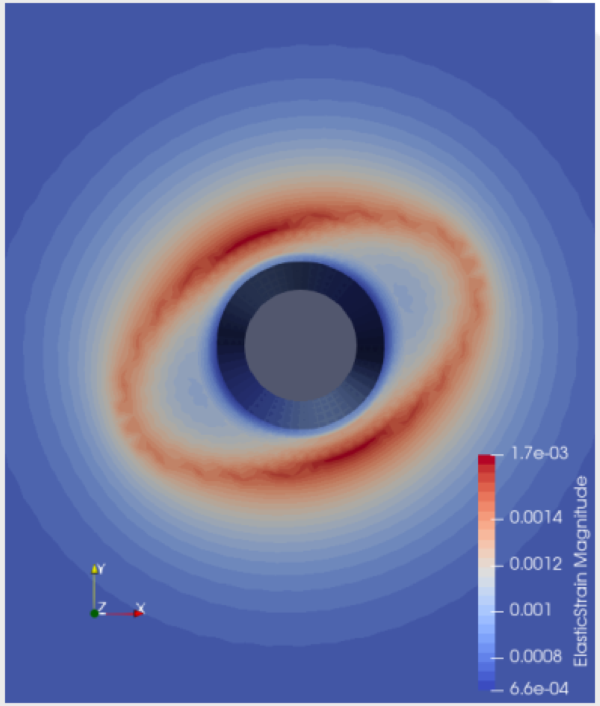

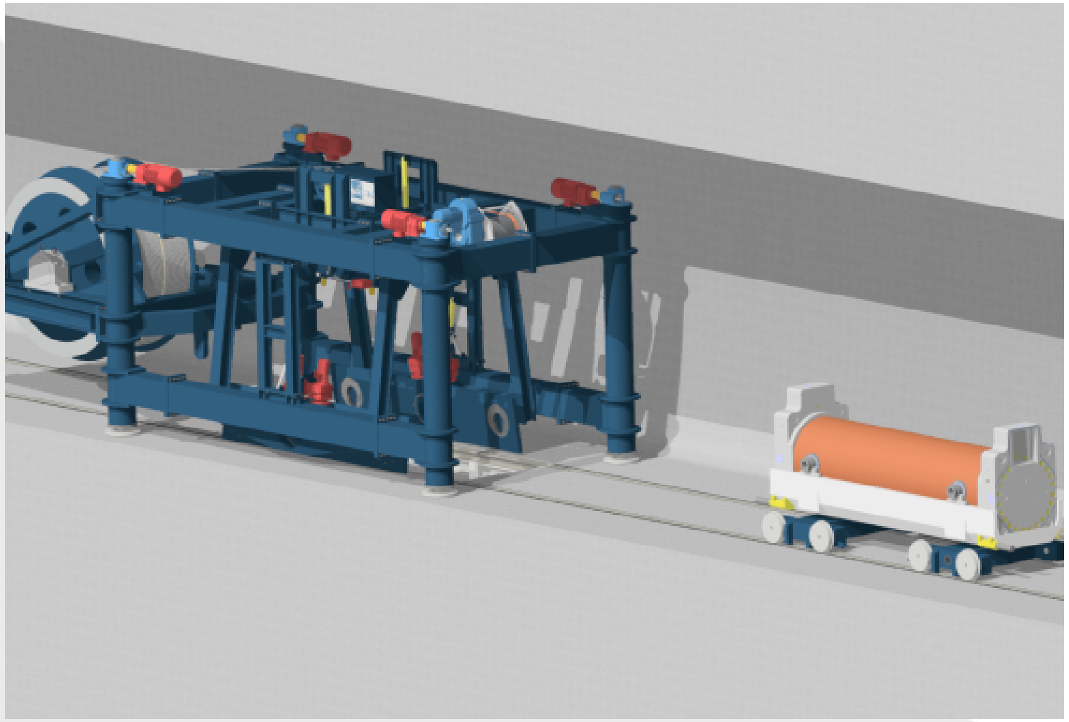

RANGERS – Methodology and Numerical Applications

Eric Simo et al.

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RANGERS

- **RANGERS stands for:** Methodology for design and performance assessment of geotechnical barriers in a HLW repository in salt formations
- **Joint-Project between BGE TECHNOLOGY and Sandia National Laboratories**
- **Main goals:**
  - Compilation of existing knowledge and experience to design geotechnical barriers and compilation of Engineered Barrier System (EBS) materials to be used in salt
  - Development of a methodology based on the state of the art in science and technology for the design and verification of geotechnical barriers.
  - Preliminary design and verification of the geotechnical barrier system for the selected repository system based on the developed methodology.
- **Secondary goals:**
  - Estimation of the optimization potential of EBS in salt repositories
  - Analysis of the impact of gases on EBS in salt
  - Exploiting synergy effects between BGE TEC and SANDIA in the numerical treatment of EBS in the course of the overall safety assessment of salt repositories

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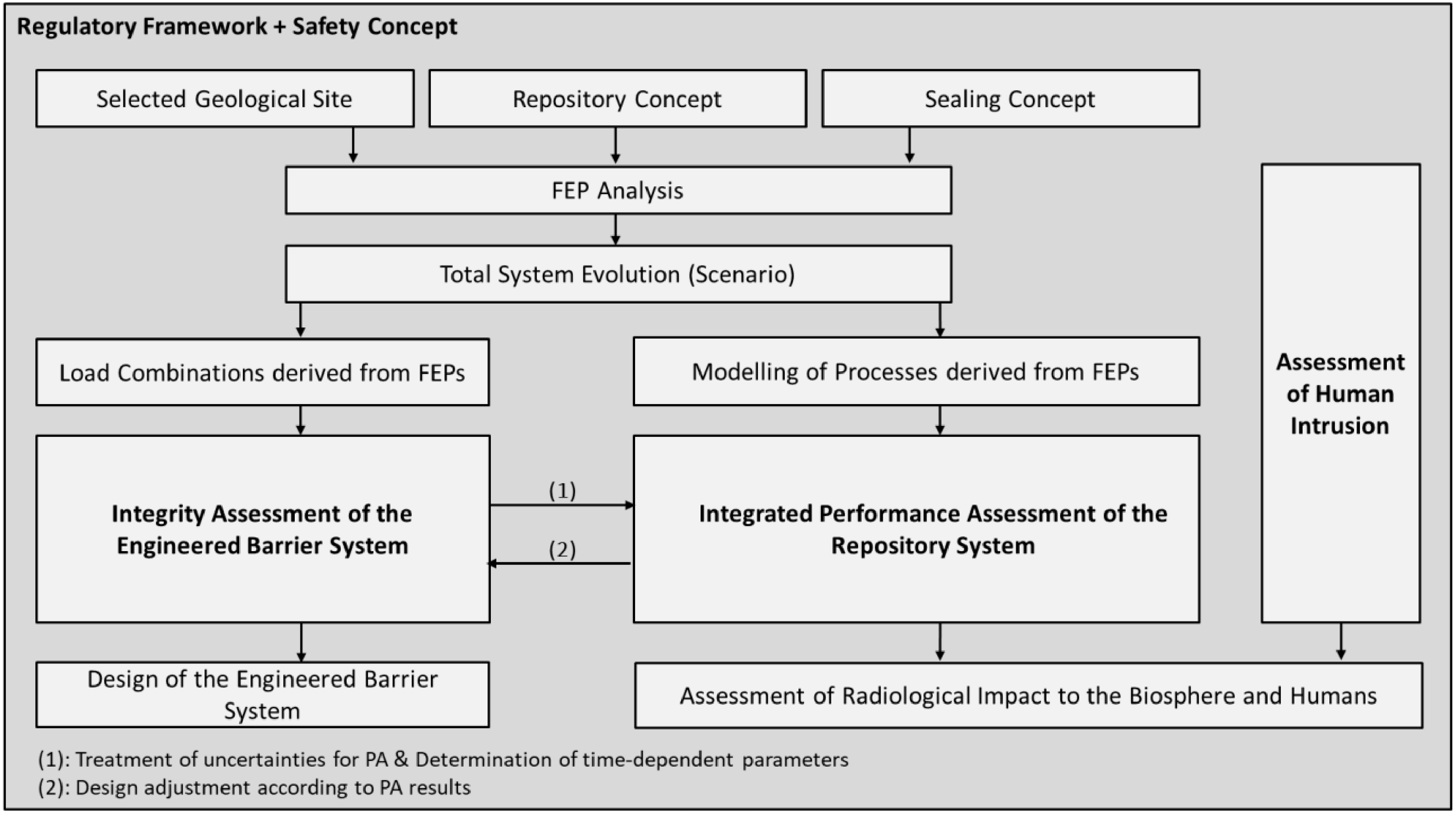
RANGERS-Methodology



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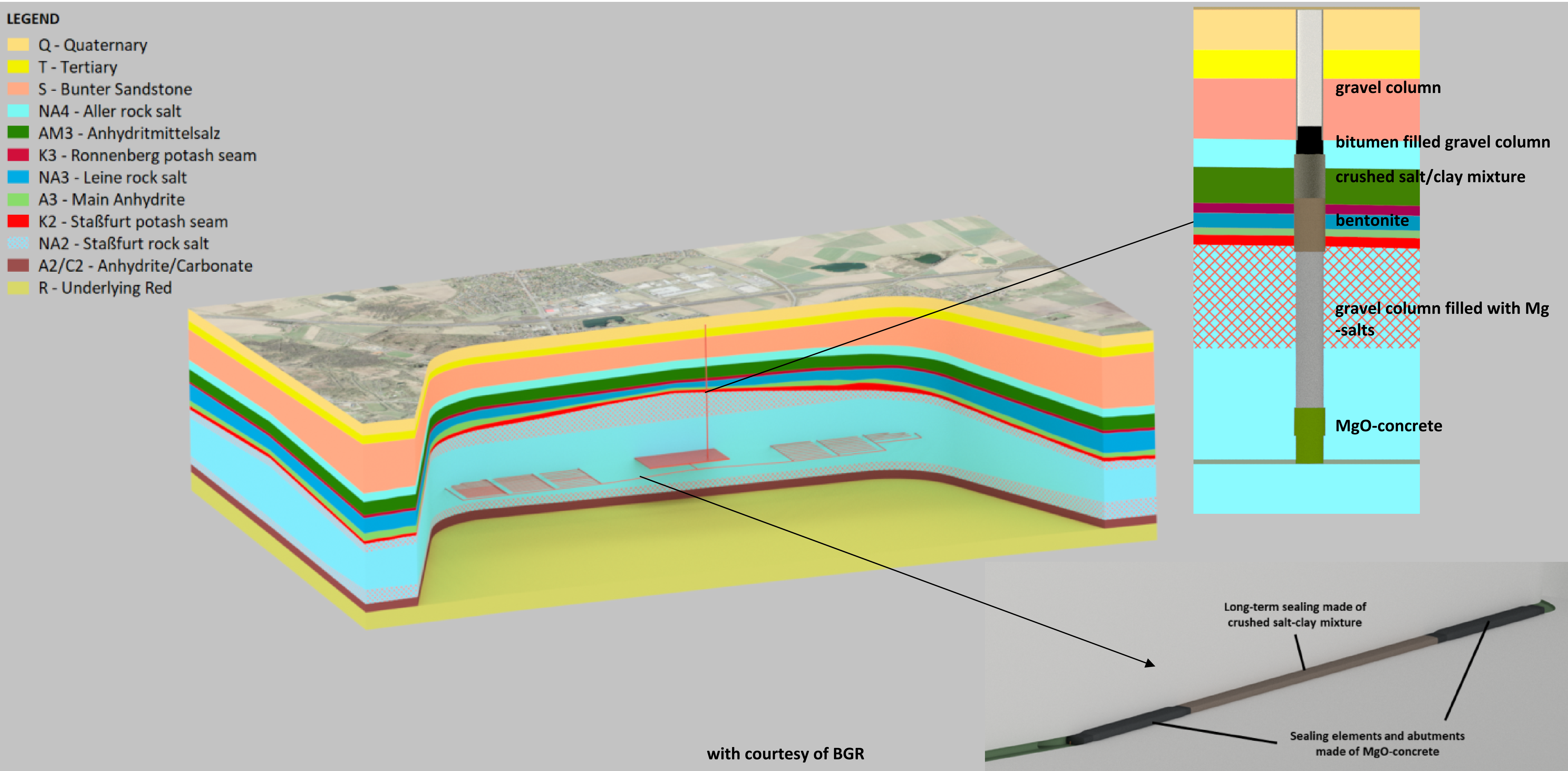
Developed Repository in the Selected Geological Site



with courtesy of BGR

Development of FEPs for EBS in Salt Formations

Sub-system: Drift	Process Group	FEP	Description	Impact on EBS	Components affected by process														
					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Components		1: Drift seal																	
		3: Drift Backfill																	
		10: Concrete injection																	
		7: EDZ																	
		XX: ...																	
Processes/ Events	Mechanical	Example: Earth quake	The release of accumulated geologic stress via rapid relative movements within the earth's crust usually along existing faults or geological interfaces.	tectonic movements resulting from an earth quake may yield in fractures in the drift seal. The drift lining may collapse.	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Hydraulic	Example: Gas flow processes	Describes the gas flow due to potential gradients. Gas flow is responsible for transport of volatile compounds.	Gas flow transport is important for chemical processes and radio-nuclide spreading.									x						x
	Thermal	Example: Heat flow	Means the energy transport as a result of temperature differences. There are 3 main sources for heat flow: climate, geothermic and radionuclide decay of the waste	The impact of waste produced heat on geotechnical barriers depends on the distance between barrier and empla-cement field.	x	x	x	x	x		x	x	x	x	x	x	x	x	x
	Chemical	Example: Concrete corrosion	Describes the chemical degradation of concrete	The corrosion processes will impair the function of all concrete components in the drifts	x	x	x	x				x		x	x				

FEP = Features, Events & Processes

Scenarios Relevant for Salt EBS

- **Reference Scenario**: The EBS retains its function over 50000 years
  - Case 1: Water flow from overburden through the shaft to the disposal zones
  - Case 2: Gas production inside the repository from corrosion of the casks
  - Case 3: Water source inside the repository from inter-/ intragranular salt solutions
  - Case X : ...
- **Alternative Scenario 1**: Shaft seal loses its function and drift seals retain their function
  - Same cases
- **Alternative Scenario 2**: Shaft seal retains its function and drift seals lose their function
  - Same cases
- Alternative Scenario x:
  - Cases ...

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FEP Analysis and System Evolution

- Deriving the modelling concept from the FEP-Analysis

FEP Analysis

↓

Total System Evolution (Scenario)

↓

Load Combinations derived from FEPs | Modelling of Processes derived from FEPs

	Specification of hydraulic resistance			Demonstration of structural integrity				
	Hydraulic resistance -sealing element	Hydraulic resistance -contact zone	Hydraulic resistance -EDZ	Structural stability	Crack limitation	Deformation limitation	Filtration stability	Long-term stability
Reference Scenario: The EBS retains its function over 50000 years								
Case 1: Water flow from overburden through the shaft to the disposal zones	**H**: determination of flow rate and passing time (constant permeability) **HM:** including compaction of crushed salt (time dependent permeability)			**TM:** structural analysis of the EBS components			No modelling intended	**C**: determination of geochemical stability of the sealing elements against water/brine **T**: temperature effects on EBS-materials
Case 2: Gas production inside the repository from corrosion of the casks	**HM:** crushed salt compaction under gas pressure build up			No modelling intended			No modelling intended	No modelling intended
Case 3: Water source inside the repository from inter-/ intragranular salt solutions	**H:** determination of flow rate and passing time (constant permeability) **HM:** including compaction of crushed salt (time dependent permeability)			**TM:** structural analysis of components inside the drift (concrete abutments)			No modelling intended	**Geochemical analysis:** determination of geochemical stability

	Processes							Target Criteria	
	Nuclide decay	Advection	Diffusion	Convection/ conduction	2-Phase-flow	Boiling	Recon-densation	Target 1 (Germany): Radionuclide release	Target 2 (USA): Dose constraints
Reference Scenario: The EBS retains its function over 50000 years									
Case 1: Water flow from overburden through the shaft to the disposal zones + Gas production inside the repository from corrosion of the casks (Case 2)								not considered	
Case 3: Water source inside the repository from inter-/ intragranular salt solutions + Gas production inside the repository from corrosion of the casks (Case 2)								not considered	

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Modelling Concept for the EBS Integrity Assessment

	Specification of hydraulic resistance			Demonstration of structural integrity				
	Hydraulic resistance -sealing element	Hydraulic resistance -contact zone	Hydraulic resistance -EDZ	Structural stability	Crack limitation	Deformation limitation	Filtration stability	Long-term stability
Reference Scenario: The EBS retains its function over 50000 years								
Case 1: Water flow from overburden through the shaft to the disposal zones	**H**: determination of flow rate and passing time (constant permeability) **HM:** including compaction of crushed salt (time dependent permeability)			**TM:** structural analysis of the EBS components			No modelling intended	**C:** determination of geochemical stability of the sealing elements against water/brine **T**: temperature effects on EBS-materials
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BGE TEC (purple) **SANDIA** (green)

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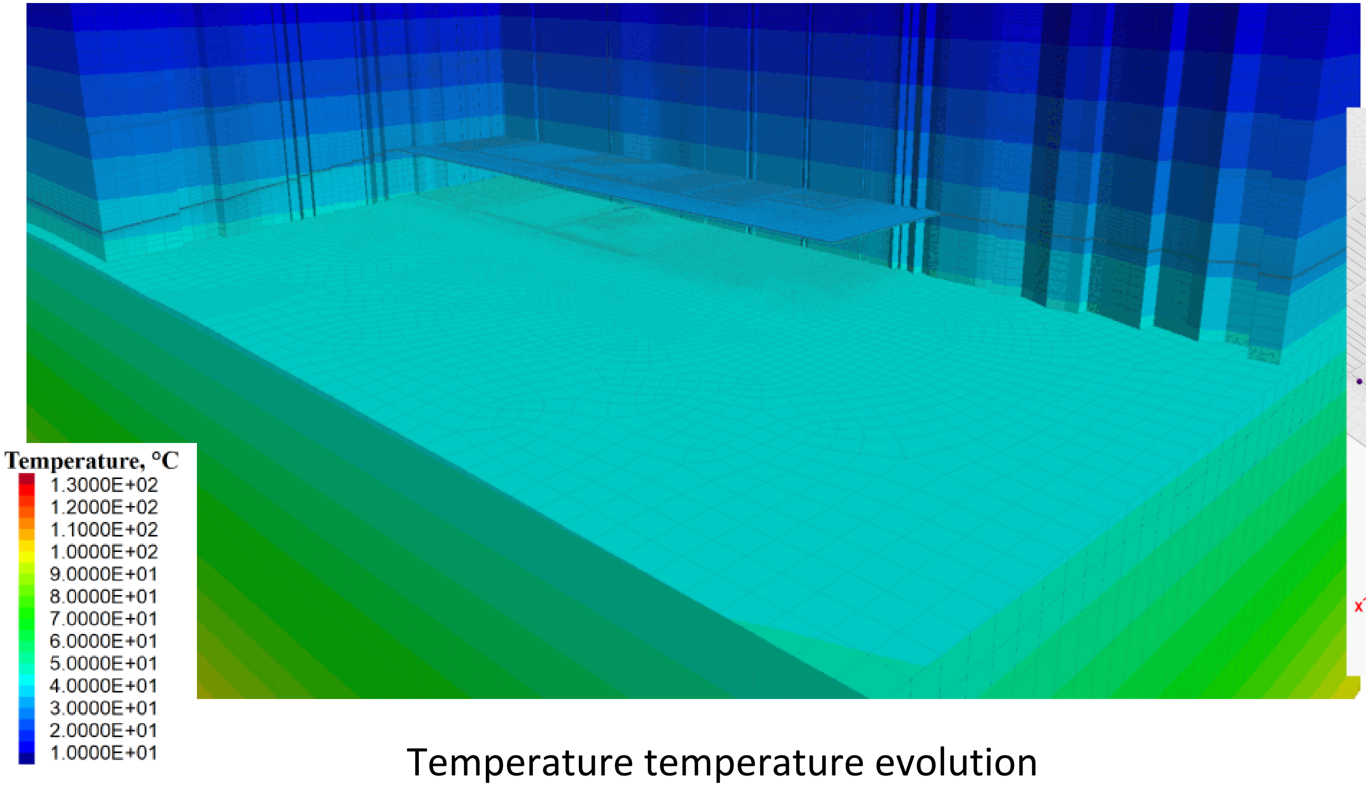
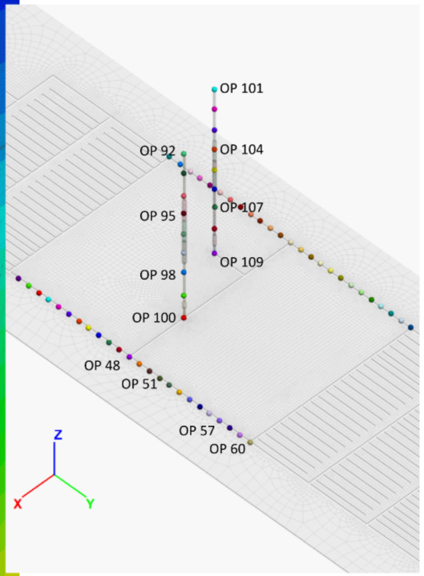
Numerical Applications: Temperature Effects

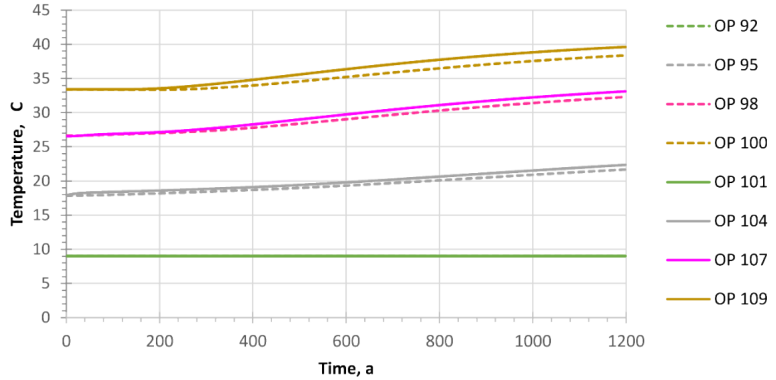
- Temperature effects on EBS-materials based on thermal analyses
  - Maximum temperature rise in the drift seal: less than 20°C
  - Maximum temperature rise in the shaft seal: about 5°C



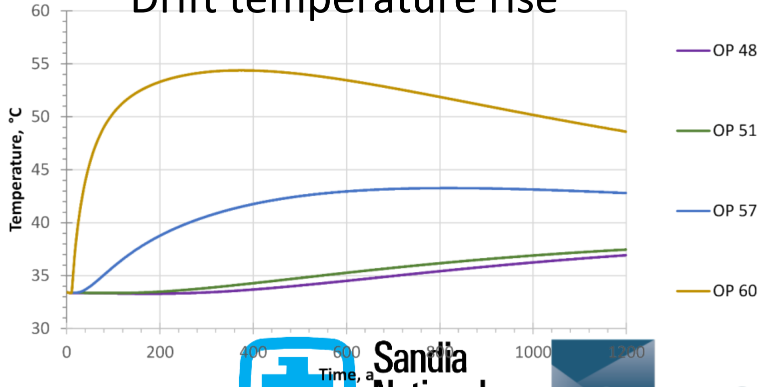
Temperature temperature evolution



Shaft temperature rise



Drift temperature rise



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Numerical Applications: Geochemical Stability

- Modelling water interaction with “crushed salt” layer
  - Assuming salt and host rock of same composition
  - Surface water and cap rock water with different compositions

			NaCl	CaSO4	MgSO4	KCl	MgCO3
	length [m]	[%]	Halite	Anhydrite	Kiserit	Silvinit	Magnesit
Am3	10	12%	90%	10%	0%	0%	0%
K3	18	21%	60%	0%	15%	25%	0%
NA3	26	31%	98%	2%	0%	0%	0%
A3	12	14%	0%	95%	0%	0%	5%
K2	18	21%	60%	0%	15%	25%	0%
Total	**84**		**67%**	**15%**	**6%**	**11%**	**1%**

- Equilibrium and reaction calculations via EQ3/6[1]

- Reacted salt layer by layer in listed table order (Am3 → K3 → NA3 → A3 → K2)

- Reactions:
  - Temperatures: 25 °C and 40 °C; Pressure at 1 bar
  - Batch reaction with 15 mol of each phase present in that layer, such that most phases will be in excess

Element	**Konzentration [mol/kg H_2O]**	
	Regenwasser	**Gipshutlösung**
Na^{+}	8,07E-05	4,96E+00
K^{+}	1,90E-06	3,61E-02
Ca^{++}	1,98E-04	3,52E-02
Mg^{++}	n.e.	5,64E-02
Cl^{-}	8,07E-05	5,07E+00
SO^{4-}	1,98E-04	5,15E-02
SiO_2(aq)	n.e.	5,49E-04
Al^{+++}	n.e.	1,19E-05
HCO^{3-}	3,19E-06	2,10E-03
pH	5,81	6,3

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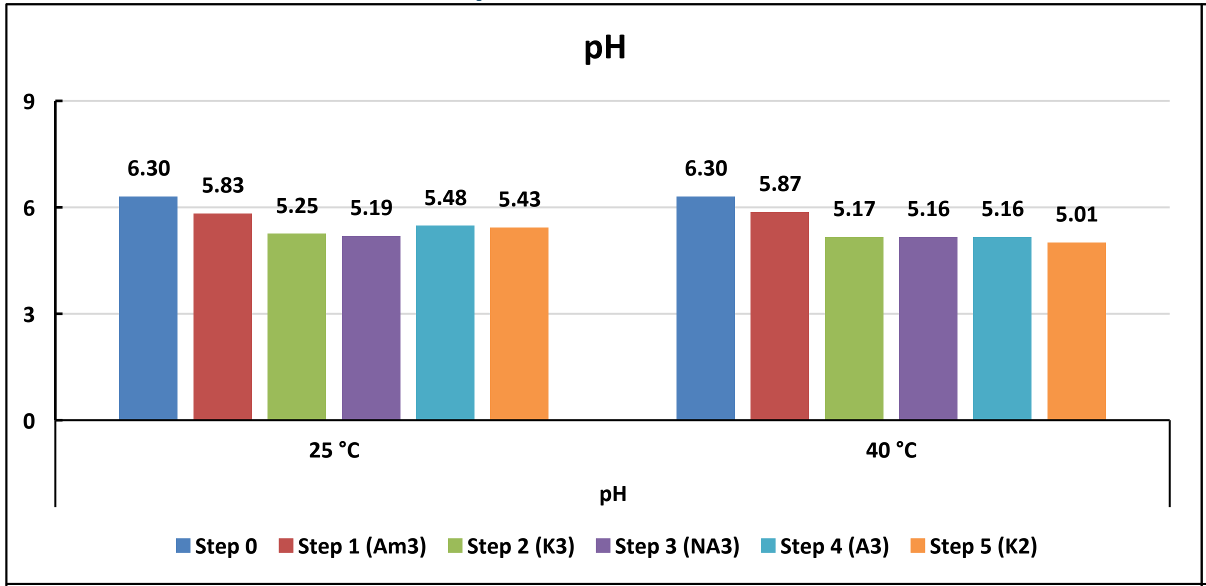
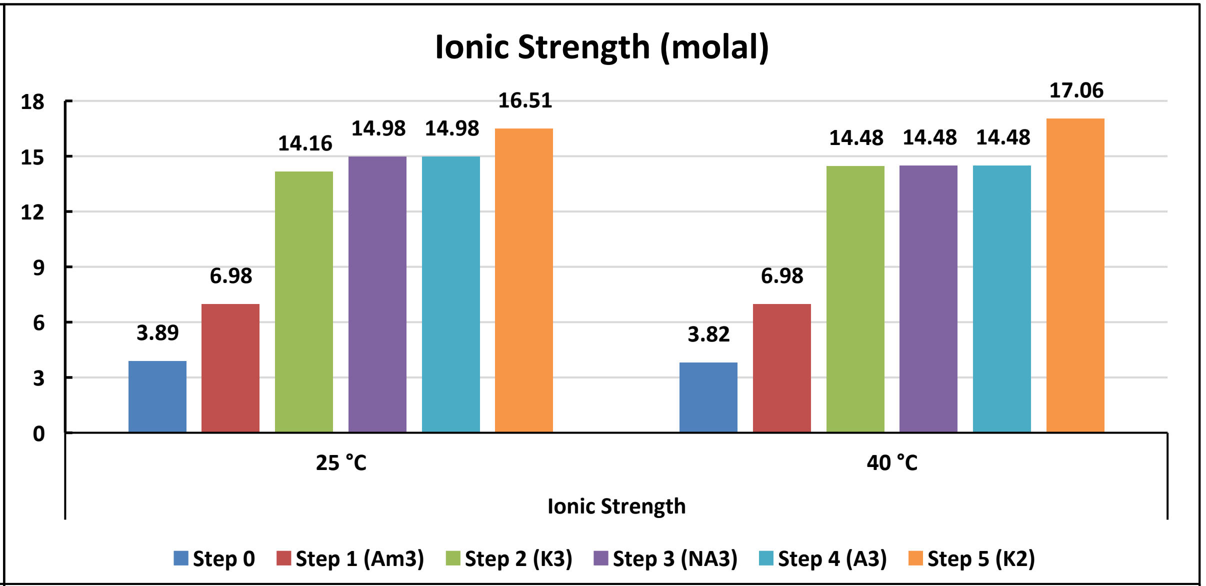
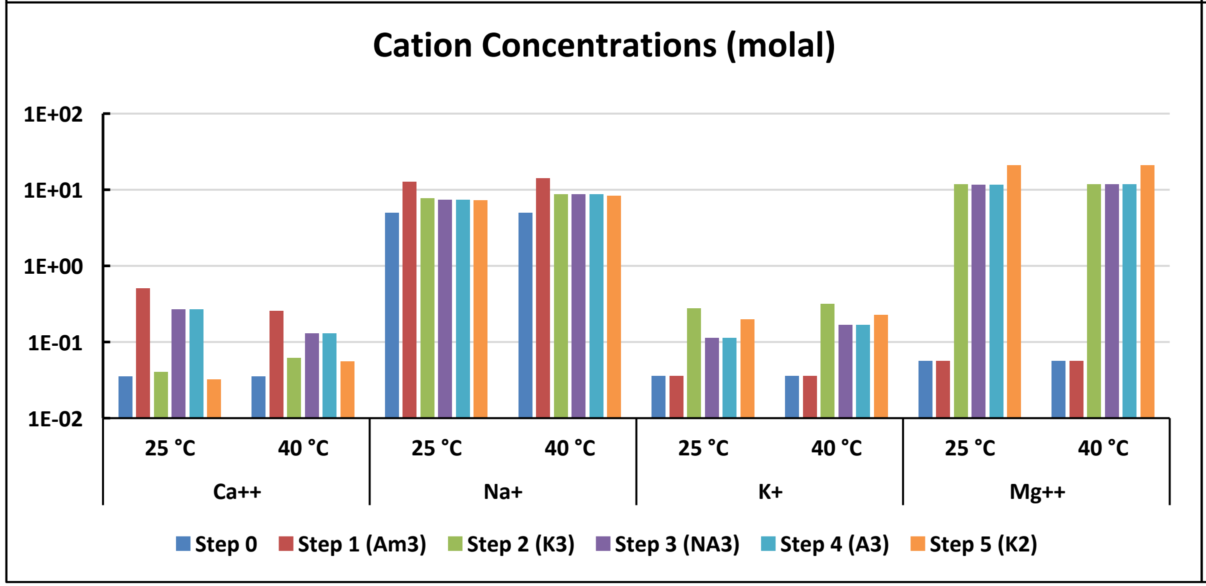
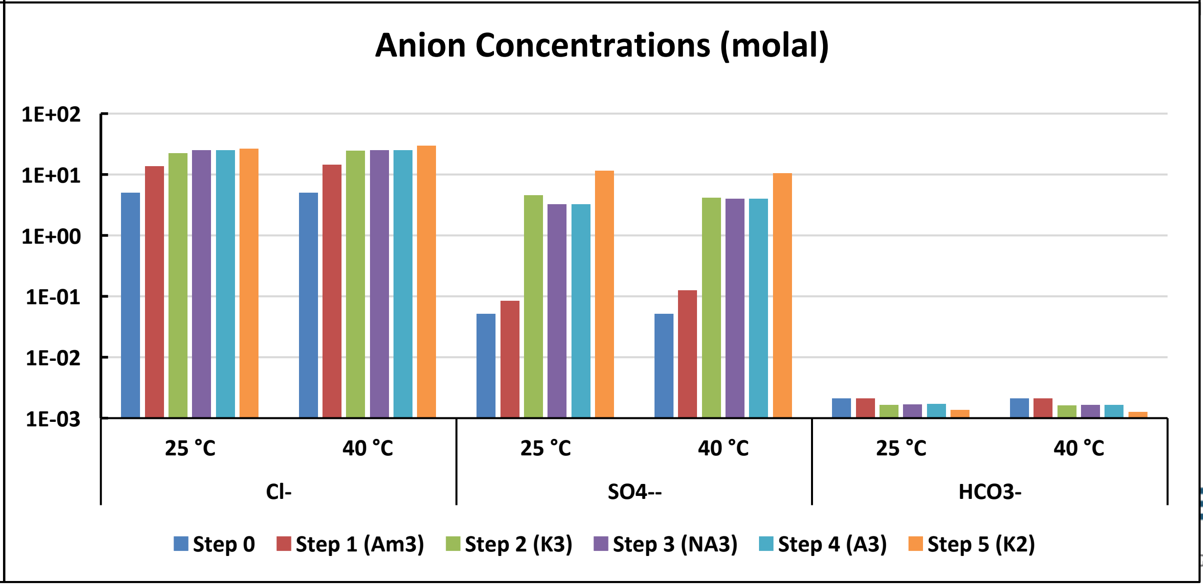
Numerical Applications: Geochemical Stability

- Results for cap rock water









Modelling Concept for Repository Performance Assessment

- **Based on the same mesh used in integrity assessment simulation (>3.4 million elements)**
  - All drifts, shafts & layers resolved
  - Individual waste packages not resolved
- **Drifts initially open, backfilled with crushed salt at emplacement**
- **Two-phase flow: brine and air:** Gas generation term handled easily
- **Decay heat leads to boiling water:** Numerically difficult problem
- **Porosity will eventually change to follow FLAC results**
  - New mode in PFLOTRAN allowing time-variable porosity (late 2021)

	Processes							Target Criteria	
	Nuclide decay	Advection	Diffusion	Convection/ conduction	2-Phase-flow	Boiling	Recon-densation	Target 1 (Germany): Radionuclide release	Target 2 (USA): Dose constraints
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Case 3: Water source inside the repository from inter-/ intragranular salt solutions + Gas production inside the repository from corrosion of the casks (Case 2)								not considered	

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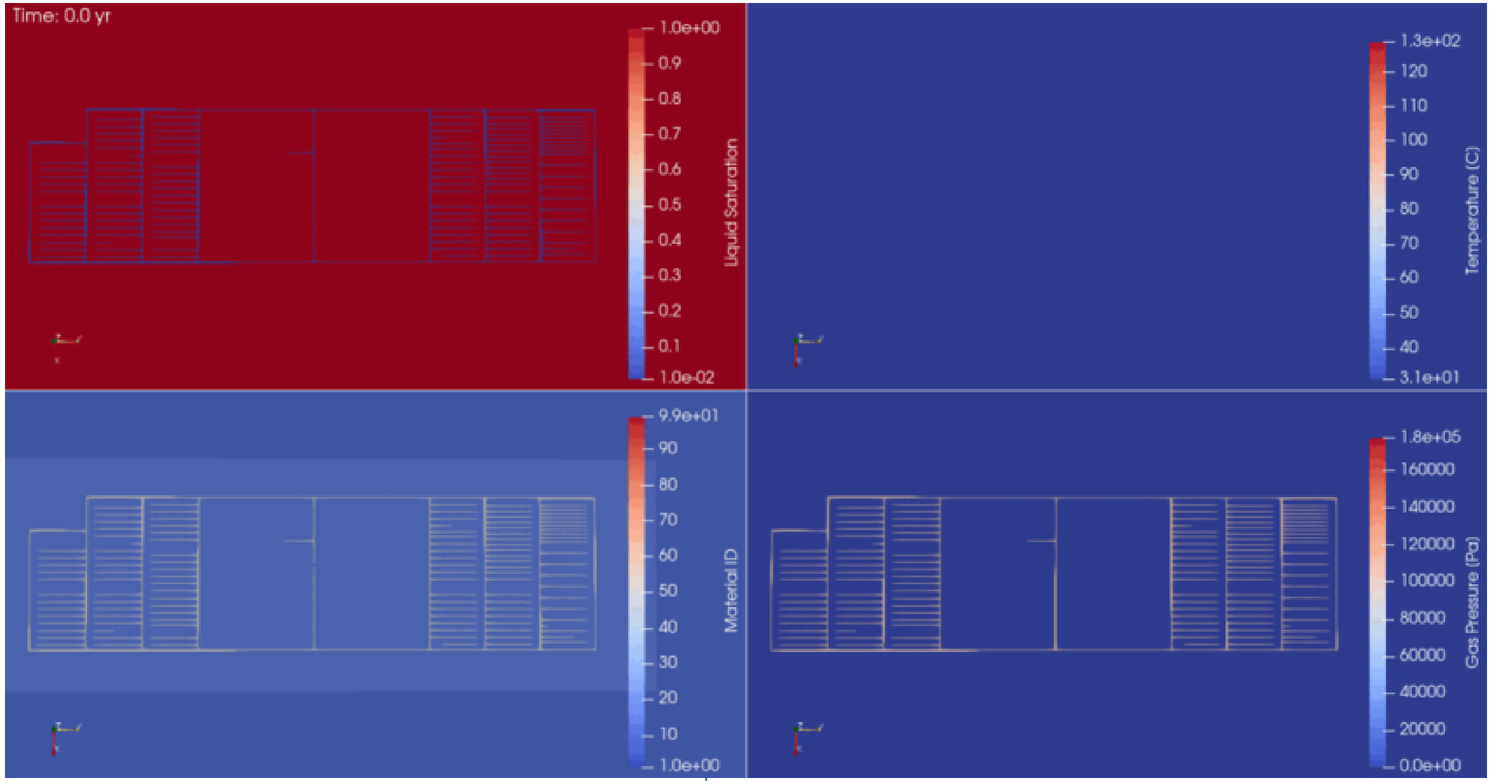
Numerical Applications: Performance Assessment

- **Cutting-edge PA simulation capability being developed during this project**
  - New brine equation-of-state (EOS) implemented in PFLOTRAN (2022)
  - New non-linear solver implemented in PFLOTRAN (2022)
  - Implicit mechanical coupling to cover the TH²MC-range of processes
  - Radioactive source terms will be added
  - Integrity assessment and performance assessment based on a single large scale FE-model



Conclusions

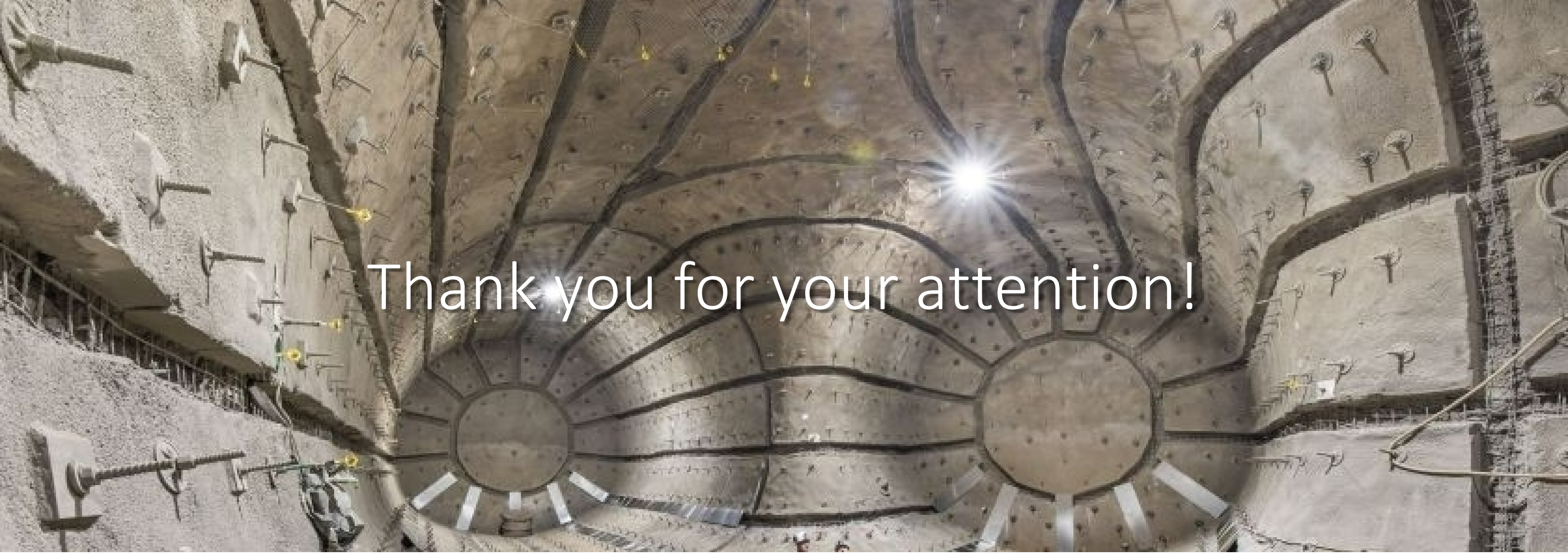
- A methodology for the for design and performance assessment of EBS in a HLW repository in salt formations has been developed

- The engineered barrier system for a repository system in salt have been developed based on the experience and insights gained from previous research project and salt repositories in construction

- The methodology has been applied for the preliminary design of the EBS of a generic repository system in Germany based on the generic salt pillow model developed in the KOSINA project

- The methodology is now being used to assess the integrity of the EBS and the long term evolution of the repository system

Thank you for your attention!



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Karlsruher Institut für Technologie

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