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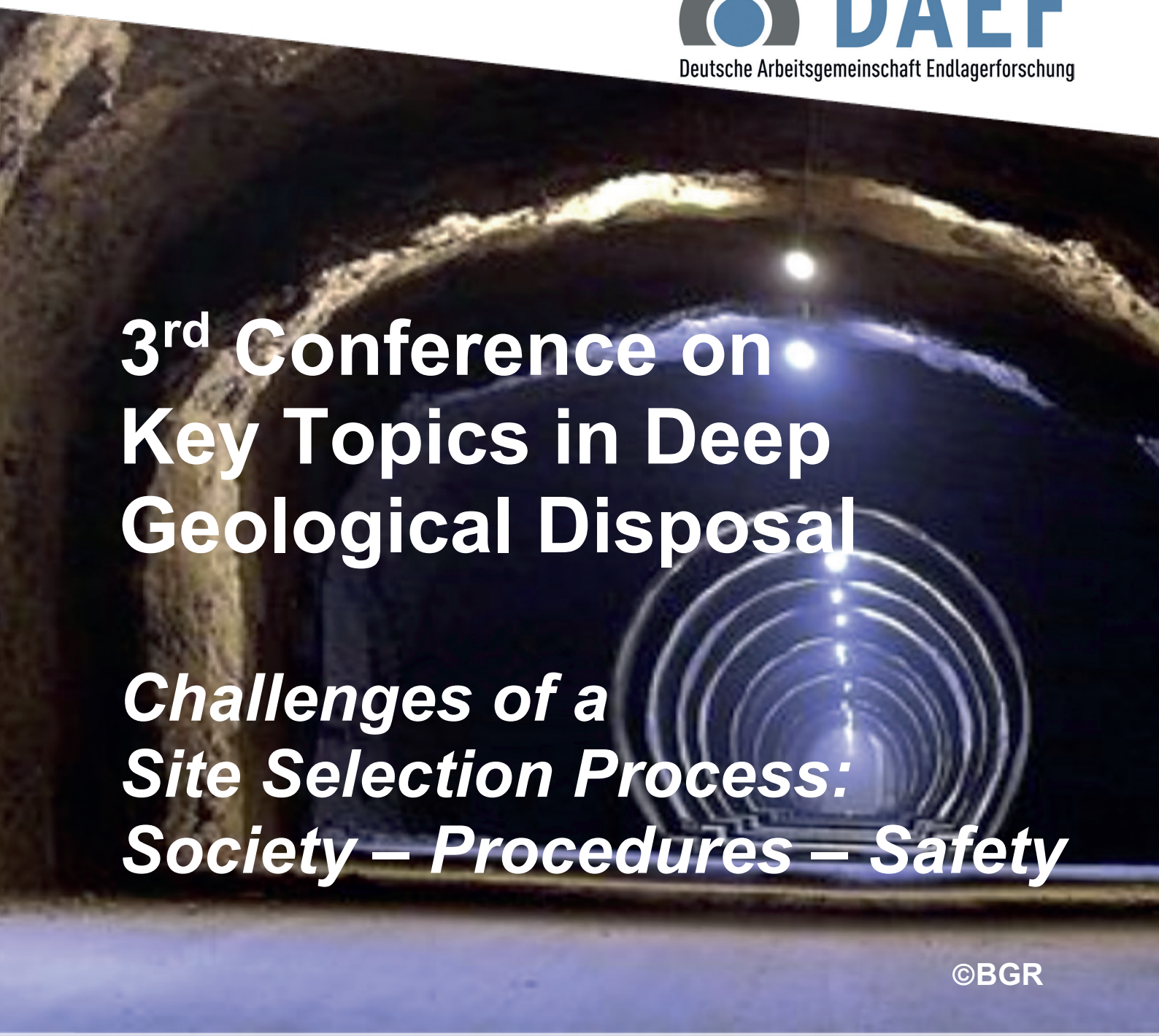

3rd Conference on Key Topics in Deep Geological Disposal

Challenges of a Site Selection Process: Society – Procedures – Safety

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Cologne, 04 – 06 July 2022

BOOK OF ABSTRACTS

MONDAY (04 JULY 2022)

17:00	**REGISTRATION**
19:00	**ICEBREAKER**

TUESDAY (05 JULY 2022)

07:30	Registration – Conference office opens
08:15	Welcome

SESSION 1 HIGH-LEVEL WASTE / SPENT NUCLEAR FUEL MANAGEMENT STRATEGIES AND GOVERNANCE: RESEARCH IN HUMANITIES AND SOCIAL SCIENCES (TOPIC 4 – PART 1)

Chairs: *J. Ahlswede (Germany) and M. Schreurs (Germany)*

08:30	BUILDING CONFIDENCE IN THE FACE OF UNCERTAINTY: THE ROLE OF THE SAFETY CASE *L. Bailey, P. Künzi (**Keynote**) (UK, Switzerland)*	**S1-01**
09:00	TRANSDISCIPLINARY RESEARCH ON NUCLEAR WASTE MANAGEMENT – CAN IT WORK? A CASE STUDY ON REPOSITORY SAFETY *K.-J. Röhlig, M. Ebeling, A. Eckhardt, P. Hocke, P. Krütli (Germany)*	**S1-02**
09:20	COGNITIVE BIASES AND GROUP BIASES IN ORGANIZATIONS - DEVELOPMENT OF A QUESTIONNAIRE FOR THE BIAS-RELATED DIAGNOSIS OF PLANNING PROCESSES *F. Englisch, O. Sträter (Germany)*	**S1-03**
09:40	REVIEW OF COPPER CORROSION BY THE SWEDISH RADIATION SAFETY AUTHORITY (SSM) IN THE CONTEXTS OF THE LOT EXPERIMENTS AT THE ÄSPÖ FACILITY AND THE ONGOING LICENSING PROCESS FOR ESTABLISHING A REPOSITORY FOR SPENT NUCLEAR FUEL IN SWEDEN *B. Strömberg (Sweden)*	**S1-04**

TUESDAY (05 JULY 2022)

10:00	SPATIAL EFFECTS OF SURFACE FACILITIES FOR FINAL DISPOSAL: PERCEPTIONS OF THE SAME AND IMPACT ON PLACE ATTACHMENT – A TRANSDISCIPLINARY EXPERIMENTAL SETTING *M. Mbah, J. Neles, S. Bremer, T. Leusmann, D. Lowke (Germany)*	**S1-05**
10:20	COFFEE BREAK	

SESSION 2 HIGH-LEVEL WASTE / SPENT NUCLEAR FUEL DISPOSAL: RESEARCH AND DEVELOPMENT IN NATURAL SCIENCES AND ENGINEERING (TOPIC 3 – PART 1)

Chairs: *L. Bailey (UK) and B. Grambow (France)*

10:50	MICHIGAN INTERNATIONAL COPPER ANALOGUE (MICA) PROJECT – RECENT ADVANCES *H. Reijonen, I. Aaltonen, C. Lilja, A. Liebscher, S. Norris, P. Keech, N. Diomidis, T. Bornhost (Finland)*	**S2-01**
11:10	EXPERIMENTAL INVESTIGATION OF RADIONUCLIDE RELEASE FROM SPENT NUCLEAR FUELS UNDER CONDITIONS EXPECTED IN A DEEP GEOLOGICAL REPOSITORY LOCATED IN ARGILLACEOUS, CRYSTALLINE OR SALINE ROCKS – STATE OF KNOWLEGDE *M. Herm, E. Bohnert, L. Iglesias-Pérez, T. König, V. Metz, A. Walschburger, H. Geckeis (Germany)*	**S2-02**

TUESDAY (05 JULY 2022)

11:30	THE OPENGEOSYS SOFTWARE FRAMEWORK FOR REACTIVE TRANSPORT AND CHEMO-MECHANICAL MODELING IN DEEP GEOLOGICAL DISPOSAL *V. Montoya, J. Garibay-Rodriguez, R. Lu, H. Shao, D. Naumov, K. Yoshioka, J. Poonoosamy, O. Kolditz (Germany)*	**S2-03**
11:50	INTRODUCTION OF POSTER PRESENTATIONS *V. Brendler, F. Charlier (Germany)*	**S2-04**
12:30	LUNCH BREAK	

SESSION 3 STATUS OF HIGH-LEVEL WASTE / SPENT NUCLEAR FUEL REPOSITORY SITING IN GERMANY: VIEWS OF DIFFERENT ACTORS (TOPIC 1)

Chairs: *P. Künzi (Switzerland) and K.-J. Röhlig (Germany)*

14:00	FINALIZING PHASE ONE – TOWARDS THE IDENTIFICATION OF SITES OF INTEREST FOR A SURFACE EXPLORATION FOR A GERMAN HIGH LEVEL RADIOACTIVE WASTE REPOSITORY *L. Seidel, S. Reiche, W. Rühaak (**Keynote**) (Germany)*	**S3-01**
14:30	ENABLING AND SUPERVISING A UNIQUE & NOVEL PROCEDURE - BASE'S STATUTORY TASKS & VIEW ON THE GERMAN APPROACH TO SITE SELECTION FOR A DEEP GEOLOGICAL DISPOSAL REPOSITORY FOR HIGH-LEVEL WASTE AND ITS CURRENT STATUS *C. Weiss, C. Borkel, S. Drees, F. Emanuel (**Keynote**) (Germany)*	**S3-02**
15:00	SUPPORTING THE DEVELOPMENT AND PRESERVATION OF TRUST IN THE SEARCH OF A HIGH-LEVEL RADIOACTIVE WASTE DISPOSAL SITE IN GERMANY *M. Schreurs, A. Grunwald (**Keynote**) (Germany))*	**S3-03**

TUESDAY (05 JULY 2022)

15:30 DISCUSSION

16:00 COFFEE BREAK

SESSION 4 STATUS OF HIGH-LEVEL WASTE / SPENT NUCLEAR FUEL DISPOSAL PROGRAMMES IN VARIOUS COUNTRIES: TECHNICAL AND SOCIETAL ASPECTS (TOPIC 2 – PART 1)

Chairs: *J. Mönig (Germany) and T. Vietor (Switzerland)*

16:30 THE SUCCES AND FAILURE OF HIGH LEVEL NUCLEAR WASTE MANAGEMENT PROGRAMS. SCIENCE AND TECHNOLOGY VS SOCIAL ACCEPTANCE AND POLITICAL (IN)ACTION **S4-01**
J. Bruno (Spain)

16:50 POSIVA SUBMITTED THE OPERATING LICENCE APPLICATION FOR ENCAPSULATION AND FINAL DISPOSAL FACILITY **S4-02**
J. Makkonen, R. Ylöstalo (Finland)

17:10 REGULATORY REQUIREMENTS FOR ESTIMATING THE ADDITIONAL MEAN EFFECTIVE ANNUAL DOSE IN THE CONTEXT OF THE GERMAN SITE SELECTION PROCEDURE **S4-03**
C. Borkel, A. Diener, S. Hellebrandt, M. Jendras, M. Krauß, O. Onkun, S. Schöbel, F. Schulzeck, M. Steiner (Germany)

17:30 BREAK

TUESDAY (05 JULY 2022)

SESSION 5 POSTER SESSION (19:00 – 22:00)

Incl. Dinner buffet

TOPIC 2: STATUS OF HIGH-LEVEL WASTE / SPENT NUCLEAR FUEL DISPOSAL PROGRAMMES IN VARIOUS COUNTRIES: TECHNICAL AND SOCIETAL ASPECTS

P1-01 ANALYSIS OF INTERACTIONS BETWEEN OPERATIONAL SAFETY AND POST-CLOSURE SAFETY OF A HLW REPOSITORY
A. Lommerzheim, J. Wolf, N. Bertrams, D. Buhmann, B. Förster, P. Herold, J. Leonhard, U. Noseck (Germany)

TOPIC 3: HIGH-LEVEL WASTE / SPENT NUCLEAR FUEL DISPOSAL: RESEARCH AND DEVELOPMENT IN NATURAL SCIENCES AND ENGINEERING

P2-01 ICROSS – INTEGRITY OF NUCLEAR WASTE REPOSITORY SYSTEMS – CROSS-SCALE SYSTEM UNDERSTANDING AND ANALYSIS: A MULTIDISCIPLINARY COLLABORATIVE RESEARCH PROJECT IN THE HELMHOLTZ ASSOCIATION
D. Bosbach, H. Geckeis, O. Kolditz, M. Kühn, T. Stumpf, G. Deissmann, iCross Team (Germany)

P2-02 THE CORI PROJECT ON CEMENT-ORGANIC-RADIONUCLIDE-INTERACTIONS – AN ACTIVITY WITHIN THE EC EURAD PROJECT
M. Altmaier (Germany)

P2-03 IMPLEMENTATION OF RETRIEVABILITY IN GERMAN REPOSITORY CONCEPTS FOR HIGH-LEVEL RADIOACTIVE WASTE IN CRYSTALLINE FORMATIONS
P. Herold, J. Leonhardt, A. Keller, R. P. Leon Vargas (Germany)

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P2-04 RECENT ADVANCES IN THE LABORATORY COMPACTION OF CRUSHED SALT
B. Laurich, K. Svensson, K. Zemke, D. Stührenberg (Germany)

P2-05 FEP AND SCENARIOS – BASIC TOOLS FOR THE DESIGN AND PERFORMANCE ASSESSMENT OF GEOTECHNICAL BARRIERS
A. Lommerzheim, N. Müller-Hoeppe (Germany)

P2-06 THE USE OF NATURAL ANALOGUES IN THE SITE SELECTION PROCESS
N. Marcos, H. Reijonen (Finland)

P2-07 FROM FRACTURES TO MODELS: IT'S ALL ABOUT NETWORKING
C. Müller, J. Flügge, A. Hassanzadegan, H. Zhao (Germany)

P2-08 OVERVIEW OF BGR'S PARTICIPATION IN EXPERIMENTS AT THE MONT TERRI ROCK LABORATORY, SWITZERLAND
D. Rebscher, BGR Mont Terri Project Team (Germany)

P2-09 CONTRIBUTION OF BENTONITE AND CEMENTITIOUS MATERIAL TO ACTINIDE RETENTION UNDER HYPERALKALINE CONDITIONS AND INCREASED IONIC STRENGTH
K. Schmeide, (Germany)

P2-10 SHAFT SEALING BY SANDWICH SEAL SYSTEMS: A LARGE-SCALE EXPERIMENT PERFORMED AT THE MONT TERRI ROCK LABORATORY
K. Wieczorek, K. Emmerich, R. Schuhmann, J. Hesser, M. Furche, D. Jaeggi, S. Schefer, J. Aurich, J. Carlos Mayor, S. Norris, K. Birch, M. Sentis, J. L. García-Siñeriz, F. Königer, U. Glaubach, C. Rölke, R. Diedel (Germany)

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P2-11 VOLUME CHANGE BEHAVIOR OF UNSATURATED CLAYSTONE/ BENTONITE MIXTURE SAMPLES CHARACTERIZED BY DIFFERENT INITIAL DRY DENSITIES
M. Middelhoff, O. Cuisinier, F. Masrouri, J. Talandier (France)

P2-12 ASSESSMENT OF RADIONUCLIDE SOLUBILITY AND RADIONUCLIDE SOURCE TERMS FOR DIFFERENT HOST-ROCK CONDITIONS
D. Fellhauer, X. Gaona, M. Altmaier, H. Geckeis (Germany)

P2-13 THEREDA – THERMODYNAMIC REFERENCE DATABASE FOR THE NUCLEAR WASTE DISPOSAL IN GERMANY
F. Bok, H. C. Moog, X. Gaona, D. Freyer, L. Wissmeier (Germany)

P2-14 A SYSTEMATIC APPROACH FOR SURFACE EXPLORATION OF SITES – A DATABASE TO RESEARCH AND EVALUATE SUITABLE METHODS
R. Dlugosch, T. Beilecke, T. Kneuker, L. Pollok, L. Richter, N. Schubarth-Engelschall, R. Semroch (Germany)

P2-15 COMPACTION OF CRUSHED SALT FOR THE SAFE CONTAINMENT – OVERVIEW OF PHASE 2 OF THE KOMPASS PROJECT
L. Friedenberg, J. Bartol, J. Bean, O. Czaikowski, U. Düsterloh, N. Müller-Hoeppe, B. Laurich, C. Lerch, S. Lerche, C. Lüdeling, M. Mills, T. Popp, B. Reedlunn, K. Svensson, L. Wenting, K. Zemke, J. Zhao (Germany)

P2-16 OVERCORING OF NUCLEAR WASTE CANISTERS FOR RETRIEVAL FROM SHORT VERTICAL BOREHOLES
A. Keller, P. Herold (Germany)

P2-17 ADVANCING TRANSIENT SIMULATION OF HYDRO-MECHANICALLY COUPLED SYSTEMS IN GEOLOGICAL DISPOSAL APPLICATIONS
D. Kern, T. Deng, F. Magri, V. I. Malkovsky, T. Nagel (Germany)

TUESDAY (05 JULY 2022)

P2-18 INFLUENCE OF RESIDUAL STRESSES ON BARRIER INTEGRITY DEMONSTRATION FOR ROCK SALT
Nina Müller-Hoeppe (Germany)

P2-19 SIMULATION OF RADIONUCLIDE DIFFUSION PROFILES IN BENTONITE – PREDICTION FOR THE LONG TERM IN-SITU TEST AT GRIMSEL TEST SITE (GTS), SWITZERLAND
U. Noseck, T. Schäfer, I. Blechschmidt (Germany)

P2-20 GEOPHYSICAL CHARACTERISATION OF TECTONIC FAULT ZONES IN THE VICINITY OF POTENTIAL REPOSITORY SITES: A CASE EXAMPLE FROM SWITZERLAND
T. Spillmann, H. Madritsch, T. Diehl, A. Hölker (Switzerland)

P2-21 IMPLEMENTATION OF A TEMPERATURE- AND STRESS-DEPENDENT APPROACH TO DESCRIBE BITUMEN MATERIAL BEHAVIOUR AS SEALING MATERIAL
R. P. León-Vargas, P. Herold, E. Simo (Germany)

P2-22 RETENTION OF RADIONUCLIDES IN THE SURROUNDINGS OF A REPOSITORY FOR NUCLEAR WASTE: SELECTED SCENARIOS
J. Lützenkirchen, F. Heberling, A. Skerencak-Frech, M. Altmaier, V. Metz, H. Geckeis (Germany)

P2-23 AN INTERNATIONAL JOINT EXERCISE ON SENSITIVITY ANALYSIS: FIRST RESULTS
E. Plischke, K.-J. Röhlig (Germany)

P2-24 SPANNEND PROJECT: 3-D STRESS MODELLING IN THE UPPER CRUST OF GERMANY
O. Heidbach, K. Reiter, S. Ahlers, S. Morawietz, L. Röckel, T. Hergert, A. Henk, B. Müller, F. Schilling (Germany)

TUESDAY (05 JULY 2022)

TOPIC 4: SCIENTIFIC ASPECTS OF THE NUCLEAR WASTE DISPOSAL SAFETY CASE

P3-01 ON HUMAN CLOSENESS AND SAFETY: PARTICIPATION IN THE PRODUCTION OF EXECUTIVE ORDER LAW FOR THE IMPLEMENTATION OF THE GERMAN SITE SELECTION ACT
U. Smeddinck (Germany)

TOPIC 5: COMPETENCE BUILDING AND KNOWLEDGE TRANSFER

P4-01 RECERTIFICATION OF THE WASTE ISOLATION PILOT PLANT: PERFORMANCE ASSESSMENT CALCULATIONS TO DEMONSTRATE REGULATORY COMPLIANCE
T. R. Zeitler, S. Brunell, D. Kicker, J. Long (USA)

WEDNESDAY (06 JULY 2022)

08:00 Registration – Conference office opens

SESSION 6 COMPETENCE BUILDING AND KNOWLEDGE TRANSFER (TOPIC 5)

Chairs: *K.-J. Röhlig (Germany) and O. Sträter (Germany)*

09:00 LONG-TERM STRATEGIES FOR COMPETENCE BUILDING AND KNOWLEDGE TRANSFER FOR A SAFE DISPOSAL OF NUCLEAR WASTE **S6-01**
*J. Ahlswede (**Keynote**) (Germany)*

09:30 IMPLEMENTATION OF KNOWLEDGE MANAGEMENT (KM) IN THE GERMAN WMO **S6-02**
P. L. Wellmann, G. Hoefer (Germany)

SESSION 7 STATUS OF HIGH-LEVEL WASTE / SPENT NUCLEAR FUEL DISPOSAL PROGRAMMES IN VARIOUS COUNTRIES: TECHNICAL AND SOCIETAL ASPECTS (TOPIC 2 – PART 2)

Chairs: *K.-J. Röhlig (Germany) and O. Sträter (Germany)*

09:50 THE LAST 15 YEARS OF SEISMIC EXPLORATION IN NORTHERN SWITZERLAND: CONTRIBUTIONS TO DEFINITION, CHARACTERIZATION AND SELECTION OF SITES FOR DEEP GEOLOGICAL DISPOSAL **S7-01**
H. Madritsch, P. Birkhäuser, M. Hertrich, M. Schnellmann, T. Spillmann, T. Vietor (Switzerland)

10:10 THE ROLE OF SAFETY ASSESSMENTS IN DEVELOPING CONSISTENT AND PLAUSIBLE SITE SELECTION AND POST-CLOSURE SAFETY ARGUMENTS **S7-02**
T. U. Kaempfer, X. Li, P. Marschall (Switzerland)

WEDNESDAY (06 JULY 2022)

10:30 COFFEE BREAK

SESSION 8 HIGH-LEVEL WASTE / SPENT NUCLEAR FUEL DISPOSAL: RESEARCH AND DEVELOPMENT IN NATURAL SCIENCES AND ENGINEERING (TOPIC 3 – PART 2)

Chairs: *P. Herold (Germany) and A. Liebscher (Germany)*

11:00	EURAD: A STEP CHANGE IN EUROPEAN JOINT COLLABORATION TOWARDS SAFE RADIOACTIVE WASTE MANAGEMENT *B. Grambow, T. Beattie, P. Carbol, E. Salat, L. Theodon, R. Winsley, P. Zuidema* ***(Keynote)*** *(France)*	**S8-01**
11:30	RESEARCH AND DEVELOPMENT FOR HIGH-LEVEL NUCLEAR WASTE REPOSITORY IN GERMANY *A. Göbel, A. Liebscher, A. Strusińska-Correia, T. Knuuti (Germany)*	**S8-02**
11:50	SAFETY FACING UNCERTAINTY – STEPS TOWARDS A HOLISTIC AND MORE COMPREHENSIVE ASSESSMENT OF UNCERTAINTIES IN THE SAFETY CASE *A. Eckhardt, K.-J. Röhlig (Switzerland)*	**S8-03**
12:10	A SYSTEMATIC APPROACH TO DEVELOP RECOMMENDATIONS FOR SURFACE EXPLORATION IN GERMANY – BGR PROJECTS „GEOMEPS AND ZUBEMERK“ *L. Richter, T. Beilecke, R. Dlugosch, T. Kneuker, L. Pollok, N. Schubarth-Engelschall, R. Semroch (Germany)*	**S8-04**

WEDNESDAY (06 JULY 2022)

12:30	DEEP BOREHOLE DISPOSAL OF LONG-LIVED INTERMEDIATE LEVEL WASTE – GENERIC SITE SCREENING TOOLS ACCOUNTING FOR GEOLOGICAL FAULTS *U. Kelka, T. Poulet, P. Schaubs, H. Sheldon, L. Esteban, D. Mallants (Australia)*	**S8-05**
12:50	LUNCH BREAK	

SESSION 9 HIGH-LEVEL WASTE / SPENT NUCLEAR FUEL DISPOSAL: RESEARCH AND DEVELOPMENT IN NATURAL SCIENCES AND ENGINEERING (TOPIC 3 – PART 3)

Chairs: *A. Göbel (Germany) and U. Noseck (Germany)*

14:00	KOMBILYSE: COMBINED APPROACH TO SAFETY-RELEVANT ASPECTS FROM THE PERSPECTIVE OF EXTENDED STORAGE AND DISPOSAL OF HIGH-LEVEL RADIOACTIVE WASTE *O. Bartos, J. Krüger, K. Hummelsheim, J. Nicol, F. Rowold, F.-N. Sentuc, M. Tzivaki (Germany)*	**S9-01**
14:20	SYSTEMATIC TOP-DOWN APPROACH TO DEVELOP WASTE CONTAINERS FOR HEAT-GENERATING RADIOACTIVE WASTE AND SPENT FUEL IN DIFFERENT HOST ROCKS – RESULTS OF THE R&D PROJECT KOBRA *W. Bollingerfehr, A. Wunderlich, S. Prignitz, H. Völzke, C. Herold, D. Wolff (Germany)*	**S9-02**
14:40	DEVELOPMENT OF MAGNESIA SHOTCRETE WITH HARD STONE AND SALT SURCHARGE *J. Arendt, D. Freyer, M. Gruner, W. Kudla (Germany)*	**S9-03**

WEDNESDAY (06 JULY 2022)

15:00	SUPPORT OF UNDERGROUND OPENINGS IN A HLW/SF REPOSITORY IN CLAY STONE *J. te Kook, A. Studeny, B. Pflüger, C. Scior, A. Hucke (Germany)*	**S9-04**
15:20	LONG-TERM PERFORMANCE OF CONCRETE-BASED SUPPORT STRUCTURES FOR A HIGH-LEVEL RADIOACTIVE WASTE REPOSITORY IN CLAYSTONE *P. Herold, E. Simo, H.-J. Engelhardt, H. Räuschel, M. Manica, T. Meyer (Germany)*	**S9-05**
15:40	SAFETY AND SCIENCE: THE FRAGILE CONNECTION *B. Grambow, R. C. Ewing (France)*	**S9-06**
16:00	COFFEE BREAK	

SESSION 10 HIGH-LEVEL WASTE / SPENT NUCLEAR FUEL MANAGEMENT STRATEGIES AND GOVERNANCE: RESEARCH IN HUMANITIES AND SOCIAL SCIENCES (TOPIC 4 – PART 2)

Chairs: *K. Fischer-Appelt (Germany) and M. Mbah (Germany)*

16:30	LEGAL, CULTURAL AND POLITICAL CHALLENGES FOR TRANSBOUNDARY PUBLIC PARTICIPATION IN THE CONTEXT OF THE SITING PROCEDURE FOR HIGH-LEVEL RADIOACTIVE WASTE *F. Sperfeld, M. Mbah, S. Schütte (Germany)*	**S10-01**
16:50	FUTURE PICTURES FOR FINAL DISPOSAL *S. Enderle, P. Hocke (Germany*	**S10-02**

WEDNESDAY (06 JULY 2022)

17:10	NUCLEAR WASTE AS “MATTER OF CARE”: OPPORTUNITIES FOR A PARADIGM SHIFT IN THE LONG-TERM GOVERNANCE OF HLW AND SPENT FUEL IN BELGIUM *A. Bergmans, C. Parotte (Belgium)*	**S10-03**
17:30	CLOSING	
17:40	END	

OVERVIEW

Monday, 04 July 2022

17:00 ***Registration***

19:00 ***Icebreaker***

Tuesday, 05 July 2022

08:30 - 10:20 ***Session 1***
Topic 4: High-level waste / spent nuclear fuel management strategies and governance: Research in humanities and social sciences – Part 1

10:50 - 12:30 ***Session 2***
Topic 3: High-level waste / spent nuclear fuel disposal: Research and development in natural sciences and engineering – Part 1

14:00 – 16:00 ***Session 3***
Topic 1: Status of high-level waste / spent nuclear fuel repository siting in Germany: Views of different actors

16:30 - 17:30 ***Session 4***
Topic 2: Status of high-level waste / spent nuclear fuel disposal programs in various countries: Technical and societal aspects – Part 1

19:00 - 22:00 ***Session 5***
Poster Session

Wednesday, 06 July 2022

09:00 - 09:50 ***Session 6***
Topic 5: Competence building and knowledge transfer

09:50 - 10:30 ***Session 7***
Topic 2: Status of high-level waste / spent nuclear fuel disposal programs in various countries: Technical and societal aspects – Part 2

11:00 - 12:50 ***Session 8***
Topic 3: High-level waste / spent nuclear fuel disposal: Research and development in natural sciences and engineering – Part 2

14:00 - 16:00 ***Session 9***
Topic 3: High-level waste / spent nuclear fuel disposal: Research and development in natural sciences and engineering– Part 3

16:30 - 17:40 ***Session 10***
Topic 4: High-level waste / spent nuclear fuel management strategies and governance: Research in humanities and social sciences – Part 2

S1-01: Building Confidence in the Face of Uncertainty: The Role of the Safety Case

Lucy Bailey [1], Pascale Kunzi [2]

[1] RWM, UK, IGSC Chair

[2] BFE, Switzerland, FSC Chair

Since 2016, two OECD-NEA sister groups, the Integration Group for the Safety Case (IGSC) and the Forum on Stakeholder Confidence (FSC), have been collaborating to make use of the Safety Case to enhance dialogue between scientists and the public to build confidence in deep geological disposal of radioactive wastes.

This collaboration began with the publication of a report, Communication on the Safety case for a Deep Geological Repository , produced by the IGSC and reviewed by the FSC, but it was quickly recognised that the true value of collaboration lay in engaging stakeholders throughout the safety case development process, not just in finding better ways of communicating the safety case. This was recognised in the first joint IGSC-FSC workshop held in September 2017 which used the highly interactive world café approach to identify topics and methods for collaboration.

The IGSC Safety Case Symposium in October 2018 included a dedicated session on the safety case and non-technical stakeholders, which concluded that although preparing and assessing the safety case is the work of specialists, active public participation leads not only to better acceptance, but also to faster and safer implementation, through the exchange of knowledge and experience with other disciplines. A second joint IGSC-FSC workshop held in October 2019 focused on managing uncertainty in the siting and implementation of a deep geological repository, where group discussions identified the following key points:

- Uncertainties and unresolved issues should be addressed openly and competently to build confidence. If stakeholders perceive that uncertainties are being downplayed, they are more likely to interpret the uncertainty as a threat.
- Stakeholders want to receive information they can trust, to be guided in coming to their own decision (which may include a risk assessment based on the uncertainties). They want to be able to form their own view as to whether risks are acceptable and, where possible, to have some control in mitigating the risks.
- To trust technical information, stake-holders first need to trust the integrity of the information provider.
- Uncertainties are part of daily life – they are “business as usual” for scientists and geological repository development is no exception.
- It is important to distinguish between risk (potential for harm) and uncertainty (lack of knowledge) in safety communications.
- Not all uncertainties are the same – stakeholders may be willing to accept some uncertainties but not others; hence, it is important to understand stakeholder values and concerns. Uncertainties should always be presented in a context to which the stakeholder can relate. The more familiar an uncertainty, the more likely it is to be accepted (e.g. uncertainties regarding travel, weather, medical X-rays are generally accepted).
- Different generations can have different approaches to accepting uncertainty – it may be easier for younger people to accept uncertainty.

The IGSC and FSC have planned a third joint workshop for May 2022, which will also involve local stakeholders from the siting regions being considered for a deep geological repository in Switzerland. The aims of this workshop are to:

- develop an understanding of what local stakeholders may need to gain confidence in the safety case – for example, to what extent they wish to understand the safety case themselves and/or have confidence in independent assessment of the safety case; and
- better understand how the safety case (including the management of uncertainties) is perceived by local stakeholders and what role local stakeholders may play in debate, participation, governance and decision-making.

In conclusion, collaboration between the IGSC and FSC to date has identified that trust in both the expertise of those assessing safety and the integrity of the experts and the organisations they represent is paramount to building stakeholder confidence. This is particularly the case regarding the management of the inevitable uncertainties associated with deep geological disposal. Empowering community stakeholders through early dialogue and developing the safety case in a way that reflects their needs and expectations will increase both the robustness of the safety case and confidence in the safety case.

References

1 Communication on the Safety case for a Deep Geological Repository, NEA Report No. 7336, OECD, 2017

2 IGSC Safety Case Symposium: Current Understanding and Future Direction for the Geological Disposal of Radioactive Waste, Rotterdam, Netherlands, October 2018

3 Managing Uncertainty in Siting and Implementation – Creating a Dialogue between Science and Society, Flyer for 2nd Joint IGSC-FSC Workshop, 9 October 2019

S1-02: Transdisciplinary research on nuclear waste management – can it work? A case study on repository safety

Klaus-Jürgen Röhlig[1], Marcel Ebeling[1], Anne Eckhardt[2], Peter Hocke[3], Pius Krütli[4]

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[2] risicare GmbH, Switzerland

[3] Institute of Technology Assessment and Systems Analysis (ITAS) at KIT, Germany

[4] Transdisciplinarity Lab, Eidgenössische Technische Hochschule (ETH), Switzerland

Complex societal challenges such as the disposal of high-level radioactive waste require not only the successful cooperation of different scientific disciplines, but also of practitioners and academia. A closer look at the literature on transdisciplinarity reveals that there is a variety of interpretations of the term (cf. e.g. Klein 2013). While it is used by some to describe a specifically high degree of integration of different scientific disciplines, others go a step further by using it for describing research involving « external », e.g. non-academic actors when jointly defining a research project (« co-design ») or acquiring knowledge (« co-production »). In addition, there are different views on the extent transdisciplinary research should be « transformative », i.e. aiming to change the « real world ».

The authors of this paper are part of a team of researchers from 16 institutes and departments of nine German and two Swiss universities and research institutions carrying out the joint project TRANSENS (Transdisciplinary Research on the Management of High-level Radioactive Waste in Germany, www.transens.de). The TRANSENS team understands transdisciplinarity as a reflexive, integrative, methodology-guided scientific principle directed at a societal problem and related scientific challenges by involving non-specialists and actors from practise. We aim at integrating a variety of knowledge bodies, values and expectations coming not only from academia but also from the dialogue with other actors.

One of several transdisciplinary work packages within TRANSENS is devoted to repository safety. While acknowledging that there are methods and tools available to technically assess safety (cf. e.g. NEA 2013), we also recognise scepticism and controversy about repository safety amongst stakeholdes, in the media and the interested public, a most recent example in Germany being the debate on the German Safety Requirements (EndlSiAnfV 2020).

In the working package, we aim at gaining input about optimisation potential for the tool « Safety Case » from various actors. In a stepwise approach, we involve actors with experience or scientific expertise concerning repository safety, scientists of relevant disciplines but without experience in the field of nuclear waste disposal, and a permanent group of non-specialists . By the end of 2021, we plan to complete the transdisciplinary formats involving the latter. Results and experiences especially from these formats will be at the core of the conference presentation.

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S1-03: Cognitive Biases and Group Biases in Organizations - Development of a Questionnaire for the Bias-Related Diagnosis of Planning Processes

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The quality of good decisions of all relevant actors is vital for the current process of finding a final nuclear disposal. There are several prominent examples of events where wrong decisions in the planning process led to catastrophic consequences. These include for instance the mass panic at the 2010 Love Parade in Duisburg, Germany, the Boeing 737 max accidents or the Fukushima nuclear disaster in 2011. The list of such cases could be continued at will. The question therefore arises as to where the causes of wrong decisions in planning lie and how decision-making processes of organisations can be structured in such a way that a thorough analysis of all opportunities and risks is always carried out in advance. There is robust evidence that in many cases the negative consequences could have been avoided because sufficient information was available at the time of the decisions that would have revealed the relevant risks as part of an adequate planning process and thus made them controllable (Synolakis & Kânoğlu, 2015). Often, event analyses reveal that certain individual or collective psychological effects - so-called cognitive biases or group biases - led to a deviation from a situation-appropriate decision-making process and thus to momentous misjudgments (Murata, Nakamura, & Karwowski, 2015; Sträter, 2005).

Biases are the consequences of cognitive or social heuristics (rules of thumb) that generally make everyday life easier, because through unconscious behavior patterns, they reduce complexity of decision making, while being accurate most of the time. But especially in novel and complex situations - such as those typical for planning processes in organizations - lead to errors. An example of this would be the Confirmation Bias, which is the human tendency to seek, remember, and interpret new information in a way, which coincides with existing beliefs, while most of the time it would be advisable to seek counterinformation and to question currently held assumptions. An example of a social heuristic is Groupthink, where people feel a strong coherence within their group, which can lead them to adjust their contrarian opinion to the their group's opinion. Furthermore the group might disregard the opinion from other stakeholders, which are not considered to be part of the group.

As part of a PhD study the Author operationalized cognitive biases and group biases in the context of organizational decision processes in order to develop a questionnaire for self-assessment regarding those biases.

When considering how to operationalize these cognitive and group biases for the context in question, it became apparent that organizational culture, and specifically safety culture according to Reason (1997), provides a suitable basis for applying bias-related behaviors to planning and decision-making processes. Five critical components of safety culture are defined: reporting culture, just culture, flexible culture, learning culture and informed culture. Accordingly, the questionnaire aims to capture how each bias is reflected in these aspects: in the general working atmosphere, in the way information is shared, in the way information is incorporated into decisions, in learning processes, and in the degree of flexibility with respect to changing conditions.

According to these fundamentals, a questionnaire was developed to diagnose the quality of decision-making behavior in organizations in relation to the occurrence of these biases. The aim of the questionnaire is to serve as a self-assessment method for groups and organizations, ultimately helping them to improve their decision-making processes.

The questionnaire is structured to describe behaviors for each bias that correspond to different aspects of safety culture. Accordingly, each item represents a situation or behavior that potentially increases or decreases the likelihood of the bias occurring in planning and decision-making situations.

For example, answering the question *"In decision-making processes, a critical and inquiring approach to making judgments is reinforced"* on a 5-Point Likert-Scale with a high value would be an indication for a low tendency towards Confirmation Bias. The Questionnaire comprises 9 Cognitive Biases and 11 Group Biases with a total 47 Items and is currently being validated in the PhD study.

In practice the questionnaire should be completed by all employees and managers of the respective organizational unit who are involved in decision-making processes. To ensure a sufficient degree of anonymity a surveyed team should consist of at least five people. Likewise only demographic data, that doesn't point to individual persons should be included in any particular survey.

The prerequisite for the process is that the managers and employees are motivated to change and that there is a certain psychological security, which is necessary for those involved to express themselves honestly. The same applies to the questionnaire itself. As employees evaluate their own department, fear of change or of a negative reaction from the manager can lead to socially desirable and false response behavior. Thus a questioning basic attitude within the organizational unit is helpful.

For the evaluation of the standardized procedure, mean values are determined at the item level, bias level and an overall score in order to be able to evaluate results in varying degrees of detail. For low scores that imply a high risk of bias, a report is automatically generated with content explanations regarding the bias and general suggestions to counteract the undesired behavior – for example if there is a high indication of Overconfidence or Optimism one could consider using techniques like Pre Mortem or Devil's Advocate to counteract those tendencies.

It should be noted that the resulst of the screening tool and the report are only initial indications of potential for improvement, as each organization or department has individual conditions. Accordingly, the results should be taken up in a workshop within the department concerned and discussed together with the entire team as to how exactly decision processes can be improves and what interventions would help the most.

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S1-04: Review of copper corrosion by the Swedish Radiation Safety Authority (SSM) in the contexts of the LOT experiments at the Äspö facility and the ongoing licensing process for establishing a repository for spent nuclear fuel in Sweden

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Inputs to consultations and external reviews of the ongoing licensing process for establishing a repository at the Forsmark site emphasize a long debate on copper corrosion processes in Sweden [1-2]. Those viewpoints are mainly from NGOs and a research group at the Royal Institute of Technology, Stockholm. The controversy is also reflected by the Swedish Land and Environment court who requested complementary information about copper corrosion [3].

The Swedish Nuclear Fuel and Waste Management Company (SKB) operates the LOT experiments at the Äspö facility since 1999 [4]. These experiments consist of six electrically heated copper cylinders surrounded by bentonite blocks. A few of the experiments were terminated early to ensure functionality of the tests. One experiments was terminated after 5 years [5] and two after 20 years [6]. The LOT experiments are just one of several different types of tests at Äspö. The particular significance of LOT is the judgement that they would provide a critical evaluation of the use of copper.

Copper is mainly expected to corrode under initially oxidising conditions, and after that under reducing conditions with sulphide ions [7-9]. This is well-established science, but the controversy relates to a proposed third form of corrosion during which copper reacts with water molecules under hydrogen formation [10]. It is suggested that the 20-year LOT experiments could demonstrate that this third form result in much higher rates of corrosion than accounted for in safety assessment [11].

Early in 2018 SSM completed the review of long-term safety in the license application [12]. The associated statement to the Swedish government recommended approval although it was pointed out additional efforts would be needed in a stepwise-continued licensing process [13]. A year later SSM also reviewed the requested complementary information on copper corrosion [14] issues with a similar outcome [15]. SSM's review covered LOT with a conclusion that corrosion in the 5 years experiment was as expected. The work presented in this paper was requested by both NGOs as well as from the responsible ministry so that the 20-year experiments would be addressed prior to the government making a final judgement.

SSM recently completed a review of the 20-year experiments in-house [16] and with external experts [17] covering quality assurance and the scientific aspects. SKB's assessment of copper corrosion processes during the 20-year experiment is regarded as comprehensive and well-structured. SSM observed that the results from the 20-year experiment are broadly similar to those from the 5-year experiments both in terms of the extent of corrosion and in terms of the characteristics of the formed corrosion products. The 20-year experiments nevertheless shows clearer signs of an early onset of a sulphide corrosion phase. An alternative interpretation of the experiments is that all available oxygen was more or less instantly consumed by other processes (concluded based on other field experiments) and that formation of copper oxide phases had occurred under oxygen free conditions by the reaction mentioned above [18]. SSM's judgement is nevertheless that observations from the 20-year LOT experiments are consistent and well explained by the more established forms of corrosion.

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S1-05: Spatial effects of surface facilities for final disposal: perceptions of the same and impact on place attachment – a transdisciplinary experimental setting

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Building a deep geological repository for final disposal of nuclear wastes implies not only changes underground, but also landscape changes on the surface. These transformations vary over time, from construction over disposal towards closure phase. During all phases, transportation infrastructure is needed, first for the removal of excavated soil later also for the transport of materials and the delivery of waste casks. During construction phase the construction site equipment needs additional areas and mine dump will also be necessary. Later, the site will be dominated by the surface facilities, such as the mine shaft and the processing facility. During disposal and closure (including monitoring) several surface facilities are required.

The dimensioning and conceptual design of these surface facilities including the storage buildings depends on the amount and type of casks for transport as well as for the final disposal. The dimensions of the disposal casks, in turn, depend on the host rock of the repository. Another important factor is the operational throughput of the conditioning plant. The storage buildings have to be designed for an appropriate buffer storage of the filled transport casks, the final disposal casks and the empty casks as well. After closure of the repository, the surface facilities can be deconstructed to a large extend. Nevertheless, plant components must remain in place for possible recovery of the nuclear waste, during the operating phase (cf. BMU 2017).

Infrastructurally induced landscape changes, influence perceptions attitudes as well as actions of residents in a particular place. Structural transformations such as those seen in former coal mining regions, which transformed to industrial regions or regions of renewable energy production, might change the physical and visual appearance of a region considerably (cf. Gailing et al. 2020; Llewelyn et al. 2017). Landscape transformations are accompanied by changes in attitudes, e.g. regarding socio-economic and leisure activities. These changes have effects on place attachments of individuals and collective groups who live in those transformed regions. Place attachment refers to personal ties and social interactions to memories and interpretations of spatial artefacts as well as wishes and emotions. Place attachment is developed in a specific action setting which is characterized by certain attributes. If (some of) those attributes change then the place attachment changes as well. Place attachment influences acceptability and participation depending on e.g. the dimension, time span and controllability of change. Strong place attachments lead to stronger reactions, as well positively as negatively (cf. Devine-Wright & Bathel 2017; Drasdo 2018; Mihaylov & Perkins 2014).

In the project TRANSENS we conduct an empirical study on the role of place attachment for infrastructure planning. For this purpose, we chose three different regions in Germany in which we analyze landscape markers as well as emotions and actions towards infrastructural landscape effects as important factors for place attachment (cf. Knaps 2021; Kühne 2018). Furthermore, we conduct an experiment with a group of people in these regions and a reference group, to analyze the perceptions of different visualized models of landscape changes induced by surface facilities for final disposal. The surface facilities to be developed will be parameterized and modularized in such a way that they can be flexibly customized to an adaptive disposal process of radioactive waste. Furthermore, the visualization will be able to show possible alternatives in the planned experiment. Our research questions are: How do residents with different place attachments perceive landscape changes? May landscape changes affect place attachments negatively? With this study, we aim to contribute to the research on the role of place attachment in infrastructure planning and landscape transformation.

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S2-01: Michigan International Copper Analogue (MICA) project – recent advances

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One of the key requirements for the deep geological disposal of high level nuclear waste is the assessment of its long-term performance and safety (up to 1 Ma). Regarding engineered barrier system materials, such as copper, much of the data available comes from short-term investigations, such as laboratory experiments at different scales. Copper is an important part of many waste packaging and disposal concepts, e.g. KBS-3 developed in Sweden and Finland and Mark II developed in Canada.

Natural analogues provide another important way of obtaining understanding on potential repository system behaviour. Observations made from the geological systems can be utilized in the safety case, providing information on the assessment time scale. Copper analogue studies (both natural analogues and archaeological analogues) have been reported in the literature and they have been extensively reviewed by various authors (e.g. Miller et al. 2000) and by safety case projects (e.g. Reijonen et al. 2015) within waste management organisations. So far, only a few studies have focussed on the general stability of native copper within its natural media (e.g. Milodowski et al. 2000 and Marcos 2002).

Keweenaw Peninsula native copper occurrences (Lake Superior, US) have been mentioned as a qualitative source of information (e.g. in Miller et al. 2000), however, data to be used in process based safety assessments for geological disposal is lacking. These deposits have been mined for a long time and there is a great deal of knowledge related to them as well as samples collected, but no formal review has been made from the geological disposal point of view. The native copper of the Keweenaw Peninsula reflects various environments from bedrock to anthropogenic mine site remnants and geochemical environments (e.g., anoxic vs. oxic, sulphur-free vs. sulphur-bearing). Thus, it provides a unique complementary data source that will be useful for estimating processes governing behavior of metallic copper. The MICA Project Phase I has systematically collected and reviewed the existing literature and data on the Michigan copper analogue sites and available sampling potential. Here, we present the recent advances of the project regarding assessment of the types of natural analogues for native copper identified, including preliminary consideration of their feasibility for Phase II.

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S2-02: Experimental investigation of radionuclide release from spent nuclear fuels under conditions expected in a deep geological repository located in argillaceous, crystalline or saline rocks – state of knowlegde

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Spent nuclear fuel (SNF) is designated for final disposal in a deep geological repository in many countries with nuclear power plants. With the aim to safely isolate the SNF from the biosphere, ad infinitum, primarily three types of host rocks are being considered for a repository on an international level. Namely argillaceous rock, crystalline rock (e.g. granite) and rock salt. The various host rocks have their strengths and weaknesses. However, common to all deep underground repository concepts is the access of ground water and the eventual contact of the respective pore water solutions with the emplaced wastes, in the long-term. Thus, in safety analyses of such facilities, the failure of canisters and the loss of the cladding integrity, finally leading to a release of radionuclides from the SNF into the aqueous and gaseous phases has to be taken into account.

Evaluation of the performance of SNF in the near field of deep geological disposal systems requires process understanding of SNF dissolution and rates as well as the quantification of radionuclides release from SNF under reducing conditions of a breached container. With the aim of deriving a radionuclide source term, the SNF dissolution and alteration processes can be assigned to two steps: (i) instantaneous release of radionuclides upon cladding failure from gap and grain boundaries and (ii) a long-term release that results from dissolution of the fuel grains itself (Ewing 2015).

In this context, research at KIT-INE is dedicated to the behaviour of SNF (irradiated UO_2 and MOX fuels) under geochemical conditions (pH, redox and ionic strength) representative of the near field of various repository concepts, including the interaction of SNF with backfill material such as bentonite as well as the influence of iron corrosion products such as magnetite and the consequence of radiolytic reactions on SNF dissolution mechanisms.

This contribution will give an overview on the state of knowlegde of process understanding and quantification of the radionuclide release from dissolving SNF under near field repository conditions. In particular, the dependence of radionuclide release on the chemical composition of the aqueous and gaseous phase in the near-field of repositories in different types of host-rocks will be discussed.

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S2-03: The OpenGeoSys software framework for reactive transport and chemo-mechanical modeling in Deep Geological Disposal

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OpenGeoSys (OGS) is a scientific open-source initiative for the numerical simulation of thermo-hydro-mechanical/chemical (THMC) processes in porous and fractured media. OGS provides a flexible numerical framework using primarily the Finite Element Method (FEM) for solving multi-field coupled processes with application in different scientific and technical disciplines, including Nuclear Waste Disposal. Since the mid-eighties (Kolditz, 1990) OpenGeoSys is in continuous development evolving through Fortran to C^{++} implementation with the current released version being OpenGeoSys 6.4 (Bilke et al. 2019). Regarding reactive transport processes, different approximations have been implemented in OGS along its development in order to consider multicomponent mass transport and bio/geochemical reactions.

For example, Ballarini et al. (2014) used an internal library to simulate kinetically controlled bio/geochemical reactions. In other cases, OGS has been coupled in a sequential non-iterative approach with well-known external geochemical solvers (i.e. PHREEQC, GEMS, BRNS and ChemApp). Very recently, an alternative coupling solution of reactive transport has been developed and implemented by approximating the complex chemical reactions with look-up tables (Huang et al. 2021). The novel implementation provides fast and efficient simulations, a feature especially relevant for long-term simulations. Reactive transport calculations referred above have been mainly performed with OGS-5. The new OGS-6 version with iPHREEQC coupling includes a new implementation with direct memory access allowing efficient computational simulations (Lu et al. 2021). Recent applications of OGS on reactive transport modelling in the framework of Nuclear Waste disposal include long term cementitious materials/clay interactions (i.e. Idiart et al. 2020), laboratory scale precipitation/ dissolution processes in combination with i) density driven flow and clogging effects (i.e. Poonoosamy et al. 2020) and with ii) mechanical processes in fracture media (Lu et al. 2018), concrete degradation due to reactive aggregates in combination with multi-phase transport of CO_2 (Huang et al. 2021) and radionuclide migration in clays (Águila et al. 2021). Recently the look up table approach has also been applied to model gas and humidity transport in combination with concrete/ organic matter degradation and corrosion of metals in a waste package during 100 years of intermediate storage (Huang et al. 2021).

Finally, OpenGeoSys was and is participating in several international model development, validation and benchmarking initiatives, i.e., DEVOVALEX, CO_2BENCH, SeS Bench and HM-Intercomp), providing ongoing series of benchmark books and tutorials. For more information please refer to the OpenGeoSys webpage (www.opengeosys.org).

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S3-01: Finalizing Phase One – Towards the identification of sites of interest for a surface exploration for a German high level radioactive waste repository

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With the publication of the sub-areas interim report in September 2020, the first step of phase one of the site selection procedure was successfully completed. The sub-areas are areas in which favorable geological conditions for the final disposal of high-level radioactive waste can be expected. The map of Germany is no longer white: 90 sub-areas in the host rocks of rock salt, claystone and crystalline rock were identified over about 54 % of the area of Germany.

The site selection, following the amendments of the repository site selection act in 2017, continues with step two of phase one. On the basis of the sub-areas, representative preliminary safety assessments pursuant to section 27 StandAG and the ordinances on "Safety Requirements" (EndlSiAnfV) and "Preliminary Safety Assessments" (EndlSiUntV) will be applied to the sub-areas. The subsequent implementation of the geoscientific weighing criteria (section 24 StandAG) will identity site regions that have the potential to become the site with the best possible safety for a high-level radioactive waste repository. During the second step of phase one, the planning-scientific weighing criteria (Section 25 StandAG) can be applied for the first time.

Main challenges in the science-based, participative, transparent, self-questioning and learning site selection procedure are:

(a) application of criteria and requirements on the remaining area of Germany and to develop geosynthesis, safety and repository concepts within various sites of interest within the published regions.

(b) further collection, homogenization and provision of a huge amount of very different geological data,

(c) finally, a further developed geoscientific weighing will be applied together with planning-scientific weighing criteria,

(d) continuous communication with the public, the scientific community and various stakeholders.

In this early stage of the search, various repository concepts within the three different host rocks are possible. However, starting with studies on possible canisters and an updated inventory of the radioactive waste, first decisions have to be made based on a thorough safety analysis.

The current status of the work will be shown and discussed.

S3-02: Enabling and supervising a unique & novel procedure - BASE's statutory tasks & view on the German approach to site selection for a deep geological disposal repository for high-level waste and its current status

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In 2011, right after the accident in Fukushima Daiichi in Japan, the German legislator reconfirmed its 2002-decision to phase out nuclear power generation in Germany. The last of the remaining three power plants will be taken off the grid by December 31, 2022, leaving behind their high-level radioactive waste legacy, that needs to be disposed of safely in a final repository.

With regard to time, German radioactive waste management is divided into two parts: at first, a site for the high-level waste facility has to be found. Afterwards, the repository will be licensed in an independent process.

A previous attempt for finding a safe repository site in Germany has proven unsuccessful. Learning from the mistakes of the past and from international experiences, there was broad legal consensus in 2013 for a new approach to finding a final storage site for high-level radioactive waste. The German site selection process follows strict rules laid down by the law.

The Site Selection Act consists of detailed provisions concerning the three-phase site selection process. This allows for an innovative and comparative process based on geological criteria. The process is designed to identify the site with the best-possible safety for 1 million years and is intended to be participatory, science-based, transparent, self-questioning and learning. At the end of each phase, decisions will be made by the Federal Parliament, the highest democratically legitimated body in Germany.

As a result of the process, the best possible site will be enshrined in federal law. This legal decision will be binding for the location of the repository in its subsequent licencing process.

The decision to restart the site selection process has finally set the ground for a complete remodelling of tasks in the field of nuclear safety in Germany.

The Federal Office for the Safety of Nuclear Waste Management (BASE) was established in 2014. On the one hand, BASE serves as the nuclear regulator and supervisory authority for the site selection process. Therefore, BASE is also engaged in securing potential sites. Applications for approval of certain underground activies in so-called identified areas require the agreement of BASE. BASE engages in rulemaking. It has drafted, for example, a guideline for estimating the potential radiation dose resulting from the construction of a high-level radioactive waste repository. On the other hand, BASE is responsible for initiating public participation as stipulated by law.

The Federal Office also engages in scientific research to be able to evaluate the scientific and technological state-of-the-art beyond strictly legal considerations. With a strong engagement in research, BASE guarantees an independent and thorough review of the complex deliverables of the implementer. Moreover, it intends to make the findings more comprehensible and better accessible for the public.

As to the current status, following the publication of the interim report by the implementer BGE mbH (the Federal Company for Radioactive Waste Management), BASE initiated the first mandatory public participation format – the Sub-areas Conference, in autumn 2020. Its goal was to facilitate a broad public discussion about the interim report and to collect initial feedback, questions and criticism from the public. The conference was open to all interested

stakeholders across Germany. Moreover, to enable the public to take over responsibility and work independently, the legislator had introduced the principle of self-organization for the conference, meaning it was up to the participants to determine a work mode, the conference's agenda and topics for discussion. After an opening meeting and three consultation meetings between October 2020 and August 2021 with a total of 4.900 registrated participants, the conference submitted its results to the implementer in September 2021, who is legally obliged to consider these results in its ongoing work.

As the regulatory authority, BASE is now waiting for both the implementer's enhanced project time table and the proposal for siting regions for underground exploration, once the implementer has concluded its examinations. BASE will then thoroughly review this proposal and provide suggestions for the legislator.

To continue monitoring the implementer's progress on the way to its proposal for siting regions, BASE has developed a participation concept in a co-creative dialogue process together with representatives from civil society. A pilot format was launched in November 2021.

Current research at BASE focuses on topics related to nuclear waste disposal such as the site selection procedure or to long-term safety aspects. Open questions from various disciplines are being considered, ranging from human sciences to modelling of Thermo-Hydro-Mechanical-Chemical (THMC) processes and experimental work in conventional laboratories and underground research laboratories. Research is performed both in-house and externally by other organisations following public tendering processes. BASE promotes young scientists for example by giving them the opportunity to write their M.Sc. theses in connection with specific projects and initiating doctoral theses projects in collaboration with universities. Research results are open to the public. In 2021, the international research symposium safeND was held for the very first time, with the intention to provide a platform for broad scientific and interdisciplinary exchange on all topics related to the management of radioactive waste.

BASE is closely following the site selection process and accompanies the procedure laid down in the law (Site Selection Act). In the long run, the novelized site selection procedure as defined by the legislator will prove to be efficient and purposeful. The legal basis for the procedure provides a valuable and practical approach to finding a site for a repository for high-level waste – and to overcome several challenges by engaging and shaping the learning procedure together.

S4-01: The succes and failure of high level nuclear waste management programs. Science and technology vs social acceptance and political (in)action

Jordi Bruno

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In 1982 (Biedermann et al, 1982), I started what would become my scientific career in the field of aquatic geochemistry mainly devoted to develop a safe methodology for spent fuel geological disposal. I was fortunate to collaborate to develop what became the KBS3 concept, which was developed by SKB and has been adopted by Posiva in Finland and it is the basis for the generic concepts for the UK and the Canadian programs. As I was presenting my PhD thesis in 1986, Enresa started in Spain a similar R&D programme for the deep geological disposal of spent fuel.

At that time, my objective was to see these two concepts licenced and maybe under construction before the end of my professional career.

Some 35 years later the situation is that, maybe, if I'm fortunate and relatively long-lived, I will be able to see the licencing of the deep geological repository in Sweden and certainly the construction and maybe the operation of the Posiva one. Certainly, the licencing of the Spanish repository, if it happens, it will not occur during my lifetime.

The consensus is that while the scientific basis for nuclear waste management have reached a maturity level and the safe disposal of HLNW can be demonstrated for over 100.000 years (Hedin et al, 2008) , we have not been able to convey this message properly to society and transfer this conviction into the necessary political action to take proper responsibility for our nuclear waste.

In my presentation I will analyse and discuss in a comparative manner the development of the Swedish and Spanish nuclear waste management programmes in order to ascertain which have been the strong and weak points of the two programmes from the scientific, technical, social but also the political angle.

Hopefully, by this comparison I will be able to point out some of the mistakes we have made and which are the necessary steps that have to be taken in order to implement a HLNW management programme in complex societies like the ones we are living in.

Certainly, I do not pretend to have the definitive solution for such a complex issue but I really hope that my experiences in this field and other similarly difficult environmental issues like CCS implementation may help to clarify which are the hurdles and how can be surmounted.

We should not forget that is the duty of our generation(s) to achieve a proper and safe solution for the disposal of high level nuclear waste.

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S4-02: Posiva submitted the operating licence application for encapsulation and final disposal facility

Posiva is the first in the world to apply for an operating licence application for encapsulation and final disposal facility. The application was submitted to the Finnish Government at the end of 2021.

Posiva is applying for an operating licence for the final disposal of 6,500 tonnes of uranium from the five nuclear power plants in Olkiluoto and Loviisa. For its operation Posiva has previously been granted two Decisions-in-Principle and a building permit.

The Ministry of Economic Affairs and Employment will review the operating licence application and eventually forward it to the Council of State for approval. The Radiation and Nuclear Safety Authority of Finland (STUK) will conduct a safety assessment of the application and is in charge of the oversight of the construction and commissioning of the nuclear facility. The actual final disposal activities are designed to start in mid-2020s.

According to Posiva's CEO and President, Mr. Janne Mokka, the submittal of the application for the operating licence is a significant milestone for the entire emission-free and climate-smart nuclear energy sector.

- We can all take pride in the long-term and responsible approach of the various parties in the use of nuclear energy in Finland with Posiva now having the capability to launch the first, demonstrably safe final disposal operation of spent fuel in the world here in Olkiluoto. We have a solution, Mr. Mokka says.

- The work carried out for several decades to demonstrate long-term safety and develop the final disposal facility concept ONKALO® to suit the conditions of Olkiluoto has now been finalised and we can concentrate on the installation of equipment in the encapsulation plant and the final disposal repository, commissioning of the facility and preparations for operational activities.

The multi-disciplinary project has required world-class expertise, and still does. The main roles of the project have been played by Posiva's own personnel and our extensive network of partners, developing the safe final disposal concept for more than 40 years.

Completing and submitting the operating licence application has been an enormous project for Posiva. It is accompanied by 250 scientific studies demonstrating the long-term safety of final disposal. All together comprising 17 000 pages of material.

Final disposal has been solved in a safe way, which is a prerequisite for the operation of nuclear power plants in Finland and in the world in the future as well. The solution consists of a final disposal concept, an encapsulation and final disposal facility and a final disposal process.

Spent nuclear fuel should be isolated from the habitat for a very long time. Decreasing radioactivity to a level that is insignificant to the safety of the habitat will take hundreds of thousands of years. Therefore, the most important thing in the final disposal is the long-term safety of the solution, which is assessed and demonstrated by a Safety Case.

According to the international definition, Safety Case refers to all technical data, analyses, observations, experiments, tests and other evidence that justify the reliability of assessments of the long-term safety of a disposal facility.

- The research of more than 40 years means a detailed description of the geological disposal solution, the analysis of various development processes and the demonstration of the safety of final disposal in the bedrock conditions of Olkiluoto, Jalonen says.

The Safety Case has taken into account various changes in nature over a long period of time, such as earthquakes in the distant future and future ice ages of up to a million years.

S4-03: Regulatory Requirements for Estimating the Additional Mean Effective Annual Dose in the Context of the German Site Selection Procedure

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The Site Selection Act specifies that at the end of the site selection process for a Deep Geological Repository (DGR) for disposal of high-level radioactive waste generated in Germany the site with best possible safety has to be selected. All possible sites have to fulfill certain requirements defined in the law. One important aspect is that the site needs to ensure the best possible safety for the long-term protection of man and the environment against ionising radiation and other harmful effects of such waste for a period of one million years. For this reason, the potential additional exposure to radiation possibly caused by a DGR for high-level radioactive waste has to be assessed.

Legislation refines the fundamental requirements for estimating possible radiation exposures in the *Safety Requirements for Final Disposal of High-Level Radioactive Waste Ordinance*[i] and in the *Requirements for Conducting Preliminary Safety Analyses Ordinance*[ii]. It is called for a consistent approach in all preliminary safety investigations carried out in the context of the site selection procedure. In particular, a uniform calculation basis (German '*einheitliche Berechnungsgrundlage*') has to be used when estimating possible doses. This is mandatory in the preliminary safety analyses in the 2nd and 3rd preliminary safety analyses. However, this uniform calculation basis did not exist so far.

In order to develop the concerning uniform calculation basis, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) commissioned the Federal Office for the Safety of Nuclear Waste Management (BASE) and the Federal Office for Radiation Protection (BfS). The first draft, drawn up under the auspices of BASE, was made publicly available in September 2020.

This contribution intends to highlight the requirements when estimating the dose in the context of the long-term safety analysis as part of the preliminary safety analysis during the site selection procedure. The calculation basis addresses all aspects from mobilisation of radionuclides over transport through barrieres and the geosphere in general and entrance into the biosphere until reaching the human body. In particular, the new requirements regarding modelling the geosphere and the biosphere differ substantially: For the geosphere, basically boundaries are defined within that models will have to be developed, while for the biosphere a calculation model was set up which only has to be extended where site-specific characteristics or developments make it necessary. The underlying reason for these two different approaches is the different ability in describing evolutions and hence in dealing with accompanying uncertainities of both compartments.

The draft will be discussed in the context of a public participation process which will take place in 2021.

[i] Verordnung über Sicherheitsanforderungen an die Endlagerung hochradioaktiver Abfälle.
[ii] Verordnung über Anforderungen an die Durchführung der vorläufigen Sicherheitsuntersuchungen im Standortauswahlverfahren für die Endlagerung hochradioaktiver Abfälle

P1-01: Analysis of Interactions between Operational Safety and Post-Closure Safety of a HLW repository

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In a safety case, a comprehensive set of safety arguments must be compiled and the operational and long-term safety of the disposal facility must be demonstrated. The human-induced activities and naturally occurring processes and events during the operational phase define the initial state for the repository system at the beginning of the post closure phase. Therefore an assessment and documentation of the interactions between operational safety and post-closure safety is needed.

A comprehensive analysis of features, processes and events (FEP) forms the basis for the post-closure safety analyses.

The need to ensure operational safety during the operational phase will require specific measures that might influence the design and operational planning of a deep geological disposal repository. The consequences of those interactions are only little investigated up to now.

Commonly, the operational safety analysis bases on the identification and evaluation of naturally occurring and human-induced hazards, that have the potential to impact operational and public safety. Standard procedure is to develop a list of hazards applicable to a repository by expert judgement. But it is difficult to demonstrate the completeness of such a list, as it is required for a hazard analysis.

In a long term safety assessment the description of the repository system by a FEP catalogue is a standard methodology to ensure the comprehensiveness and transparency of system description and to provide data for scenario development.

In the course of the R&D project BASEL- funded by BMWi/PTKA - an adequate FEP catalogue for the operational phase is developed for the first time. This FEP catalogue compiles the characteristics of the surface and underground facilities for existing national repository concepts for salt, clay and crystalline rocks. To identify internal hazards all repository components were systematically combined with all occurring processes and the resulting consequences were evaluated. Additionally, the external hazards as defined in national regulations, have been considered. Thus a comprehensive list of safety relevant internal and external hazards has been developed. As a next step, technical and organizational measures for prevention or mitigation of consequences of those hazards were identified. They are relevant parts of the initial conditions for the post closure phase. Therefore the possible impact of those measures on long term safety was evaluated.

Another check of the interactions between the operational safety and the long term safety is the analysis of a FEP catalogue for the post closure phase to identify resulting requirements for the operational phase. Important aspects that have been recognized were requirements for waste packages (e.g. design, material, thermal output) and repository design (e.g. geometry and arrangement of mine excavations and smooth excavation techniques to minimize the EDZ). Examples of concurring requirements for operational and long term safety include the drift lining and installations for retrievability.

As a result of the R&D project BASEL, a methodology has been developed to evaluate the interaction between operational and long term safety. Safety relevant inconsistancies may become starting points for repository concept optimization.

P2-01: *iCross* – integrity of nuclear waste repository systems – cross-scale system understanding and analysis: A multidisciplinary collaborative research project in the Helmholtz Association

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A reliable and consistent assessment of the safety of a deep geological repository for heat generating radioactive waste over time scales of hundred thousands of years requires an advancement of process understanding and simulation tools for a close-to-reality description of repository evolution scenarios. This is notably required due to the challenging task to compare and assess the safety of different repository concepts in different host rocks within the German site selection process.

The aim of the *iCross* project, jointly funded by the Federal Ministry of Education and Research and the Initiative and Networking Fund of the Helmholtz Association, is to provide a holistic scientific view onto repository system evolution and to describe and analyse the integrity of nuclear waste repository systems across scales. Within *iCross*, an in-depth understanding of coupled physical, chemical and microbiological processes provided by dedicated experiments on the laboratory scale and in underground research laboratories (URLs) – including radionuclides and radioactive waste forms, site characterization and system monitoring is synergistically connected to highly sophisticated numerical simulations up to the visualization and analysis of complex repository system evolutions.

This innovative and multidisciplinary research project combines research competencies of five Helmholtz centres from the research fields “Energy” and “Earth & Environment” related to the topics nuclear sciences, radio-(geo)chemistry, geosciences, biosciences and environmental simulation in a unique coordinated collaborative activity. As full members of the international Mont Terri consortium, the *iCross* partners develop and perform *in-situ* URL experiments and, thus, set one focus on investigations of processes in a tentative repository in clay rock. Priority studies deal with (i) the migration of radionuclides and gases across the canister-bentonite interface in an evolving near field of a deep geological repository for nuclear waste, and (ii) the heterogeneity of the Opalinus clay sandy facies and its impact on radionuclide mobility and migration across scales.

P2-02: The CORI project on cement-organic-radionuclide-interactions – an activity within the EC EURAD project.

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The CORI (Cement-Organics-Radionuclides-Interactions) Workpackage integrated into EURAD [1] performs reseach to improve the knowledge on the organic release issues which can accelerate the radionuclide migration in the context of the post closure phase of geological repositories for ILW and LLW/VLLW including surface/shallow disposal. The R&D in CORI extends the current state-of-the-art and will contribute to optimize disposal solutions and consider questions of regulatory concern. CORI results will help member states to further develop their national R&D programs and support programs at an early implementation stage.

CORI research is addressing topics in the context of cement-organics-radionuclides-interactions. Organic materials are present in some nuclear waste and as admixtures in cement-based materials and can potentially influence the performance of a geological disposal system, especially in the context of low and intermediate level waste disposal. The potential effect of organic molecules is related to the formation of complexes in solution with some radionuclides of interest (actinides + lanthanides) which can (i) increase radionuclide solubility and (ii) decrease radionuclide sorption. Organic substances require special attention since a significant quantity exists in the waste and in the cementitious materials, with a large degree of chemical diversity. Cement-based materials will be degraded with time, leading to specific alkaline pH conditions under which the organics can degrade, thus increasing their impact on repository performance. CORI has prepared a State-of-the-Art document [2] which gives an introductin to the main research topcis targeted in CORI.

The three R&D Tasks in CORI are:

Organic Degradation. Focus is on the characterization of soluble organic species generated by radiolytic and hydrolytic degradation of selected organics (PVC, cellulose, resins, superplasticizers). Studies also include the analysis of degradation and stability of small organic molecules such as carboxylic acids and the determination of degradation rates.

Organic-Cement-Interactions. Studies focus on investigating the mobility of selected organic molecules in cement-based materials. Mobility of organic molecules includes sorption and transport properties. Organics will also include small ^{14}C bearing molecules as identified in the EC EURATOM project CAST. Both retention on individual cement phases and cementitious systems are investigated.

Radionuclide-Organic-Cement-Interactions. Consistent with the set of organics, individual cement phases and materials identified in the above two Tasks, radionuclide migration processes are studied in the ternary system. The role of organic molecules on the transfer properties of radionuclides are investigated through sorption and transport experiments. Selected radionuclides cover a range of chemical characteristics and redox states relevant for conditions in L/ILW disposal.

References

[1] EURAD – European Joint Programme on Radio-active Waste Management. https://www.ejp-eurad.eu/

[2] The CORI State-of-the-Art report is available at the EURAD Website at: https://www.ejp-eurad.eu/publications/eurad-deliverable-31-cori-sota-cement-organic-radionuclide-interactions-content-lilw

The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 847593.

P2-03: Implementation of retrievability in German repository concepts for high-level radioactive waste in crystalline formations

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The new German ordinance on safety requirements for the disposal of high-level radioactive waste (EndlSiAnfV) includes retrievability of already disposed waste packages as a major design requirement. Retrievability of the waste packages is required from the time the first waste package is disposed to the beginning of closure. This requires implementation of retrievability in the repository concepts as well as the development of retrieval concepts and technologies.

In accordance with the safety requirements, all German repository concepts include the parallel realisation of the major operating processes excavation of emplacement cells, emplacement, and backfilling/closure. Waste packages are quickly transferred to the passive safety system of the repository. The retrieval of waste packages corresponds to their extraction from this passive safety system and returning them back into human care. Suitable technical solutions for the implementation of retrievabiliy have already been developed for different disposal concepts in salt and clay formations, see Herold et al. (2018). However, a direct transfer of the existing solutions to crystalline formations is not possible. Within the R&D project called KOREKD – funded by the German Ministry for Economic Affaires and Energy (BMWi), retrieval concepts for three different emplacement concepts were developed:

- modified KBS-3 concept,
- multiple containment providing rock zone (CRZ) concept and
- overlying CRZ.

The concept of overlying CRZ describes a situation where the crystalline rock provides a stable environment for the underground facilities and is covered by a long-term relevant natural barrier (salt or clay). Horizontal drift disposal of shielded waste packages is proposed as disposal concept. To guarantee retrievability, no adaptations of the disposal concept are needed. Retrieval corresponds to a reverse emplacement operation. The buffer can be removed by partly modified mining equipment.

The concept of multiple CRZ splits the repository into different emplacement fields, each representing an independent CRZ. Inside every CRZ, vertical borehole disposal is considered. To guarantee retrievability, an inner steel liner and a non-compacting backfill material (sand) are implemented in every borehole, similar to salt and clay concepts. The technical concepts for retrieval are similar, too. An additional analysis of the removal process identified further requirements to the sand and the technical design of the retrieval technology. Adaptation of sand mixtures allow a minimization of stresses and reduce the forces necessary to remove the waste package. Cylindrical and conce-shaped canisters were investigated, too.

Within the modified KBS-3 concept, the natural barrier has no significant long-term sealing function. The engineered barriers waste package and buffer provide the major sealing functions. The implementation of addiontal components to ease retrievability, like steel liners, are not tolerated. If retrieval is necessary, the waste packages have to be removed from the buffer. Technical solutions to do this are known from other international programmes like Sweden, Finnland, and Japan. All follow a hydro-dynamic approach to disintegrate the bentonite buffer before the waste package will be removed. Due to

multiple technical and regulatory requirements, this approach seems not suitable for the German concept. Alternative options were investigated. Eventually, a coupled mechanical/pneumatic solution was identified as preferred option.

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P2-04: Recent advances in the laboratory compaction of crushed salt

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Crushed salt is long considered as a backfilling material in the disposal of radioactive waste. The overarching challenge for this material is a quantitative, reliable prediction of the salts' compaction behaviour by means of physics based numerical models in the first ~1000 years after its in-situ emplacement. Despite more than 40 years of research (e.g. Wieczorek et al. 2017), still manifold and demanding scientific tasks remain:

(1) Enhancement of the consitutive laws from empirical to physics based approaches.
(2) Realisation of more appropriate laboratory studies that serve for model development and validation.
(3) Improvement of more specified laboratory equipment and redesigned procedures allowing for better sample fabrication for subsequent triaxial testing.
(4) Systematic studies with crushed salt originating also from bedded (flat-lying in contrast to salt domes) salt formations, e.g. Teutschenthal.
(5) Characterization of highly compacted, lower porous, (< 5 %) and lower permeable crushed salt, and linking its further compation behavoiur with explicit effective deformation mechanisms.

Here we present our recent results regarding tasks (2-4), some of which were recently reported in the KOMPASS-project (Friedenberg et al., this venue).

For task (3) we present a novel pre-compaction apparatus with a suspended odoemetric cell that allows the loading forces to affect both sample ends simultaneously, resulting in a more homogeneous sample fabrication than conventional oedomeric tests.

We further show results on crushed salt originating from Teutschenthal mine (task 4). The material was dryed, sieved into fractions and subsquently mixed to resemble a designed grading curve. The loose, mixed material then underwent a multi-step, strain rate controlled oedometric compaction procedure (cell dimensions: 300 mm diameter x 150 mm height). The more rapid compaction conditions (v< 3.6 mm/h) are intended to quickly consolidate the material, while the slower ones (v< 0.0036 mm/h) are used to measure the materials' response during an in-situ similar loading rate. We mainly focus on the diminution of porosity and the simultaneous increase in backfill resistance, i.e. the load necessary to compact at a given strain rate (see Figure 1).

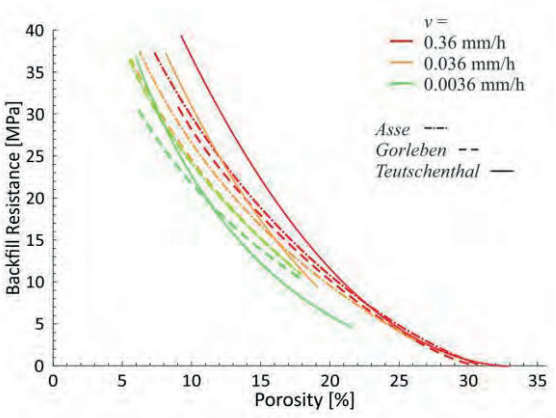

Figure 1: Backfill resistance vs. porosity for compacted crushed salt from different origins.

For highly compacted crushed salt (task 5), we show preliminary results of low porosity samples and identified acting deformation mechanisms. Those were obtained by comparing pyknometric and powder X-Ray diffraction methods (solid matter density approach) and optical analysis of selected thin-sections for the quantification of micro-deformation mechanisms.

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P2-05: FEP and Scenarios – Basic Tools for the Design and Performance Assessment of Geotechnical Barriers

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Based on the international methodological standards, the evolution of HLW/SF repositories in salt formations has to be analysed in terms of a safety case, which means an assessment of the total system performance (IAEA, NEA). In Germany, the safety concept is based on the enclosure of radioactive waste in a Containment Providing Rock Zone, as well as on the restoration of the host rock's integrity by the engineered barrier system (EBS). The EBS consists of shaft, drift and borehole seals as well as a suitable backfill material. These barriers will seal the mine openings for a limited functional period with well-predictable boundary conditions. During the barriers' functional period, the compaction of the backfill will proceed until it's hydraulic properties are close to the surrounding host rock. Then the backfill will function equivalent to the geological barrier. FEP and scenarios describe the potential future evolution of the repository system and are thus important tools for the development of a safety case.

Basing on the results of different R&D projects and relying on experience from the Morsleben Repository and the Asse Mine, a methodology has been developed in the RANGERS project to design the EBS in a siutable manner and to accomplish the integrity assessment of EBS for the future repository system evolution. The methodology for performance assessment of EBS is based on the technical regulations of EUROCODE which demand the concept of 'ultimate limit states' in combination with the 'partial safety factor method'. For the functional demonstration, different actions, the barrier resistances and the design situations have to be determined to define the load cases. The corresponding information can be obtained from the FEP catalogue and the scenarios. In addition to the overall description of the repository system, it's useful to describe the nearfield of the barriers in detail as sub compartments for the functionality demonstration. The FEP catalogue identifies processes that will directly affect the functionality of the barriers. To specify the intensity of those processes, the FEP interactions have to be analyzed and evaluated for the nearfield and for the farfield. The resistances of the barriers are specified in the corresponding component FEP. The design situations can be derived from the expected scenarios as well as the alternative scenarios (deviant evolutions with lower probability). For the numerical functional demonstration of the EBS, different load cases that cover the most relevant impacts have to be defined. In this context hydraulic (fluid pressure in combination with chemical actions) and hydromechanical (in combination with thermal) load cases are the most relevant. The design of the barriers has to be robust for the boundary conditions defined by the expected scenarios. This includes all potential chemical, hydraulic, mechanical, and thermal actions. Other load cases will analyse the consequences of the failure of a barrier (shaft or drift seal), the water inflow from reservoirs in the host rock, high gas generation rates etc. on the repository system evolution (alternative scenarios). E.g. a failure of the shaft seal would result in a flooding of the infrastructure area, an unilateral hydraulic load on a drift seal as well as an intensified concrete corrosion due to the different hydrochemistry of the ground water from the overburden.

P2-06: The use of natural analogues in the site selection process

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Natural analogues have been mostly used in qualitative arguments of safety and the overall social acceptance of the geological disposal of nuclear waste. Some of them have also provided a quantitative estimation of the duration of the materials to be used in geological disposal in cases where the conditions of the analogue are representative of the conditions of the planned geological disposal. Natural analogues have contributed also to increase process understanding, especially for processes that may operate over timescales of thousands to millions of years.

Natural analogues have been used in the site selection process to a much lesser extent, although valuable information could be provided given the knowledge of the geology of the site/s and the intended repository design and the materials to be used. In Finland, the safety assessment prior to the selection of Olkiluoto (TILA-99 by Vieno & Nordman 1999), made use of the Hyrkkölä U-Cu mineralisation in southwestern Finland (Marcos 1996, Marcos et al. 1999) as an analogue of the durability of copper canisters under evolving groundwater types. The Palmottu Natural Analogue Project (Blomqvist et al. 1998) was mentioned to ascertain the results of hydrogeological models used in the site selection process. Other analogues were referred to a general level for they use in the public acceptance of geological disposal (Cramer & Smellie 1994, Miller et al. 1994).

During the site selection process, valuable information could be acquired concerning the performance and compatibility of the selected engineered barrier materials in the different geological formations under scrutiny. For example, the performance of the bentonite barrier in crystalline rock could be supported by studies of swelling clays in fracture fillings (e.g., Marcos 2002, Reijonen & Marcos 2016). The understanding of retardation processes like sorption, precipitation, and incorporation of radionuclides in certain mineral lattices and the performance of the geological barrier itself could be enhanced.

If not only long-term safety is considered, but also constructability and operational feasibility, then anthropological analogues can be used, e.g. mines in salt rock, claystone or crystalline rock. From these we can learn how to account for the configuration and properties of the fracture network to construct and operate safely, minimize disturbances, and obtain information on the processes mentioned above, if not concerning radionuclides, at least at a general level.

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P2-07: From fractures to models: It's all about networking

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According to the Site Selection Act, rock salt, clay rock and crystalline rock are generally considered as a host rock for the disposal of high-level radioactive waste in Germany. Crystalline rock is a hard rock, that may feature faults and a network of fractures embedded in rock matrix with a very low permeability. Therefore, potential fluid flow mainly occurs through the network of fractures.

Methods have to be developed to represent the different fracture orders in regional hydrogeological models. In principle, fractures in hydrogeological models are usually represented as equivalent porous media (EPM) or as discrete fracture networks (DFN).

In DFN models, the geometric properties of each fracture and the connectivity between them are represented, which is why they are often used when the fractures in a rock mass have to be simulated as realistically as possible. Due to the large number of fractures, their spatial complexity and associated numerical limitations, DFN models cannot be used for large-scale flow and transport calculations. Therefore EPM modelling approaches are often used here, which try to homogenise the heterogeneous properties of the crystalline rocks. However, this means that flow and especially transport processes are often not adequately represented.

The aim of the research project is therefore to develop a modelling strategy with which regional flow and transport modelling in fractured crystalline rocks can be carried out in the context of performance assessments. For this purpose, several modelling approaches specified for fractured media are being investigated for their suitability by developing the corresponding numerical models based on a previously defined structural geological model. This makes it possible to illustrate the influence of different approaches on the modelling of flow and transport processes and to determine their impact on performance assessments for high-level nuclear waste disposal in crystalline rock.

P2-08: Overview of BGR's participation in experiments at the Mont Terri rock laboratory, Switzerland

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The rock laboratory Mont Terri (Bossart et al., 2017) is dedicated to non-site-specific research in claystone with the focus on nuclear waste storage in the geological subsurface. Two years after the start of the international cooperation in 1996, the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) joined the consortium, which expanded further to now uniting 22 equal partner organisations from nine countries. In addition, numerous universities, research institutes, and smaller contractors contribute to the scientific effort, led by the Swiss Bundesamt für Landestopografie (swisstopo).

The underground research laboratory is embedded in the locally about 150 m thick Opalinus Clay Formation of the Swiss Jura Mountains. The relatively low permeability and the self-sealing ability of the marly argillaceous claystone are two prominent characteristics in regard to exploration and evaluation of potential storage sites.

About 300 m under the eponymous mountain Mont Terri, a network with a length of about 1200 m of tunnels and niches offers excellent conditions to facilitate state-of-the-art in-situ experiments. About 100 experiments have already been successfully concluded, their topics covering the three phases of the evolution of a nuclear waste repository, i.e., (i) initial condition, (ii) early time perturbation, and (iii) transient to late time equilibrium (Bossart et al., 2017).

Focusing mainly on the first two phases of a potential repository's lifespan, presently BGR is partner in almost half of the ongoing 45 experiments. Complementary to elaborate in-situ experiments, intricate laboratory and modelling studies are conducted. Conform with the German Repository Site Selection Act, four of BGR's main interests in relevant basic knowledge (Schuster et al., 2019) cover:

- Characterisation of clayrocks,
- Investigations on technical and geotechnical barriers,
- Development of examination methods,
- Participation in demonstration experiments.

The required multidisciplinary approaches study physical, chemical, and microbiological processes relevant to the safe disposal. Here, novel examples include:

- Hydromechanical disturbances of the rock due to excavation,
- Influence of ventilation in the excavation damage zone,
- Detection of rock deformation with high-resolution in space and time.

Also recently, BGR's fields of interest in the Mont Terri Project broadened even more, as the vast knowledge obtained so far is also of high relevance for other potential uses of the subsurface. For instance, synergies are exploited in accordance with the topic of secure geological storage of carbon dioxide.

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P2-09: Contribution of bentonite and cementitious material to actinide retention under hyperalkaline conditions and increased ionic strength

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Our research aligns to conditions reported by the 'AnSichT' project, which evaluated the feasibility of a repository in German clay formations (Jobmann et al. 2017). According to the developed site model 'NORD', Ca-bentonite and concrete will be used in the geo-engineered barrier as buffer and borehole sealing material as well as for stabilization of disposal tunnels. Pore waters of the North German clay deposits are characterized by high ionic strengths up to 4 M (Lommerzheim & Jobmann 2014; Brewitz 1982). The contact of such saline formation waters with concrete can result in an enhanced corrosion of concrete which will lead to formation of secondary phases and to the evolution of highly alkaline cement pore waters (10 < pH < 13). The hyperalkaline solutions, in turn, can influence the retention potential of the bentonite buffer as well as of the surrounding clay host rock towards radionuclides.

The U(VI) retention on Ca-bentonite at hyperalkaline conditions in mixed electrolyte solutions ('diluted Gipshut solution', I = 2.6 M) was found to be very effective at pH>10, even in the presence of carbonate and despite the prevalence of anionic aqueous uranyl species (Philipp et al. 2019). Above a certain pH, depending on the concentration of carbonate in solution, carbonate does not play a role in the aqueous U(VI) speciation anymore due to the predominance of hydrolysis. Two U(VI) surface complexes were identified by site-selective TRLFS and XAS.

The stability of U(VI) and Cm(III) doped calcium (aluminate) silicate hydrate (C-(A-)S-H) phases, as main phases of hardened cement paste, at high ionic strengths conditions was studied applying leaching solutions which simulate the contact with North German claystone formation water (Wolter et al. 2019a,b). With regard to C-S-H stability and radionuclide release, differences were found in dependence on C/S ratio, composition of leaching solution and kind of radionuclide. The high retention capability of C-S-H gel towards U(VI) and Cm(III) remained constant in NaCl- and Na_2SO_4-containing solutions with increased ionic strength. In the presence of carbonate, however, U(VI) retention was coupled to the alteration stage of the C-S-H structure as well as to pH evolution of leaching solution. The Cm(III) mobilization from C-S-H gel was very low due to additional Cm(III) incorporation into secondary phases as shown by site-selective TRLFS and XRD.

The results show that both bentonite and cementitious material constitute an important retention barrier for actinides under hyperalkaline conditions and increased ionic strength.

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P2-10: Shaft sealing by Sandwich seal systems: A large-scale experiment performed at the Mont Terri rock laboratory

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The role of shaft sealing systems for a nuclear waste repository is to limit the fluid inflow from the adjacent rock in the early stage after closure of the repository and to delay the release of possibly contaminated fluids from the repository at later stage. Current German concepts of shaft seals contain the hydraulic Sandwich sealing system as a component of the lower seal in the host rock (Kudla & Herold 2021).

The Sandwich sealing system, developed by KIT, consists of alternating sealing segments (DS) of bentonite and equipotential segments (ES) that are characterized by a high hydraulic conductivity. Within the ES fluid is evenly distributed over the cross section of the seal. Water bypassing the seal via the excavation damaged zone, or penetrating the seal inhomogeneously, is contained and a more homogeneous hydration and swelling of the DS is obtained.

Proof of functionality of the system has been produced in semi-technical scale experiments (Schuhmann et al. 2009). The next step, an in-situ experiment that addresses the interaction between seal system and host rock, was prepared in the frame of a joint international pre-project between 2017 and 2019 (Emmerich et al. 2019).

In July 2019, the large-scale experiment was launched at the Mont Terri rock laboratory. It consists of two experimental shafts of 1.18 m diameter and 10 – 12.6 m depth, constructed using a core drilling technique in a new niche in the sandy facies of the Opalinus Clay. The seal in Shaft 1 consists of four DS (calcigel) of 1 m thickness and five ES (fine-grained quartz sand), each 30 cm thick, while Shaft 2 will host a slightly modified system emplaced 1 – 1.5 years later. The sealing systems will be saturated from pressure chambers located at the shaft bottoms via inclined lateral feeding boreholes. The seals and the surrounding rock are intensely monitored.

The experiment objectives are to demonstrate the feasibility of installation, to investigate the saturation process, to qualify measurement and monitoring techniques, and to assess the sealing effectiveness (at a later stage of the experiment). The second shaft is dedicated to risk management (back-up system), but it also allows additional information to be obtained, by 1) allowing for the evolution of a pronounced excavation damaged zone before seal emplacement and 2) using a modified emplacement technology. The in-situ work is backed by laboratory testing and model simulation.

Measurements in the rock (geophysics, pore pressure and total stress) were started between August 2019 and March 2020. Shaft sinking began in August 2020 with a custom-made drill rig and was completed in November 2020. Cores weighing up to 4 tons were retrieved in one piece.

Already in October 2020 characterization of the excavation damaged zone along the shaft walls was performed by geophysical and surface packer measurements. The sealing system and instrumentation for Shaft 1 were emplaced afterwards, and hydration of the Shaft 1 seal started in May 2021. Data and experience obtained to date will be presented.

Acknowledgment

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P2-11: Volume change behavior of unsaturated claystone/ bentonite mixture samples characterized by different initial dry densities

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In the context of the French Cigéo-project (Andra, 2005), a mixture composed of 70 % processed Callovo-Oxfordian claystone spoil (COX_c) and 30 % MX80-bentonite in weight could be a potential backfill material. Its installation aims to stabilize the surrounding rock formation and to limit the propagation of the excavation damaged zone (EDZ). The backfill material must accordingly sustain the overburden pressure, despite it might be exposed to different hydraulic and mechanical loads. Referring to the installation technique, the reference concept considers employing conventional compaction techniques, although their employment likely induces spatial variations in the dry density after compaction (e.g. SKB, 2001).

Since the initial dry density has a significant impact on the swelling and compression behavior of smectite-containing backfill materials, it is of major importance to relate the probable variations in the initial dry density to differences in the behavior. This experimental laboratory study aimed to analyze how variations in the initial dry density affects the volume change behavior of the claystone/ bentonite-mixture, in particular in unsaturated state.

The experimental program comprised suction-controlled oedometer experiments, in which samples characterized by different initial dry densities were exposed to different hydro-mechanical paths. The analysis of microstructural and water retention characteristics complemented the program (Middelhoff et al., 2020).

Major results indicated that the magnitude of free swell potential at a given suction depended considerably on the initial dry density, in particular as suctions were lower than the air entry value. The impact of the initial dry density on the one-dimensional compression behavior vanished as higher vertical stresses or lower suctions were imposed. Interestingly, despite of the suction imposition, the compression curves of unsaturated samples converged into those of saturated samples (Middelhoff et al., 2021).

The results obtained in the study can be employed to integrate more adequately the impact of variations in the initial dry density in future constitutive models being developed to reproduce the hydro-mechanical behavior of smectite-containing backfill materials.

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P2-12: Assessment of radionuclide solubility and radionuclide source terms for different host-rock conditions

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Detailed scientific knowledge and quantitative process understanding of radionuclide behavior in aqueous solutions are essential factors contributing to the nuclear waste disposal Safety Case. In order to assess and quantify radionuclide retention in the containment-providing rock zone (*Einschluss-wirksamer Gebirgsbereichs*) for a repository for high-level radioactive waste in Germany, it is important to understand and quantify main processes related to radionuclide mobilization and solubility control in the near field of the waste. This information is essential in order to derive realistic and reliable radionuclide source terms. Within this presentation, the methodology and scientific concepts related to the radionuclide source term estimations for different generic systems reflecting different host-rocks, i.e. clays and clay rock, crystalline and rock salt, will be discussed. Arguments will be supported by examples from recent research performed on both the national level and in the international frame.

For assessing radionuclide solubility control in solution, several aspects need to be analyzed from a (geo)chemical perspective in order to account for the relevant key processes. The chemical boundary conditions defined by a specific multi-barrier system and repository concept need to be considered. The specific features and chemical characteristics of the host-rock type as well as potential engineered barrier materials present likewise need close analysis.

Following the release of radionuclides from the waste matrix (in the case of HAW this is spent nuclear fuel and vitrified waste) the maximum concentrations of radionuclides in the aqueous phase will in many cases be limited by a thermodynamic control of solubility.

The solubility of a given radionuclide depends on several (geo)chemical factors which may vary strongly for different repository concepts and potential sites. Radionuclide solubility is determined by the respective solubility limiting solid phases and the processes controlling chemical behavior and speciation (i.e. complex formation by inorganic and organic ligands) in solution. The solubility is usually strongly pH-dependent and differs for different redox states, for example in the important plutonium or technetium systems, which are discussed in this presentation as typical examples. The radionuclide solubility is also highly sensitive to the amount of dissolved salts (ionic strength) in solution. Based on both empirical evidence from experimental studies and geochemical modeling using the thermodynamic databases developed on a national [1] and international level [2] it is possible to estimate the maximum solubility of radionuclides for the large set of geochemical boundary conditions expected for different host-rocks and repository concepts.

The presentation provides a general overview on key methodologies and the present scientific state-of-the-art regarding radio-nuclide source term estimations for different generic conditions reflecting different host-rock characteristics, and will also include a discussion of main related uncertainties.

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P2-13: THEREDA – Thermodynamic Reference Database for the nuclear waste disposal in Germany

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The disposal of nuclear waste including the assessment of long-term safety is still an open question in Germany. In addition to the pending decision about the repository host rock (salt, crystalline, or clay) and the associated site selection, the basic necessity of a consistent and obligatory thermodynamic reference database persists. Such a database is essential to assess potential radionuclide migration scenarios accurately and to make well-founded simulations about the long-term safety up to one million years. Specific challenges are comprehensive datasets covering also elevated temperatures and high salinities. Concerning the required elements (actinides, fission products as well as matrix and building materials), no other thermodynamic database is available that is compatible with the expected conditions. Due to these deficiencies THEREDA (Altmaier et al., 2008; Moog et al., 2015) a joint project of institutions leading in the field of safety research for nuclear waste disposal in Germany and Switzerland, was started in the year 2006.

Database features

THEREDA offers evaluated thermodynamic data for many compounds (solid phases, aqueous species, or constituents of the gaseous phase) of elements relevant according to the present state of research. In particular, all oxidation states expected for disposal site conditions are considered. In the present release, THEREDA includes data for actinides and their chemical analogues (Th, U, Np, Pu, Am, Cm & Nd), fission products (Se, Sr, Tc & Cs) and matrix elements (Na, K, Mg, Ca, Al, Si | Cl, SO_4, CO_3). For the calculation of cementitious phases the current version of CEMDATA (18.1) was integrated (Lothenbach et al, 2019). The capabilities of THEREDA are demonstrated using approximately 450 application case calculations, whose results were compared with experimental values published in literature (*e.g.* Figure 1 & 2).

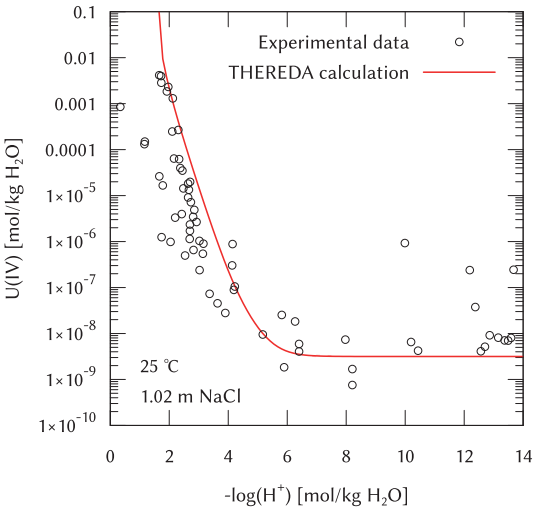

Figure 1: Solubility of amorphous uranium(IV) hydroxide in 1 m NaCl solution at T = 25 °C. Experimental data points were taken from Ryan et al. (1983), Rai et al (1997) and Neck et al. (2001) (open symbols), calculation was done using THEREDA (red line).

THEREDA is based on a relational databank whose structure intrinsically ensures the internal consistency of thermodynamic data. Data considered respond to the needs of both Gibbs Energy Minimizers (ChemApp, GEMS) and Law-of-Mass-Action codes (Geochemist's Workbench, PHREEQC, ToughReact). The database is designed generically so that it can store interaction parameters for various models. Namely, the PITZER ion interaction approach to describe activity coefficients of hydrated ions and molecules in saline solutions (Pitzer, 1991) as well as ideal and non-ideal solid solution approaches are considered in the actual dataset.

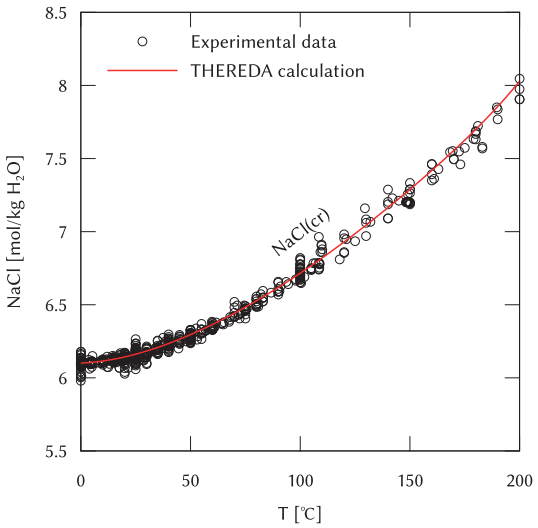

Figure 2: Temperature-dependent solubility of halite in the range of T = 0–200 °C, Experimental data points were taken from Krumgalz (2017) (open symbols), calculation was done using THEREDA (red line).

THEREDA is accessible via internet through www.thereda.de. This is not only a portal to view the data, uncertainties and the primary references of the data; it provides also additional information on issues concerning the database. Ready-to-use parameter files are available for download in a variety of formats (geochemical code specific formats and generic ASCII type). They are also used for internal test calculations – an essential element of the quality assurance scheme.

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P2-14: A systematic approach for surface exploration of sites – A database to research and evaluate suitable methods

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The site selection procedure for a high-level radioactive waste repository in Germany is based on the Repository Site Selection Act (StandAG, 2017), which comprises three phases. In phase 2, the Federal Company for Radioactive Waste Disposal (BGE) will conduct surface exploration. Based on the exploratory findings, the further-developed preliminary safety analyses, the common requirements and criteria, and socio-economic potential analyses will be applied feeding into proposed sites for underground exploration.

Commissioned by BGE, the Federal Institute for Geosciences and Natural Resources (BGR) contributes to this procedure with the projects “GeoMePS“ and “ZuBeMErk“, which compile and assess geoscientific and geophysical methods and programs for surface exploration. Their common goal is to develop recommendations for surface exploration of siting regions. For this purpose, BGR has developed a systematic approach that includes (1) deducing 186 exploration targets (Kneuker et al., 2020) based on the requirements defined by StandAG, (2) compilation of geoscientific and geophysical exploration methods in a database structure, and (3) analysis of case studies of national and international exploration programs for high-level radioactive waste disposals.

During step (2), BGR developed the database “GeM-DB” which utilizes MS SQL Server 2017 and PHP-scripts for a browser-based interface (Beilecke et al., 2021). Both leads to a highly customizable, user-friendly database enabling further adaptions, expansions and analyses of its content. Merging the knowledge of about 100 BGR experts, the database currently comprises approx. 140 geoscientific and geophysical exploration methods, including basic information and essential metadata to evaluate the general applicability of the methods for surface exploration of the three defined host rocks (crystalline rock, claystone, rock salt). Additionally, the methods are rated according to their suitability for the previously defined exploration targets.

In step (3), BGR screens national and international waste disposal programs exploring for crystalline rock, claystone, and rock salt and feeds the obtained information back into “GeM-DB”. The entire systematic approach of the projects “GeoMePS“ and “ZuBeMErk” aims to develop recommen–dations for a non-destructive and minimal invasive surface exploration program of siting regions in Germany, regarding the lithological, structural, mechanical, and hydrogeological characterization of the different host rock formations.

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P2-15: Compaction of crushed salt for the safe containment – Overview of Phase 2 of the KOMPASS project

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In Germany, crushed salt will be used as backfilling material and sealing measure for a possible repository for heat-emitting radioactive waste in rock salt. The creep of the rock salt leads to crushed salt compaction with time, whereby initially high porosity of crushed salt is reduced from 30 – 40 % to a value comparable to the porosity of undisturbed rock salt (≤ 1 %).

The compaction behaviour of crushed salt is rather complex and involves several THM-coupled processes (Kröhn et al., 2017; Hansen et al., 2014). It is influenced by internal properties, like humidity and grain size distribution, as well as boundary conditions such as temperature, compaction rate and stress state.

The current process understanding of crushed salt compaction has some important gaps with respect to material behaviour. The experimental database and the numerical modelling need to be extended and validated, especially in the low porosity ranges.

Within the first phase of the KOMPASS project, the development of methods and strategies for the reduction of deficits in the prediction of crushed salt compaction began, aiming to improve the prognosis quality (KOMPASS1, 2020). The work is currently followed up in a second project phase, which includes:

- Advancement of different techniques for producing pre-compacted samples for further investigations;
- Systematic investigations of permeability for demonstration of hydraulic tightness in long-term;
- Advancement of the tools for microstructure investigation methods for verification of pre-compacted samples, assessment of long-term compacted samples, and investigation of moisture impact on deformation behaviour;
- Execution of long-term compaction experiments following the complex experimental investigation strategy developed in KOMPASS1 to derive necessary model parameters considering individual functional dependencies;
- Benchmarking of the long-term compaction tests with various existing numerical models for model development and optimization;
- Application of a numerical demonstrator to illustrate the relevance and progress achieved in the project;
- Evaluation of numerical models with respect to the requirements for the long-term safety analysis.

Overall the KOMPASS project makes significant progress in the approaches solving the open questions with regard to long-term safety of a HLW repository in rock salt. The results will be presented at the conference.

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P2-16: Overcoring of nuclear waste canisters for retrieval from short vertical boreholes

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Although the foreseen emplacement of nuclear waste in deep geological disposal facilities is consensus amongst many countries, reasons may arise that require the reversal of this decision. Depending on the disposal concept, the retrieval must be carried out with special techniques that are tailored to the local conditions.

In one disposal concept for crystalline rock formations that is considered e.g. in Germany, single cylindrical canisters are emplaced in vertical boreholes below an emplacement drift. Compacted bentonite blocks or bricks, and granular bentonite surround the canister up to the host rock. Over time and due to the contact with moisture or water from the rock mass, the bentonite will swell and fill the remaining gaps which will in turn slow down the movement of water between the rock mass and the canister.

In order to retrieve such canisters, their close contact with the bentonite must be broken. Multiple options to do that were assessed by (Kalbantner & Sjöblom, 2000). One of the most promising options, the liquefaction of the bentonite by a low pressurized salty solution, was further investigated by (Toguri, et al., 2010). Although the results proofed the suitability of the technique in a Na-bentonite, the utilization of water as a dissolvent is contrary to the general goal of keeping water away from nuclear waste. Therefore, a mechanical technique has been designed on conceptual level to remove the bentonite above and around the canister.

In contrast to a similar mechanical mining concept described by (Simmons & Baumgartner, 1994) here only one track mounted machine is used to perform the steps required to free the canister. These steps have been adapted to the different machine concept. (1) In the beginning an auger drill including casing removes the bentonite accross the whole cross-section and down to the canister top. (2) Subsequently the top of the the canister is cleaned. (3) An adapter centers a hollow-stem auger drill at the canister (4) which removes the bentonite around the canister. Different tools on the drills allow an adjustment on the bentonites consistency.

The poster compares the principles of the hydraulic and the mechanical solution, and highlights their advantages and disadvantages in certain ground conditions.

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P2-17: Advancing transient simulation of hydro-mechanically coupled systems in geological disposal applications

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The safety assessment of Deep Geological Repositories (DGRs) strives to account for a wide range of relevant physical processes. On the one hand, there is much progress in the development of coupled thermal, hydraulic and mechanical (THM) process models and numerical codes [1,2], which are mostly quasi-static. On the other hand there are highly developed methods for wave propagation in elastic media used and developed mainly in the geophysics community [3]. The aim of this contribution is bridging the gap of fully dynamic coupled simulations, here for HM cases, with applications in the assessment of seismic hazards as well as geophysical exploration and monitoring. Using Finite-Element-Methods (FEM) [1,4], we apply the generalized-alpha method [5] for time stepping and absorbing boundary elements [6]. After verification at simple cases with known analytical solutions we focus on model problems, which are geared to realistic geologic setups still making use of isotropic, linear viscoelasticity. We demonstrate that for increasing frequency and increasing porosity fully dynamic simulations of coupled HM problems (u-p-w-formulation) make a difference compared to either quasi-static or purely elastic dynamic schemes. We discuss the propagation of slow P-waves which are only possible in porous media (HM), as well as changes in the propagation of fast P-waves and shear waves in dependence on frequency and porosity. Regarding permeability and elasticity, we assume them as correlated with porosity and make use of empirical relations.

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P2-18: Influence of residual stresses on barrier integrity demonstration for rock salt

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According to the German safety requirements, safe containment of high-level radioactive waste inside a containment-providing rock zone (CRZ) has to be demonstrated. As a consequence, the rock salt barrier integrity has to be verified showing that in the CRZ

- the anticipated stresses do not exceed the dilatancy strength
- the anticipated fluid pressure does not exceed the fluid pressure capacity

Quantitative approaches to the dilatancy strength boundary and the fluid pressure citerion are available to demonstrate that the fluid pressure capacity is not exceeded. Remarkably, both integrity criteria are formulated in stress space.

From metal (visco)plasticity it is well known that the yield limit and the failure envelope may evolve due to hardening effects induced by strain history. The so-called Bauschinger effect is technically used to raise the yield limit and the strength of steel. However, the rise of strength in one direction lowers the yield limit and the strength in the opposite direction. This kinematic/anisotropic hardening effect is generalized in three dimensions and described mechanically by the movement of the yield limit and the failure envelope in stress space (e.g. Malvern 1969). This type of kinematic/-anisotropic hardening is explained by residual stresses.

In rock salt, residual stresses have been investigated for several decades. They were caused by paleostresses and are often related to intensively deformed geologic units. They are characterized by subgrain size/density (e. g. Kneuker et al. 2018). Generally, residual stresses are not relevant as long as they do not have any influence on the macroscale. I.e. they must not affect the position of the dilatancy criterion or the fluid pressure criterion in stress space.

By comparison with metals, a process understanding was developed concerning residual stresses in salt. Natural rock salt contains a small amount of water that is mainly trapped at the grain boundaries. At low deviatoric stresses, which are typical for the paleostress regime pressure solution creep is the main deformation. Thus, due to solution and precipitation at the grain bondaries, “virgin” salt is available that was not subjected to a strain history, which explains why the residual paleostresses are restricted to the interior of the grains. This process can be compared to a melting/solidification process of a metal, which usually leads to a virgin state being free of residual stresses.

From process understanding, strong arguments are derived that residual stresses solely act inside the grains and do not affect the macroscopic stress state. Consequenly, it is concluded that residual stresses can be neglected with respect to the dilantancy and the fluid pressue criteria.

This hypothesis should be verified experimentally. Three different approaches may be applied:

- Investigate different core samples originating from the same stratigraphic unit that underwent different deformation history (e. g. Kneuker et al. 2018)
- Divide core samples of high subgrain density and anneal one part carefully by temperature rise keeping the temperature gradient low in order to avoid brine migration. Compare the results of both parts.
- Divide core samples of low subgrain density and create high subgrain density in one part, artificially. Compare the results of both parts.

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P2-19: Simulation of radionuclide diffusion profiles in bentonite – prediction for the Long Term In-Situ Test at Grimsel Test Site (GTS), Switzerland

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The work presented is performed in close co-operation with the international project „Colloid Formation and Migration (CFM)“ coordinated by Nagra (www.grimsel.com). One key experiment performed within the CFM project was the Long-term In-situ Test (LIT), where a radionuclide spiked compacted bentonite source was emplaced in the shear zone at GTS and hydraulic and hydrochemical parameters have been observed for the duration of the experiment (Noseck and Schäfer, 2017). After 4.5 years the experiment has been stopped and overcored in February 2019 and is currently being analyzed.

One key question concerns the mobility of the radionuclides in the bentonite. The calculations presented here are aiming to estimate how radionuclides are distributed in the bentonite and whether significant amounts of radionuclides are expected to have been released from the bentonite during the LIT experiment. Predictive calculations have been performed with the PA transport code CLAYPOS. Two geometries have been considered, (i) planar and (ii) radial geometry. The extension of the pathway was assumed to be 0.01 m, i.e. from the opening of the glass vials (containing a bentonite paste with the radionuclides) in the inner part of the bentonite to the outer bentonite rim at the interface between bentonite and shear zone.

Diffusion in compacted bentonite is a complex process due to pore structure dependent types of water: (i) free bentonite porewater, (ii) interlayer water with water and cations between the TOT layers of montmorillonite, devoid of anions, and (iii) diffuse double layer water containing water cations and anions. Effective diffusion coefficients derived by Van Loon (2014) to describe the diffusion considering all three types of water are applied. Sorption coefficients are taken from Bradbury and Bayens (2010). For the outer boundary of the bentonite a high flow of 1m/a is assumed.

The calculation results indicate, that the actinides in the tetravalent state, Pu(IV), U(IV) and Np(IV) will be rather immobile showing steep decreasing spatial profiles in a distance of less than 0.001 m after 4.5 years duration of the LIT experiment. The spatial distributions calculated for Pu(III), Am(III), Tc(IV) and U(VI) show a concentration decrease of one order of magnitude at a travel length between 0.005 and 0.008 m, still less than 0.01 m. This suggests that the actinides and Tc, if present in the reduced form, would have remained in the bentonite source. Only if occurring in the oxidised form Tc(VII) and Np(V) are expected to be released from the bentonite. Tc was indeed detected outside the source (Quinto et al. 2019). A comparison with data from the overcored experiment, if available, and with data from a Mock-up test will be presented.

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P2-20: Geophysical characterisation of tectonic fault zones in the vicinity of potential repository sites: a case example from Switzerland

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In Switzerland, extensive characterisation of three potential siting regions is underway to evaluate their suitability for hosting deep geological repositories for radioactive waste. All three siting regions are bounded by regional tectonic fault zones that developed in the context of the Alpine orogeny. The analysis of their structure, kinematic evolution and most recent activity forms an integral part of the site characterisation.

This contribution presents the geophysical characterisation of the Neuhausen Fault, a structure that represents the westernmost border fault of the Hegau-Lake Constance Graben system in southern Germany. Field expression of this NW-SE striking normal fault is scarce, and deformation rates in Northern Switzerland are small. The fault's existence, however, became evident in regional 2D seismic data. Detailed fault architecture, dip and throw were later characterised based on the first large-scale 3D seismic survey in Switzerland (Birkhäuser et al., 2001). Independent reprocessing of the 3D seismic data (Hölker & Birkhäuser, 2018) largely confirmed the sub-surface extent and geometry of the fault.

Current site selection procedures require more detailed characterisation of neotectonic activity as well as detailed fault imaging to support site-descriptive modelling and an assessment of the fault's potential influence on the geological long-term evolution of the siting region. In the case of the Neuhausen Fault, its neotectonic activity is the focus of several studies featuring multiple scales of investigation.

On a regional scale, tectonic activity is studied and interpreted using microseismic monitoring techniques. The Swiss national network of seismic monitoring stations has been densified to facilitate the location of microseismic events with magnitude M_L > ~1. Seismo-tectonic analyses of precise event locations and focal mechanisms depict current seismic activity in relation to the Hegau-Lake Constance Graben system.

The next scale relates to exploration seismology. To date, interpretations of robust seismic time images have provided a preliminary site assessment. The currently ongoing depth processing aims at developing detailed depth images and comprehensive inventories of structural features. The results will provide essential information for site description and will support site selection and repository design.

Finally, potential neotectonic expressions of the Neuhausen Fault were studied in newly acquired near-surface and ultra-near-surface seismic data. The fault trace was successfully imaged in the Tertiary unit while Quaternary units indicate stratigraphic undulations at the location of the fault's surface projection. Detailed interpretation of these findings is still ongoing.

It is important to note that tectonics is only one of multiple criteria to be addressed and evaluated in the site characterisation and selection process for Nagra's general licence application.

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P2-21: Implementation of a temperature- and stress-dependent approach to describe bitumen material behaviour as sealing material

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To ensure long-term safety in deep geological repositories, robust seals are required. In addition to clay and bentonite, possible sealing materials for shafts and boreholes are bitumen and asphalt. Both are suitable for the construction of sealing elements due to their favourable properties. The main advantages of these materials are their chemically inert behaviour towards bedrock and aqueous solutions and their rheological behaviour and thus, their ability to seal cracks and fissures. This advantage is valuable for geological repository system safety.

The consistency of bitumen is strongly determined by its temperature. At temperatures higher than 100°C, bitumen behaves like a Newtonian fluid, whereas at moderate temperatures, bitumen behaves not only viscous but also elastic (Cerni 2001). This material behaviour is caused by the colloid-disperse structure of bitumen, which results in a complex thermo-rheological behaviour of the bitumen (Lesueur 2009).

Besides the mentioned temperature effects, bitumen deforms also upon mechanical loading (Behzadfar and Hatzikiriakos 2013). Many authors have proposed different approaches to describe the deformation behaviour of bitumen due to thermo-mechanical gradient. The rheological material behaviour of bitumen can ideally be determined under real pressure loads. For their application in underground structures, these approaches have thus to be adapted to the conditions underground.

The aim of this work was the development of a suitable constitutional material model that adequately describes the material behaviour of bitumen. For its application to bitumen-based sealing elements for geological repositories, this model also needs to take into account stress and temperature dependency. For this purpose, the Burgers rheological model was further developed using an additional approach according to (Hase, 1995), which considers both stress and temperature dependency. This approach was incorporated into the numerical software FLAC3D through a user-defined programme in the FISH environment. To calibrate this model, laboratory tests in a shear rheometer were carried out to map the structural viscosity of bitumen on two types of bitumen - oxidised bitumen and distillation bitumen. The results of the numerical tests show a good agreement with the results obtained from theoretical calculations, indicating that the model incorporated into FLAC3D can simulate the rheological behaviour of bitumen taking into account temperature and stress dependency. The results confirmed the validity and reliability of the improved interface model.

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P2-22: Retention of radionuclides in the surroundings of a repository for nuclear waste: Selected scenarios

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At the international level, disposal in deep geological formations is considered as the best option for the management of high-level radioactive waste. In Germany, the final decision concerning the host rock for a repository has not yet been taken. In general, three rock types, argillaceous rock (here denoted as “clay-rock”), rock salt and crystalline rock (e.g. granite), are being considered, each with different strengths and weaknesses. In clay rock, the entire geological and geo-technical barriers in the near-field of the repository will become saturated with water in the long term. However, water flow rates are very low and clay rocks show very high sorption capacity for many radionuclides. Most clay rocks show a self-sealing effect due to their plastic behaviour. Furthermore, clay rocks containing smectite minerals show a distinct swelling behaviour in contact with water. Thus, the transport of the radionuclides in clay rock formations is predominantly driven by diffusion accompanied by a strong retention for some radionuclides, leading to slow migration of a major part of the stored radionuclides. Rock salt shows several favourable properties, the most advantageous one being the low permeability of genuine rock salt, resulting in the absence of moving groundwater. Hydrogeological radionuclide transport may play a role in case of limited brine access and as long as crushed salt backfill is not yet compacted. Furthermore, rock salt exhibits high thermal conductivity and high temperature resistance, which minimizes temperature effects for a given waste load, as well as viscoplasticity, which permits tight closure and self-sealing around the embedded waste. Two major weaknesses of rock salt are its high solubility in water and the comparatively low uptake of dissolved radionuclides on e.g. halite (NaCls) via sorption. However, sorption to naturally abundant rock salt is still to be expected for strongly sorbing radionuclides such as e.g. plutonium but also for the anionic long-lived activation product 36Cl. Crystalline formations are in general structurally strong, chemically stable, and relatively homogeneous in three dimensions over long distances. Even if their initial porosity and permeability is low, faults and fractures may form over time depending on tectonic stress. In addition to already existing fractures, such discontinuities would strongly increase the permeability of the host rock, leading to the formation of preferential flows paths. The primary minerals of the considered crystalline rocks (e.g. quartz, feldspars, mica) exhibit intermediate uptake behaviour with respect to radionuclides. This is, however, to some extent mediated by the formation of clay minerals as alteration products of primary silicates and other fracture filling minerals.

This presentation will give an overview over radionuclide dispersion and retention for generic disposal concepts in the three potential host rocks (i.e. argillaceous, saline and crystalline rocks), considering typical design and construction of the technical and geotechnical barriers of the repository. The focus will be on the influence of the sorption properties of selected radionuclides onto natural and anthropogenic mineral phases present in the near and far field around potential waste repositories. Besides the typical mineral phases of the host rock, secondary minerals like corrosion products of the steel containers and alteration products of concrete (which is considered as structural material in some repository concepts) will be considered. The different mineral phases and the respective sorption coefficients will be discussed, and their impact on the mobility of the radionuclides in the three generic disposal concepts will be demonstrated using simplified reactive transport models.

P2-23: An International Joint Exercise on Sensitivity Analysis: First Results

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Over the past four years, an informal working group has investigated existing sensitivity analysis (SA) methods, identified best practices, and examined new SA methods being developed. The focus is on the use of SA in case studies involving geologic disposal of spent nuclear fuel or nuclear waste. To examine ideas and have applicable test cases for comparison purposes, we have developed multiple case studies. The case studies involve computational models addressing safety assessments for geologic disposal of radioactive waste. The studies were identified based on a questionnaire. The replies were used to categorize the proposed cases by their features and complexity in order to derive an appropriate strategy for the exercise. Four of these case studies were then selected for a first phase of the exercise.

The goal of the exercise is to gain a better understanding of the strengths and weaknesses of various SA methods, identify cost vs. performance tradeoffs of the methods, and highlight best practices and lessons learned. The overall aim is to provide guidelines for performing such analyses in the context of safety assessments or safety cases for geological repository facilities.

Multiple countries participated and demonstrated various SA methods on a series of case studies. For each case study, each group presented its results using different sensitivity analysis methods and/or different implementations of the same method. The breadth and scope of the case studies as well as the large variety of SA methods used provided a rich environment to study and compare results. The exercise focused on analyses for given data, i. e. it was not possible for the participants to run the models using samples of their own choice but only to re-use data generated by the “owners” of the cases. This prevents the direct use of methods relying on prescribed sampling schemes (e. g. “pick and freeze” schemes for Sobol’ indices) but keeps computational costs at minimum.

We found that the first order variance-based index estimates are now easily generated from observational data using a variety of approaches and are one of the main SA approaches. Linear and rank correlation coefficients and regression approaches continue to be used and are informative. More advanced methods show results mostly consistent with simpler methods but there are important theoretical differences. Graphical methods also provide additional visualization which can show influences over the range of a variable. It might be advisable to start an analysis by applying such methods.

We often found that the sensitivity analyses across participants identified the same first most important parameter but differed on the importance of lower ranked parameters. Parameter rankings obtained via Sobol’ indices are mostly consistent among different sample sizes and different surrogate models, however, there are often visible numerical issues for small sample sizes.

We anticipate that the second phase of the exercise will focus on more complicated cases, leading to a synthesis and recommendations on the application of SA in safety cases.

The sensitivity analysis group is working under the auspices of Organization for Economic Cooperation and Development (OECD)/ NEA’s Integration Group for the Safety Case (IGSC).

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P2-24: SpannEnD project: 3-D stress modelling in the upper crust of Germany

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Geomechaniccal stability of deep geological repositories is affected by endogenous and exogenous processes and by geotechnical operations. Stability prediction requires estimates of future stress changes and the current stress state. However, data records on the current stress state are incomplete, sparse and spatially unevenly distributed. Therefore, geomechanical models are essential to predict the 3D stress tensor. The most important data for the model are the elastic rock properties and rock density as well as stress data for the model calibration. The aim is to find the optimal initial and boundary conditions that result in a best-fit with respect to available stress data within the model volume.

We compiled the first open access database for stress magnitude data for Germany and adjacent areas (Morawietz et al., 2020) as an extension of the existing stress orientation database (world-stress-map.org). It contains 568 data records, but only 15 % have reliable quality, which means that on average only one stress magnitude data record is available for an area of 100 × 100 km^2. Thus, the key task of the project SpannEnD (Spannungsmodell Endlagerung Deutschland) was to develop a 3-D model that covers Germany to provide first-order 3-D stress tensor predictions for regional and local scales.

Based on existing compilations of the crustal structure in and around Germany, data were merged into one structural model and populated with elastic rock properties. While the first model consists of four mechanical units and 1.3 million finite elements (Ahlers et al., 2021), the subsequent model consists of 12 units and 11.1 million finite elements.

The results of the best-fit model with respect to the stress data reveals that there are regional differences when calculating the fracture potential, i.e. the distance to failure of intact rock as well as different values of slip tendency, which provides a measure of the reactivation potential of pre-existing faults. The observed variability of the modelled stress field can be used as a first-order assessment. In addition, the model can be used to derive initial and boundary conditions for models on a regional scale. Furthermore, that makes it investigate the influence of the large-scale crustal structure on the overall stress pattern.

The modelling workflow is designed in such a way that new data and higher finite element resolution can be implemented if required. This will improve the reliability of the large scale model prediction and the initial and boundary conditions for high-resolution regional models for selected areas during the site selection process.

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P3-01: On human closeness and safety: Participation in the production of executive order law for the implementation of the German site selection act

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The German Federal Ministry of the Environment, Nature Conservation and Nuclear Safety (BMU) produced two safety regulations (executiver order law) for the implementation of the Site Selection Act. During the production a general public participated. This participation has been made possible without any obligation beyond the previous obligation to involve other experts from administration or industrial enterprises.

In this this paper, I classify this development and reveal different dimensions: a constitutional base, obligations for the participation inside production of executive order generally, preparation and implementation in this special case, and outcome of participation in the text of executive order law. Next, I discuss this foundation in the wider context of participation between both legality and legitimacy and between goodwill and routines of action.

I find that the draft of the safety executive order law for the implementation of the German site selection process means an important step for a more transparent and inclusive regulation monitored by a wider public. Since conventional forms of parliamentary-administrative participation did not meet the need of efficiency and legitimation, the enhanced participatory options and regaining of control suit best to adress democratic deficits.

However, state authorities must adopt a more emphatic understanding of closeness to the citizen:
“Proximity implies accessibility, openness, and receptiveness to others. It assumes an absence of hierarchy, an ease of communication, and a certain immediacy of interpersonal relations. It also implies an absence of formalism. A government is said to be close to its citizens if it does not stand on ceremony, if it is prepared to step down from its pedestal to confront criticism directly and engage in debate or seek outside opinions — in other words, if it recognizes that formal institutions are not enough and that it must seek to establish more flexible and direct relations with the people.” (Rosanvallon, 2011, p. 203)

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P4-01: Recertification of the Waste Isolation Pilot Plant: Performance Assessment Calculations to Demonstrate Regulatory Compliance

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The Waste Isolation Pilot Plant (WIPP), located in southeastern New Mexico, USA, has been developed by the U.S. Department of Energy (DOE) for the geologic (deep underground) disposal of transuranic (TRU) waste and is currently the only licensed deep geologic repository for the disposal of nuclear waste in the United States. As such, the WIPP project has already been through the siting process and is currently under regulation as an operating repository. Containment of TRU waste at the WIPP is regulated by the U.S. Environmental Protection Agency (EPA) according to the regulations set forth in Title 40 of the Code of Federal Regulations (CFR), Part 191. The DOE demonstrates compliance with the containment requirements according to the Certification Criteria in Title 40 CFR Part 194 by means of performance assessment (PA) calculations performed by Sandia National Laboratories (SNL). WIPP PA calculations estimate the probability and consequence of potential radionuclide releases from the repository to the accessible environment for a regulatory period of 10,000 years after facility closure.

The models used in PA are maintained and updated with new information as part of an ongoing process that began nearly 30 years ago. Improved information regarding the features, events, and processes important to the WIPP typically results in refinements and modifications to PA models and the parameters used in them. Planned changes to the repository and/or the components therein also result in updates to WIPP PA models. WIPP PA models are used to support the repository recertification process that occurs at five-year intervals following the receipt of the first waste shipment at the site in 1999.
The 2019 Compliance Recertification Application (CRA-2019) is the fourth WIPP recertification application submitted for approval by the EPA. A PA has been executed by SNL in support of the DOE submittal of the CRA-2019.

Results found in the CRA-2019 PA are compared to regulatory release limits in order to assess repository performance as part of the DOE's recertification effort. This presentation includes a summary of the changes modeled in the CRA-2019 PA, as well as the estimated releases over the assumed 10,000-year regulatory period. Changes incorporated into the CRA-2019 PA included repository planned changes, parameter updates, and refinements to PA implementation.

Overall, the total normalized potential releases for the CRA-2019 PA have increased at all probability levels, as compared to those from the previous recertification PA (CRA-2014 PA). Mean releases from each of the four potential release mechanisms tracked in WIPP PA (cuttings and cavings, spallings, releases from the Culebra formation, and direct brine releases) have also individually increased at all probability levels. Cuttings and cavings releases continue to dominate total releases at high probabilities and direct brine releases continue to dominate total releases at low probabilities. Although the calculated releases have increased, the total normalized potential releases continue to remain below regulatory limits. As a result, the CRA-2019 PA demonstrates that the WIPP remains in compliance with the containment requirements of 40 CFR Part 191.

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S6-01: Long-term strategies for competence building and knowledge transfer for a safe disposal of nuclear waste

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In 2011, right after the accident in Fukushima Daiichi in Japan, the German legislator reconfirmed its 2002-decision to phase out nuclear power generation in Germany. The last of the remaining three power plants will be taken off the grid by December 31, 2022, leaving behind their high-level radioactive waste legacy, that needs to be disposed of safely in a final repository.

The nuclear phase-out has its own challenges. Amongst others there is the challenge of how to maintain, transfer and even the building of knowlegde and competence in the now more related nuclear fields. As the building and operation of NPP recedes into the background, the safe storage and disposal of the nuclear waste is a task which will last over the next decades.

The priorities of the nuclear regulator in competence management is therefore focussing more and more on the safe and orderly regulation of radioactive waste management, the safe disposal of nuclear waste and the on-going development of the safety culture practiced in Germany. Regarding the phase-out, the competence building and development will have to focus strictly on safety and security but not on the promotion of nuclear energy.

For the nuclear regulator areas of competences have been identified in which it has to take action. Examples for these areas of competence are the site selection for the deep geological repository, its pre- and post-oprational safety, the participiation of stakeholders and the public or the documentation and long-term archiving.

In achieveing competence building and knowledge transfer in the identified areas certain strategies and actions are taken. Therefore, the German federal government adopted the Strategy for Competence Building and the Development of Future Talent for Nuclear Safety in 2020. Within this srategy, six areas of action are identified:

- Education and teaching
- Advanced and continuing training
- Research and development
- Knowledge retention, committee work and networks
- International networking and cross-border activities
- Career prospects and recognition in society

For competence building, amongst others, research and developemt is promoted by the Government and is implement e.g. by the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) and BASE. A departemental research plan with alignment on maintaining expertise is founded by BMUV and implented by BASE and BfS. Similary also a project funding program is founded by BMUV (formerly by BMWi). These measures, among others, contribute to a long-term competence building with universities and other external organisations.

S6-02: Implementation of Knowledge Management (KM) in the German WMO

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Due to the restructuring of the nuclear waste-management landscape in Germany (2016), the federal company for radioactive waste disposal (BGE) is the national competence centre in Germany for the disposal of radioactive waste, and comprises experience 50+ years' operating disposal facilities.

For many decades, R&D-work for this subject has been performed in Germany with an enormous stock of knowledge (topical and quantitative), but an overview is impaired due to diffuse and local organisation of knowledge of the nuclear waste-management landscape.

Research reports for e.g. can be found in many archives, while no archive is complete and „old stock of knowledge" has to be embedded in the new stock of knowledge.

The imminent loss of expertise due to phasing out of nuclear energy production and mining in Germany must be considered as a limiting factor especially while reflecting the age structure of the BGE-staff and the restart of the new site selection procedure.

For this reason the BGE has set up the department "R&D/Knowledge Management" to implement a KM, to establish an infrastructure for a knowledge management and create a linkage with internal and external knowledge management-platforms. This means: to elaborate and embed the results of R&D-work into the „learning organisation" - including the knowledge management of the BGE -, to establish an appropriate digital knowledge archive and to consolidate the knowledge transfer process.

As a first step a team, responsible for digital acquisition and analysis of old documents, developed and build up the digital knowledge archive.

Current works are:

- Gathering of research reports and scientific publications dealing with the disposal of radioactive waste in deep geological formations
- Scanning and archiving of digitalized documents in a database
- Synthesis of research reports and scientific publications for demanded respective topic areas

Further and future steps are:

- Systematic processing of the complete stock of archives and documents of all BGE diposal projects
- Computer-aided analysis of digitalized documents to facilitate scientific inquiries in the data stock which includes the analysis of scientific reports, a brief description of the content, and capturing the key messages
- Embedding libraries of relevant research institutes in Germany taking part in repository research programmes
- Customizing of the text analysis software and digital knowledge archive technology
- Improvement of the search and access routines

The goal is to establish a KM with a digital knowledge archive, containing the relevant research reports and results, and the
and the development of future strategies as information for all the topics/areas regarding the disposal of radioactive waste in deep geological formations while reflecting the state of the art in science and technology and to conserve expertise for the next decades.

The next steps to reach this goal will be identification, gathering, archiving, valuating and analysing existing and accessible knowledge. This includes deducing the up to date state of art in science and technology well as the dissemination and utilization of knowledge to improve the efficiency of inquiry work.

S7-01: The last 15 years of seismic exploration in northern Switzerland: Contributions to definition, characterization and selection of sites for deep geological disposal

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The area of northern Switzerland has been regarded as potential target zone for a Swiss repository for high-level since the early 1980s. In 2006, the Swiss Federal Council approved the Nagra's Safety Case for such a repository within the Opalinus Clay. In 2008, the so-called Sectoral Plan Deep Geological Repository (SGT) was launched aiming to systematically define, characterize and finally select the best disposal sites in the course of three stages. Over the last 15 years, extensive seismic exploration of the geological subsurface took place in this context. In this contribution, we will reflect upon these activities to illustrate how they supported the site selection process for deep geological disposal in Switzerland.

The initial definition of potential siting regions in northern Switzerland as part of SGT stage 1 had to largely rely on existing 2D seismic data. A key aspect during this stage was the identification and delimitation of regional fault zones and the generation of regional depth maps of geological key horizons including the base of the Opalinus Clay formation. Three potential disposal sites for high-level waste were defined on this basis. As part of SGT stage 2 aiming at a narrowing in of siting regions, the existing 2D seismic data was reprocessed and locally infilled with newly acquired lines. As a result, the key geological datasets were refined significantly. Also based on new 2D seismic interpretations Nagra proposed to not further investigate one of the three high-level waste repository sites. This narrowing-in proposal by Nagra, and particularly the underlying seismic interpretation, was intensively reviewed by the regulating authorities. The intrinsic uncertainties underlying 2D seismic interpretations were one reason for the regulator to reject the Nagra proposal. Consequently, all three sites were taken to SGT stage 3 to be investigated in greater detail, namely with 3D seismics and deep exploration boreholes. The sumptuous seismic acquisition of the earlier across densely populated areas formed a particular challenge as Nagra's siting activity became very visible in the public. The measurements were nevertheless met with great acceptance and the communication experience made are considered very valuable for the later site selection phase. To date the preliminary 3D seismic images are already available and largely confirmed previous interpretations. In addition, further constraints from the currently ongoing drilling campaign show that interpretation uncertainties were adequately assessed.

Looking ahead, the next seismic challenge concerns the integration of borehole data to generate detailed site descriptive geological models. These models will form one of the main pillars for the final site characterization and Nagra's general license application for the preferred site, scheduled for submission in 2024.

S7-02: The Role of Safety Assessments in Developing Consistent and Plausible Site Selection and Post-Closure Safety Arguments

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Post-closure safety is a key aspect in the site selection process for deep geological repositories. Accordingly, post-closure safety assessments help driving the selection process. Once a site has been selected, a safety case is developed for any licensing step in the repository development program. Throughout the process, safety assessments and arguments are essential for the technical safety demonstration and contribute to social acceptance by building trust.

On the one hand, different requirements for safety assessments arise from site selection and safety demonstration. For the former, site discriminating features must be identified and their impact on safety assessed. For the latter, it must be demonstrated that safety is robustely assured for the chosen site and disposal system. On the other hand, safety arguments for the site selection and safety case must be fully consistent to assure technical correctness and social acceptance.

In Switzerland, the site selection process is at its final stage. Nagra, the Swiss implementor, is expecting to submit the general license application for a deep geological repository within a few years. The licensing documents will encompass the site selection arguments and the safety demonstration. The Swiss regulator has clearly formulated its expectations (ENSI 2018, 2020) and Nagra has accordingly updated its methodologies.

Regarding safety assessment, the role of and interplay between its different components, namely performance assessment, scenario development, and consequence analysis, has been reviewed. The following key aspects for the development of consistent and plausible site selection and safety arguments have been identified.

Methodological aspects must be identical for site selection and safety demonstration. The methodology may then be applied with different focii.

Performance assessment proves useful in identifying and quantifying site discriminating features and the impact of remaining uncertainty. Furthermore, it is a central input to scenario development. By respecting consistent methodology, consistent arguments do follow.

Scenario development for site comparison and safety demonstration cannot be separated. Rather, site comparison uses a sub-set of scenarios that feed into a safety case. For example, hypothetical what-if scenarios used to demonstrate robustness or improve systems understanding shall not impact site selection.

Consequence analysis, i.e., dose calculations, must show that sites remaining within the selection process fullfil regulatory safety criteria. They may also, at least at an early stage, help discriminating between sites or guide selection criteria or indicator weighing and aggregation. However, once only good sites remain, it may not be adequate or even possible to quantitatively link criteria evaluation or indicator ranking to dose rates. This limit should be accounted for when developing safety arguments.

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S8-01: EURAD: A step change in European joint collaboration towards safe radioactive waste management

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In accordance with the "Waste Directive" of the European Commission, all Member States have a responsibility to manage their radioactive waste safely in the long-term. For wastes with a significant inventory of long-lived radionuclides, deep geological disposal is recognised by most as the most safe land secure long-term solution, even though some countries wish to pospone implementation of disposal or to evaluate other options in parallel. Implementing disposal at a national level presents many technical, scientific, social, economic and environmental challenges, including a large research, development and demonstration (RD&D) effort.

Guided by scientific excellence and a common long term vision, a new era of more effective and efficient use of public RD&D funding in Europe has been established in the first 5-year long European Joint Programme on Radioactive Waste Management, EURAD. Built on the basis of activities and priorities of common interest between waste management organisations (WMOs), technical support organisations (TSOs) of Regulators and research entities (RE's), the Joint Programme supports Member States at various stages of implementation.

Mandated by national ministries the various key actors are working together, while maintaining independence of their respective roles, to map existing knowledge in the field with the aim to develop a common roadmap and to update the strategic research agenda (SRA) to address remaining major challenges in research and knowledge management and to initiate strategic studies, in order to complement national efforts. EURAD will ensure cutting edge research, as well as preservation, dissemination and transfer of knowledge in view of delivering safe, sustainable and publicly acceptable solutions from cradle to grave for the long-term management of radioactive waste across Europe, allowing for cross-generational exchange over the next 2 to 4 generations from conceptualisation until final closure of nuclear waste repositories.

S8-02: Research and Development for high-level nuclear waste repository in Germany

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In Germany, the Site Selection Procedure for high-level nuclear waste (HLW) repository was (re-) started with the "Act on the search and selection of a site for a repository for high-level radioactive waste" (Site Selection Act - StandAG) in May 2017. This act sets out the procedure and requirements for the identification of a site with the best possible safety for a deep geological repository for high-level radioactive waste. Further, this act defines the principles of the siting process as science-based, participative, transparent, self-questioning and learning. Based on the concept of "a white map of Germany" and considering three types of host rock (rock salt, claystone and crystalline rock), the search area will be stepwise narrowed down over the course of three phases: starting with the entire federal territory; then surface exploration regions and subsurface exploration of sites; and finally a proposal for a repository site.

The Bundesgesellschaft für Endlagerung mbH (BGE) is assigned as the German Waste Management Organisation (WMO) and as such is responsible for implementation of the Site Selection Act. With regard to this task BGE identifies R&D needs relevant for all phases of the siting process and for issues related to the disposal of HLW, and initiates corresponding R&D activities. The R&D needs are derived i.a. from ongoing work, current national regulations (StandAG, EndlSiAnfV, EndlSiUntV), exchange with the scientific community and interested civil society as well as other scientific activities at national/interational level. A periodically updated Site Selection Research Agenda and associated Research Roadmap (BGE, 2021) describes the scope of the R&D activities for disposal of HLW, which covers five research fields: (i) radioactive waste inventory and waste radiotoxic-chemotoxic properties, (ii) geoscientific aspects, (iii) repository planning, (iv) preliminary safety assessment, (v) transfer and interactivity with respect to sociotechnical aspects. Each research field is further divided into specific research topics.

The current and planned R&D-activities cover both performing research projects and collaboration with other international WMOs, aiming at closing the identified research gaps and fostering the exchange of knowledge and experience. The research projects belong to one of the following categories or a combination thereof: (i) assessment of current state of the art in science and technology, (ii) research, (iii) development, (iv) acquirement of special expertise. In the framework of its international collaborations BGE participates in diverse organisations/initiatives (IGD-TP, DECOVALEX, Salt/Clay/Crystalline Clubs of OECD), underground research laboratories (Mont Terri, Grimsel) and research programmes (EURAD).

The presentation will highlight the scope of the Site Selection Research Agenda and will provide an overview of the focus and implementation of current R&D activities.

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S8-03: Safety facing uncertainty – Steps towards a holistic and more comprehensive assessment of uncertainties in the Safety Case

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Deep geological disposal shall ensure long-lasting safety for humans and the environment. Safety is a multi-dimensional concept (NEA 2013). When safety is assessed and debated, many factors come into play, including damage potential, controllability, risks and uncertainties as well as various risk perceptions. Uncertainty prevails, where information is not sufficient or not unambiguous enough to contribute to a Safety Case. In the context of deep geological disposal, uncertainties are particularly relevant due to the long assessment periods, the complexity of the (socio-) technical repository system and natural heterogeneities.

In the Safety Case for deep geological repositories, various good practices for dealing with uncertainties have been established, especially for handling quantifiable uncertainties. However, it remains difficult to deal with uncertainties that are hard to assess, to weigh up different types of uncertainties against each other and to come to a holistic assessment of uncertainties. An objective for the further development of the Safety Case is therefore to work out criteria for a transparent assessment and weighing up of uncertainties (Grunwald 2010, Vigfusson et al. 2007). Clues for the development of such criteria are provided, among others, by a system, designed especially for the management and communication of uncertainty in science for policy, which was established in 1990 (Funtowicz & Ravetz 1990) and has been continuously developed since then.

For the assessment of individual uncertainties, we propose a four-field scheme. This scheme encompasses the relevance of the uncertainty to safety, the sensitivity of the results of the Safety Case to the uncertainty, the quality of information on the uncertainty and the possibilities to avoid, mitigate or reduce the uncertainty. This scheme has also a potential to facilitate the holistic assessment of uncertainties in the Safety Case. Given the diversity of uncertainties, an interdisciplinary approach is required when assessing them. With a particular regard to Safety Cases, which in addition to the post-closure phase include the construction, operation and decommissioning of a deep geological repository, we propose to expand the established classification of uncertainties in the Safety Case: In addition to data or parameter uncertainties, model uncertainties and system or scenario uncertainties, anthropogenic uncertainties, human factor uncertainties and normative uncertainties contribute to a comprehensive assessment of uncertainties (Eckhardt 2020).

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S8-04: A systematic approach to develop recommendations for surface exploration in Germany – BGR projects „GeoMePS and ZuBeMerk“

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The site selection procedure for a high-level radioactive waste repository in Germany is based on the Repository Site Selection Act (StandAG, 2017), which comprises three phases. In phase 2, the Federal Company for Radioactive Waste Disposal (BGE) will conduct surface exploration. Based on the exploratory findings, the further-developed preliminary safety analyses, the common requirements and criteria, and socio-economic potential analyses will be applied feeding into proposed sites for underground exploration.

Commissioned by BGE, the Federal Institute for Geosciences and Natural Resources (BGR) contributes to this procedure with the projects „GeoMePS“ and „ZuBeMErk“, which collate and assess geoscientific and geophysical methods and programs for surface exploration. Their common goal is to develop recommendations for surface exploration of siting regions. For this purpose, BGR has developed a systematic approach that includes (1) deducing exploration objectives, (2) compilation of geoscientific and geophysical exploration methods in a database structure, and (3) analysis of national and international surface exploration programs for high-level radioactive waste disposals. Exploration objectives are based on the common criteria and requirements as defined by the StandAG (paragraphs 22–24). The identified exploration objectives (Kneuker et al., 2020) together with a large number of geoscientific and geophysical exploration methods were integrated and linked within the BGR database “GeM-DB”, a dynamically generated website (see Kneuker et al., 2021). All exploration methods in GeM-DB were evaluated according to their suitability and applicability for (a) the three host rocks (crystalline rock, claystone, rock salt) and (b) the previously defined exploration objectives.

In step (3), BGR reviews national and international surface exploration programs for high-level waste disposal in crystalline rock, claystone, and rock salt. Here, the focus of the reviews is on non-destructive and minimal invasive surface exploration techniques, such as geophysical airborne and ground-based methods or investigations in drill holes and on drill cores. The aim of this step is to identify gaps in the method catalog of GeM-DB and to infer exploration directives for surface exploration during phase 2 of the German site selection procedure. An example of an international surface exploration program is the “Site investigation” program of the Swedish site selection process. There, the site investigations are i.a. the basis for the discipline-specific “Site-descriptive models”, which were applied for design and safety assessments (SKB, 2001). The Swedish site investigation program along with surface exploration programs for high-level waste disposal of other countries considering crystalline host rocks, such as Finland or Canada, show a common ground. Their selected exploration methods together with the temporal sequences are stored in the database.

Specific queries of the linked database contents, including the suitability of the methods for exploration objectives and host rocks and the results of our analyses of international surface exploration programs for high-level waste disposal, will feed into recommendations for non-destructive and minimal invasive surface exploration programs in Germany.

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S8-05: Deep borehole disposal of long-lived intermediate level waste – Generic site screening tools accounting for geological faults

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A potential solution for disposal of appropriately conditioned long-lived intermediate level waste (ILW) in Australia is currently being evaluated using deep vertical boreholes (0.7 m diameter, ~ 2000 m deep). Most of the waste considered originates from reprocessing of research reactor fuel and radiopharmaceutical production and requires permanent geologic disposal. Given the relatively small volumes of waste requiring geological disposal (< 250 m^3) and Australia's unique geotectonic framework comprising old cratons with low neotectonic activity, deep borehole disposal could be a cost-effective technology to safely manage long-lived ILW.

Prior to commencing a field-based deep borehole demonstration test in Australia, digital site screening tools need to be developed to assess the suitability of the geologic environment that will isolate and contain the waste. Fault zones are among the geological features that pose a potential risk to long-term safety. Depending on host rock lithologies, throw and mode of displacement, faults can act as barriers or conduits to fluid flow, or a combination of both; for example, a fault may act as a barrier to transverse flow and a conduit to longitudinal flow (McCallum et al., 2018). To identify potential disposal sites, a geometric analysis of the fault network must be performed to identify areas at a safe distance from faults. Of particular importance is the distance from structurally complex zones that can be identified based on the density of fault traces and intersections.

Site screening also requires numerical simulations of the regional groundwater flow. To evaluate the impact of fault zones on groundwater flow, we utilize a mixed dimensional approach that allows for easy conversion between and combinations of the endmembers of fault zone conceptualizations (i.e. barriers and conduits). On a sub-regional scale, fault zones are represented as lower dimensional regions in a conforming mesh (Poulet et al. 2021), where the mesh can automatically be generated from fault maps provided in a vector file. A 2D numerical analysis is performed to identify areas of low flow through a fault network. With decreasing distance to the potential site, the numerical model's complexity and spatial resolution must increase, such that 3D representations of fault zones are necessary. In a nested approach the detailed 3D model uses horizontal boundary conditions derived from the larger scale 2D model. This allows for parametric studies evaluating the impact of fault zone conceptualization, fault geometry, permeability-, and porosity distributions on mass transport. To further enhance the reliability of the numerical models, a homogenization approach is used that accounts for varying stratigraphy in the host rocks by using weighted averages to calculate the permeability tensor of heterogeneous layered rocks. Appropriate porosity and permeability data for each lithology are obtained via laboratory studies.

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S9-01: KombiLyse: Combined approach to safety-relevant aspects from the perspective of extended storage and disposal of high-level radioactive waste

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Until emplacement of the waste in the disposal facility, storage of high-level radioactive waste in thick-walled transport and storage casks will be carried out on the basis of the applicable regulations. The current licences for the storage of these casks were limited to 40 years at the beginning of the 2000s and expire between 2034 and 2047. In view of the current time schedule until the commissioning of a disposal facility for high-level radioactive waste, a safe solution for the extension of this originally planned and licensed 40-year period of storage in the storage facilities has to be found.

For the licensing of storage on the basis of the requirements pursuant to § 6 of the Atomic Energy Act (AtG), the suitability for disposal is also considered, but only with regard to the handling of the waste and as to whether the waste can in principle be conditioned in the future. The effects of storage itself and the effects of possible measures during storage on the behaviour of the inventories in the disposal facility have not been part of the licences so far. When reviewing the fulfilment of the licensing requirements for extended storage, there is the possibility to directly consider the requirements for disposal in the licensing procedures.

In order to realise the first steps towards this combined approach, as an interdisciplinary approach so to speak, the KombiLyse research project (combined analysis of safety-relevant aspects from the perspective of storage and disposal of high-level radioactive waste, taking into account extended storage periods) was launched. It considers from different perspectives the effects of extended storage, the influences on radionuclide mobility in the disposal facility and then the different options for action with their respective feedback effects. The focus here is on the investigation and assessment of scientific and technical issues related to radionuclide mobilisation and mobility.

Currently, analyses are carried out on possible developments of the casks and inventories as well as the options of different measures during the time of storage until emplacement in the disposal facility. Known inventories and cask loadings are considered here while taking into account particularly unfavourable cases. In parallel, the possible influences on the safety of disposal are analysed with a focus on radionuclide mobility in the near field of the disposal facility. This is done according to the three disposal concepts selected in the first step for the host rocks claystone (Switzerland), crystalline (KBS-3, Sweden) and rock salt (Germany).

The project is funded by the Federal Office for the Safety of Nuclear Waste Management (BASE) under project number 4719F10701.

S9-02: Systematic Top-down Approach to Develop Waste Containers for Heat-Generating Radioactive Waste and Spent Fuel in Different Host Rocks – Results of the R&D Project KoBrA

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Three rock types (rock salt, claystone and crystalline rock) are considered as potential host rock formations for a repository for heat-generating radioactive waste and spent nuclear fuel in Germany. As of summer 2017, the Repository Site Selection Act (StandAG), which comprises a new procedure for siting a repository that best meets the safety requirements for a period of 1 million years, is to propose a repository site by 2031.

Safety investigations are one measure to provide – step-by-step – a more and more detailed basis to narrow down and select a site during the process. These investigations – a mandatory part of the siting procedure – rely, among other things, on a clear understanding of the repository system and on a suitable safety concept. Consequently, detailed repository designs that meet the requirements of the safety concept have to be developed. In this context, the waste container is an essential component of the repository system. First, a waste container has to provide basic safety functions like containment of the radioactive inventory, shielding, sub-criticality, and sufficient decay heat dissipation during all handling procedures. Second, a waste container has to provide these safety functions for long time periods, depending on the geologic boundary conditions. And eventually, the waste container has to meet all design criteria, including resillience in case of a future retrieval and recovery.

In the past decades, mainly rock salt was considered as potential host rock for heat-generating radioactive waste in Germany. Thus, there had not been any methodology to systematically derive requirements for waste containers for different host rock formations. Consequently, the German Ministry for Economic Affairs and Energy (BMWi) and the Project Management Agency Karlsruhe PTKA, funding generic site-independent R&D projects, launched the R&D project KoBrA (Requirements and Concepts for Waste Containers for Heat-generating Radioactive Waste and Spent Fuel in Rock Salt, Claystone, and Crystalline Rock) mid-2017. The project, accomplished in autumn 2020, was a joint endeavour of BAM (Bundesanstalt für Materialforschung und -prüfung) and BGE TECHNOLOGY GmbH.

The key result of the detailed investigation was the development of a methodic approach – a holistic top-down approach – on how to systematically derive suitable container designs that meet the requirements taking into account host rock-specific and operational boundary conditions, depending on the overall repository design. Including the existing legislation and technical guidelines as well as the current international state of the art, the approach was elaborated taking into account the entire lifecycle of the waste container. In doing so, designated phases for a waste container were identified as periods of container emplacement, optional container retrieval, optional container recoverability for 500 years after repository closure, followed by the post-operational phase. Eventually, ideas and suggestions for the implementation of the derived approach were elaborated by means of reviewing already existing international container concepts and deriving generic container concept ideas. Thus, a sound basis that facilitates the development of waste container concepts by the waste management organisation BGE was established.

All findings and results are summarised and published in a comprehensive final report with apendices.

S9-02: Development of magnesia shotcrete with hard stone and salt surcharge

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Safe closure of underground disposal facilities and future HAW ("high active waste") repositories require appropriate building and sealing materials. In a BMWi-supported project ("CARLA"), three closure elements were installed in large-scale tests in the Carnallit Mountains in the Teutschenthal mine for demonstration of their technical feasibility and suitability. The large-scale test 2 (named „GV2"), which was produced from MgO concrete using the dry-mix shotcrete procedure, is discussed here. The 10.25 m long structure consists of 104 concreting sections with an average thickness of 9.9 cm. [1]

After more than 10 years of standing and maturation, a follow-up project ("MgO-SEAL") was carried out with a fluid pressurization via the pressure chamber as well as further permeability tests in boreholes and on drill cores with different salt solutions. A significant result of these investigations was the reduction of the integral permeability from initially $2*10^{-15}$ m² and $4*10^{-16}$ m² to $<10^{-19}$ m² over a measurement period of 2.5 years. The reason for this decrease is the reduction of pore space by recrystallization of MgO and the transformation of the metastable 5-1-8-phase (5 mol $Mg(OH)_2$ – 1 mol $MgCl_2$ – 8 mol H_2O) into the long-term stable 3-1-8-phase due to the increase in volume that takes place when solution is added. So an internal sealing takes place. [2]

In the current follow-up project ("MgO-S³"), the formulation used for the GV2 will be reproduced in rock salt in a large-scale experiment and improved with regard to higher layer thicknesses. This was already achieved in summer 2020 with 2 shotcrete tests. A total of 5 layers were sprayed with layer thicknesses of up to approx. 30 cm. The higher thickness is accompanied by higher setting temperatures of up to 90°C in the centre of the layer. However, according to the current state of knowledge, it is estimated that layer thicknesses of more than 15 cm cannot be realised because the temperature rises too much in the middle of the layer. In addition, the strength of the shotcrete was determined. Immediately after spraying each layer, the early strength was determined using a penetrometer. After curing of the concrete, the compressive and tensile strength were determined after 3, 7, 14 and 28 days.

Furthermore, the replacement of the sand-gravel surcharge by salt grit was tested. Several shotcrete tests with different recipe variants have already been carried out in a technical test-size scale. With the preferred formulation determined here, a further in situ shotcrete test was carried out in the autumn of 2021.

To prove the combination of sand/gravel and salt as an aggregate of the shotcrete, experiments were carried out in test-size scale with three different compositions.

In evaluating and comparing all recipe variants and surcharges, a robust, reproducible recipe is to be developed, which provides high layer thickness, not too high setting temperatures and a low rebound.

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S9-04: Support of Underground Openings in a HLW/SF Repository in Clay Stone

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The proposed paper presents the DMT's results of the R&D study "Support of Underground Openings in a HLW/SF Repository in Clay Stone - AGEnT" prepared by BGE TECHNOLOGY GmbH and DMT GmbH & Co. KG. Within the project, the fundamental information on the influence of the geotechnical boundary conditions on the design, operation and as well on support concepts and -materials for a clay repository was gained. The contribution thus complements the work being carried out and presented by BGE TECHNOLOGY GmbH is the identification of corrosion processes inside the concrete based material used for the lining and an evaluation of the interaction of chemical corrosion with the mechanical properties during the post-closure phase.

The investigation of the behaviour of different support systems for different rock mechanical conditions was carried out by means of geotechnical modelling and parameter variations.

According to the Site Selection Act (Standortauswahlgesetz, StandAG) the depth of a repository should be at least about 300 m. The StandAG does not limit the depth of the repository to a lower limit, presumably the limit will be about 1000 m.

The geotechnical modelling has shown that in the "short-lived" storage galleries (service life < 1 year) up to 1000 m depth, arched sections with concrete lining (even without steel arches) can be used, provided that an impact movement of 10 % of the initial width is acceptable and dinting work is carried out to eliminate the floor heave.

One requirement is that as building material the so-called low-pH concretes are to be used.

In the course of the research work, various formulations for low-pH concretes were developed. The reduction of the cement content with a simultaneous increase in the proportion of pozzolana allows a considerable reduction of the pH-value. As one result of the R&D work a concrete was developed which has a pH-value below 9.0 and meets the requirements of strength class C50/60.

The storage concept shows that up to a maximum of 9 adjacent storage galleries can be open at the same time. For thermal reasons the distance between adjacent storage galleries should be 20 m (midpoint distance). The geotechnical modelling has shown that from the view of strata control under unfavourable conditions (great depth and weak clays stone) this distance is much too small. A greater distance will considerably increase the space required for a repository.

In contrast to the short lifetime storage galleries, the main galleries must be dimensioned to be stable for the entire lifetime of the repository mine (up to 50 years). It has to be taken into account, that swelling and creep movements of the claystone cannot be excluded. This leads to the result that in large depths extremely extensive closed support systems with yielding elements are required to guarantee the long-term stability.

By means of a combination geomechanical modelling and concrete development it could be shown the suitable support systems and materials are available to fulfil the requirements for galleries in a nuclear waste repository in claystone and high depth.

S9-05: Long-term performance of concrete-based support structures for a high-level radioactive waste repository in claystone

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Results of the R&D study "Support structures for underground openings in a HLW/SF repository in claystone – AGEnT" prepared by BGE TECHNOLOGY GmbH and DMT GmbH & Co. KG (DMT) are presented. This project was funded by the German Ministry for Economic Affaires and Energy (BMWi) and contributes to the development of support structures in line with operational and long-term safety requirements. The work focused on the identification of corrosion processes inside the concrete-based materials used and an evaluation of the interaction of corrosion and mechanical properties during the post-closure phase. This contribution thus complements the work being presented in parallel by DMT for the geomechanical assessment of suitable support structures depending on the geological conditions.

Based on the potential host rock formations in Germany and the requirements for support structures, the interactions of rock pressure, rock properties, geometry and support concept were investigated by means of variation calculations. As a result, favourable properties of the support structure were identified. The use of concrete-based structures should be preferred and the steel content that remained in the repository should be reduced. Other systems, e.g. used in mining with comparable rock properties, are not farourable because of the high steel content.

In accordance with the specifications of civil engineering, concretes that comply with the specifications of EN 206 are currently used for support strcutures. To ensure the passivation of steel reinforcement, these concretes have a high pH value. For a future HLW/SF repository, low-pH concretes were developed that contain high proportions of reactive additives, e.g. silica fume and/or fly ash. The mixture can be used as cast-in-place and as ready-mixed concrete (wedge blocks). In this way, a high-pH plume that could damage clay-containing seals is avoided.

Ordinary portland cement-based and low-pH concretes contain calcium silicate hydrates and calcium aluminate hydrates. Due to this fact, the same corrosion processes can take place in both materials, but with different intensity. The contents of the binder phases and the pore structures differ, which affects the penetration behaviour of corrosive substances. According to EN 206, reactive additives can be counted as binders according to the k-value concept. This concept has been extended and is now applicable to low-pH materials. Taking into account the reactivity of the additives, a model that allows conclusions to be drawn on the formation of the pore structure in the long term and the changes of the mechanical properties of concrete was developed; and alteration and transport calculations were carried out. For estimating the long-term evolution, the interactions between a wedge block support combined with compressible backfill and the excavation damaged zone were investigated by means of fully coupled hydro-mechanical simulations. With the help of the numerical calculations and known relations between corrosion and material properties, a preliminary estimation of how chemical alterations interact with the development of mechanical properties was made. As a result, the understanding of the process of support structure alteration, backfill compaction, and of the necessary lifetime of drift seals inside a repository was improved.

S9-06: Safety, Science and System Analysis

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Research on high-level nuclear waste forms, like borosilicate glass and spent nuclear fuel, has been ongoing for more than 45 years. Safety analyses show consistently that the disposal of highly radioactive waste is as safe and feasible as necessary. However, a recent debate reveals a dilemma: Guo et al., (2020) have pointed to an "overlooked" acceleration of glass dissolution at the interface with the stainless steel container. In response, Mallants and Chapman (2020) have argued that this "new" science does not affect the outcome of the safety assessment. An alarm is raised and dismissed.

Guo et al. placed a piece of simulated nuclear waste glass in contact with a steel coupon for 30 days in a large volume of an aqueous solution and, using modern analytical techniques, demonstrated an increase of corrosion depth at the contact zone. They concluded, that the interface interaction between dissimilar materials could profoundly impact the service life of the nuclear waste packages. However, the observed glass corrosion depth, even at some distance from the steel, corresponded to a corrosion rate only expected if one were to put this glass into a river; more realistically, long term corrosion rates in a confined repository space are expected to be about 10,000 times slower. Further, this effect has been documented 30 years ago (Werme et al., 1990). Why then has the paper received so much attention, not only in scientific, but political spheres, as well? The results of the paper were presented as if an important "new truth" had been missed by over 45 years of research and that this "new truth" should be an important consideration in repository performance.

Without questionning the scientific basis of the paper, Mallants and Chapman (2020) published a rebuttal noting that the observed effect does not matter, as the waste form does not have an impact on safety. Other barriers against radionuclide release and dispersion are sufficiently effective, even for hundreds of thousands of years. Following this argument, waste form research is not necessary.

The argument made in the second paper is consistent with many safety analyses that persistently show that most, if not all repository concepts, are safe for hundreds of thousands of years.

How can the waste form be so important in the first paper and of limited value in the second? The first paper ignores previous work and exaggerates its importance; the second dismisses the importantce of the waste form. What both papers fail to address is the role of redundancy in a multi-barrier system. Confidence in the safety of a repository relies on redundant lines of evidence that are informed by up-to-date science and an understanding of the engineering safety analysis. All barriers carry significant safety functions as dictated by the disposal strategy. In the case of nuclear waste forms, we simply note that this is where the radionuclides are initially located.

In our view, the two papers illustrate the danger in failing to understand the science, as well as the safety analysis. The redundancy of the multi-barrier system is a basic tenent of geologic disposal of nuclear waste. But unless the supporting science and safety analysis are fully integrated – the multi-barrier system becomes a house of cards that will fail unexpectedly with the first breeze.

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S10-01: "Legal, cultural and political Challenges for Transboundary Public Participation in the Context of the Siting Procedure for High-Level Radioactive Waste"

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For Germany, as the European country with the most neighbouring states, it is likely that some of the sub-areas, siting regions and possible sites defined in the selection procedure will be located on or in the immediate vicinity of one or more national borders.

In the construction of a repository for high-level radioactive waste, however "affectedness" does not stop at national borders, so that the public (citizens and other stakeholders) from neighbouring countries must be involved in the public participation processes at an early stage and on an ongoing basis. Already since the nineties of the last century, citizens from EU states have been able to participate in formal procedures for the approval of infrastructure projects in a neighbouring state, due to the regulations of the Espoo-Convention, which has been transposed and implemented into national law.

Participation and its characteristics and manifestation within a state, a region or a specific location is strongly dependent on the respective cultural and political framework conditions. Nation states have different characteristics in their political systems as well as political cultures. Political systems in Western Europe differ primarily in terms of their democratic model, i.e. whether, for example, they are more parliamentary-representative or direct-democratic and whether there are more centralised or decentralised responsibilities and decision-making powers.

In the context of transboundary public participation in the site selection procedure for a repository, also different attitudes towards nuclear energy in general and the contexts of experience with regard to participation in Germany's neighbouring states will have an impact on expectations towards Germany.

Due to the high politicisation potential of the topic of final disposal of highly radioactive waste, it can be assumed that the demands with regard to transboundary public participation will be diverse and comprehensive, especially with regard to the timeliness and quality of information but also consultation.

The research project HErüber, commissioned by the Federal Office for the Safety of Nuclear Waste Management (BASE) has the task to work out the specific challenges and success factors of cross-border formal and informal procedures for public participation and to transfer these to the specific case of the search for a repository site.

So far it has analysed the legal requirements for transboundary public participation under the Repository Site Selection Act (Standortauswahlgesetz), international treaties european law. Further specific cultural and political framework conditions in the neighbouring countries were assessed. The research is based on desk research as well as empirical studies in specific transboundary procedures. In this presentation we focus on risks and challenges like complexity, knowledge management, power asymmetries as well as critical success factors like fairness, balancing of interests, co-operation and sensitive handling of intercultural differences for transboundary participation. In this regard, we draw attention to specific cultural and political aspects of neighboring states which will have an effect on transboundary participation.

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S10-02: Future pictures for final disposal

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The science-based determination of a location for the final disposal of high-level radioactive waste is a major challenge, not only from a technical point of view, but also in terms of the process, which carries special expectations. Just like the design of the technical repository concept, which among other things depends on geological investigation results, the search process, which has a claim to be self-questioning and reversible, is open in its development. The search for a repository in Germany has a past marked by conflicts, yet the location selection process is future-oriented. In the course of the research project "Public participation in the search for a repository: Challenges of a cross-generational, self-questioning and learning process"[1], the Institute for Technology Assessment and Systems Analysis (ITAS) at the Karlsruhe Institute of Technology (KIT) discussed future images of a repository with young adults in an experimental format. These images were derived from an analysis of narratives on the subject. While narratives refer to the past and can have an impact on the present, images of the future illustrate concrete ideas, wishes and visions for what has not yet been experienced. In the context of the search for a repository, it is above all “socio-technical futures” (Lösch et al. 2019) that can be used for the accompanying design of a social task with technical and political means. Socio-technical futures name different and possibly also contrary futures, the outline of which generally relates to larger public debates. In the empirical study, methods of qualitative social research and concepts of technology assessment were used. Using qualitative, guideline-based interviews, experts were asked about their perspective on the site selection process for a repository for highly radioactive nuclear waste. This also included considering the context and reflecting on expected futures. The results and the following recommendations for action for the process of finding a repository are the central subject of the lecture.

[1] The research was funded by the Federal Office for the Safety of Nuclear Waste Management (BASE) - project grant no. 4717F00001. Project partners were Oeko-Institut e.V., team ewen GbR, ITAS (KIT).

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S10-03: Nuclear Waste as "Matter of Care": Opportunities for a Paradigm Shift in the Long-Term Governance of HLW and Spent Fuel in Belgium

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In this presentation, we will elaborate on the results from a study conducted in 2018-2019 by research teams from the Universities of Antwerp, Liège and Maastricht to identify building blocks for the long-term governance of high-level waste (HLW) and spent nuclear fuel in Belgium. The study was commissioned by ONDRAF/NIRAS, the Belgian national waste management organisation (WMO).

A three tier qualitative approach was taken: consisting of an thorough mapping of stakeholders and their positions taken vis-à-vis the long-term management of Belgian HLW in the past decade, a foresight exercise with ONDRAF/NIRAS staff members, and a two-step interactive survey among self-identified stakeholders regarding what they considered future challenges and key elements of a governance process. ONDRAF/NIRAS is no exception to the rule among WMOs and has been a strong advocate of geological disposal for decades. However, there is to date still no clear political decision taken in that regard. We therefore choose to question our respondents on what governance they considered should be put in place to enable decision-making on HLW waste and spent fuel, and subsequent the implementation of the chosen long-term management strategy, without an exclusive focus on geological disposal.

We drew our data from extensive document analysis, and 22 in depth interviews and 2 focus group discussions (for the stakeholder mapping), 4 foresight workshops with ONDRAF/NIRAS staff, and input to the interactive survey from 242 respondents. We held this data against findings from previously conducted research in this field by the universities of Antwerp and Liège.

Our analysis points to the need for a paradigm shift at three levels to unblock the current situation and to prevent an ever further expanding time-lag between research and official policy:

- Approaching the waste as "matter of care" (Puig De La Bellacasa 2011): acknowledging multiple ways of caring and allowing them to co-exist; establishing common-ground by starting from shared uncertainties rather than shared 'facts'.

- Talk about waste first (how it is produced, what it is, and where and how it is kept today), before talking about waste management solutions: establish a community of those who care about the waste, not only those who care about a particular end-point for it.

- Engage with all who care, and in particular those directly affected, such as local (site) communities and citizens: this throughout the entire length of the process, which will inevitably span over several decades and generations of stakeholders; intergenerational engagement should be aimed for, but can only be reached by starting with the present generation in a collective and open decision-making and governance process.