Entsorgungsforschung

2nd Chinese-German Workshop on Radioactive Waste Disposal

Karlsruhe Institute of Technology (KIT)
Campus North, Building 418
October y 15-16, 2012

A joint workshop organized by

Beijing Research Institute of Uranium Geology, (BRIUG), China
Federal Institute for Geosciences and Natural Resources (BGR), Germany
Project Management Agency Karlsruhe (PTKA) - Karlsruhe Institute of Technology, Germany

Ed. W. Steininger

Projektträger Karlsruhe
Wassertechnologie und Entsorgung (PTKA-WTE)
Herausgeber:
Projektträger Karlsruhe
Wassertechnologie und Entsorgung (PTKA-WTE)
Karlsruher Institut für Technologie (KIT)
Hermann-von-Helmholtz-Platz 1
76344 Eggenstein-Leopoldshafen
Internet: www.ptka.kit.edu

neu zusammengestellt Juli 2017

Der vorliegende Materialienband dient der aktuellen Unterrichtung der auf dem Gebiet der Entsorgung radioaktiver Abfälle arbeitenden Institutionen und der zuständigen Behörden.
Verantwortlich für den Inhalt sind die Autoren. Das Karlsruher Institut für Technologie (KIT) übernimmt keine Gewähr insbesondere für die Richtigkeit, Genauigkeit und Vollständigkeit der Angaben sowie die Beachtung privater Rechte Dritter.
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Berichte und Publikationen zu Projektstatusgesprächen, Kolloquien und Fachgesprächen sind über die Internetseite

www.ptka.kit.edu/wte/171.php

des PTKA zu finden.
Foreword

Most countries using nuclear power face the problem of safe disposal of the radioactive wastes. Although for highly radioactive wastes (spent fuel, high-level waste, and some types of long-lived radioactive waste) a repository is still pending, there is international consensus that the preferred solution is disposal in deep geological repositories in the three most favored host-rock media crystalline rocks, evaporitic / salt rocks and argillaceous rocks.

Both China and Germany are well aware that the management of radioactive waste is necessary and indispensable. It is well known that the disposal of these waste types is a challenge in a multifold way and demands sound technical and scientific knowledge and expertise to do it safely and securely.

Against this background, the common 1st Chinese-German Workshop on Radioactive Waste Disposal was successfully held in Beijing, May 2007. The main purpose of the then workshop was to present ideas, exchange information, and to foster discussion among the experts. AND: It was recognized that the exchange of information is the crucial point.

Since then in both countries progress was made and changes occurred concerning the topic “Disposal of Radioactive Waste”. It was recognized that the purpose of the first workshop still was very important. Therefore it was considered essential to inform mutually on new developments and advancements in the national HLW-disposal programs and to exchange current R&D outcomes and the progress made focusing esp. on results regarding crystalline and argillaceous host rock.

Considering this and the bilateral common interests PTKA, BGR, and BRIUG decided to organize jointly the 2nd Chinese-German Workshop on Radioactive Waste Disposal in Karlsruhe, Germany.

Twenty four Chinese and twenty two German attendants participated in the workshop. They all represented academia, industry, research, state-owned organizations and other important institutions involved in radioactive waste management activities. In total twenty three presentations were given focusing on following topics:

- Geology of potential formation
- Geomechanics and rock mechanics
- Long-term safety analysis
- Radionuclide migration
- Behavior of vitrified waste

It was agreed to collect the excellent presentations and to make it available both to document the outcomes of this event and also to have it at the disposal for the attendees and for a larger interested community.

We greatly acknowledge the contributions of all workshop participants.

Hua Shao  Walter Steininger  Ju Wang
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2nd- Chinese-German Workshop on Radioactive Waste Disposal

Karlsruhe, October 15 -16, 2012
Karlsruhe Institute of Technology
The Merger of Forschungszentrum Karlsruhe and Universität Karlsruhe
The KIT Vision

Feature of uniqueness: KIT eliminates the pillar structure!

Institutions

<table>
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<tr>
<th>Institutions</th>
<th>Number</th>
<th>Funding (FRG: State in %)</th>
</tr>
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<tbody>
<tr>
<td>DFG</td>
<td>58:42</td>
<td>0:100</td>
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<tr>
<td>Universities</td>
<td>117</td>
<td>90:10</td>
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<tr>
<td>Helmholtz</td>
<td>15</td>
<td>90:10</td>
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<tr>
<td>Max-Planck</td>
<td>80</td>
<td>50:50</td>
</tr>
<tr>
<td>Leibniz</td>
<td>84</td>
<td>50:50</td>
</tr>
<tr>
<td>Fraunhofer</td>
<td>58</td>
<td>90:10¹</td>
</tr>
</tbody>
</table>

(¹ Share of public funding 30%)

German Science System
Common Objective

Positioning as an institution of excellent research and teaching in natural and engineering sciences on an international scale, with scientific excellence and worldwide top level in

- Research
- Teaching
- Innovation

Prerequisite:
Excellent infrastructure and service units.
Staff

<table>
<thead>
<tr>
<th>Employees</th>
<th>9,139</th>
</tr>
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<tbody>
<tr>
<td>Teaching and research</td>
<td>5,636</td>
</tr>
<tr>
<td>Infrastructure and services</td>
<td>3,503</td>
</tr>
<tr>
<td>Professors</td>
<td>364</td>
</tr>
<tr>
<td>Foreign scientists</td>
<td>777</td>
</tr>
<tr>
<td>Trainees</td>
<td>509</td>
</tr>
<tr>
<td>Students (WS 2011/2012)</td>
<td>22,552</td>
</tr>
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</table>

Status 2011

Strong Teaching: 364 Professors

Internationally Attractive: 777 Foreign scientists

Excellent Training: 509 Trainees

22,552 Students
Centers and Focuses

- Zentren

Energy 01.01.08
NanoMikro 01.01.08
Elementary particle and astro particle physics 01.01.08
Climate and environment 01.01.09
Mobility systems 01.01.11

- Schwerpunkte

COMMputation 01.05.08
Humans and Technology 15.07.09
Optics and Photonics 01.01.10
Anthropomatics and Robotics 01.07.2010

- Schools

School of Optics and Photonics 13.10.06
School of Energy 2011
... Schools
Example: KIT Energy Center

Research Topics

Employees: 1250
Budget: 250 M€
New orientation of the programme nuclear safety research

Nuclear waste disposal and safety

- FZJ, HZDR, KIT
- Reduction of personnel: 11%
- Concentration on topic in the field of nuclear waste disposal

Research programme 2010 - 2014:
Total staff: 272 FTE

- HZDR: 98
- KIT: 142
- FZJ: 32

Research programme 2015 - 2019: Total staff: 242,5 FTE

- HZDR: 85.5
- KIT: 120
- FZJ: 37

-29.5 FTE
-11%
Kit - Institute for Nuclear Waste Disposal (INE)
Research on nuclear waste disposal

**Fundamental research**

Understanding processes on a molecular level
Aquatic chemistry of actinides and long-lived fission products

Elucidation and quantification of complex geochemical reactions (example: Plutonium chemistry)

Understanding of radionuclide speciation in repository systems on a molecular level

**Application oriented research**

Radionuclide retention in the multi-barrier system
Investigation of radionuclide migration in the laboratory ...

... and under natural conditions (in underground laboratories)

Spent fuel corrosion experiments

Colour of plutonium solutions at different redox states

**Development and adaption of speciation methods**

Structural informations at trace level
Elucidation of radionuclide speciation by laser spectroscopy ...

... and by x-ray spectroscopy at the INE-beamline for actinide research at ANKA

Experimental setup under remote control in shielded boxes.
Vitrification technology
Vitrification Plant China (VPC)

- Governmental environmental protection project
- Location near Guangyuan/Sichuan province
- Project duration 6 years
- HLLW design throughput 50 l/h
- Glass production rate 31 kg/h
- Approx. 1300 Glass canisters
13th International Conference on the Chemistry and Migration Behaviour of Actinides and Fission Products in the Geosphere

Migration 2011

Beijing, China
September 18 – 23, 2011

Local Organization:
Peking University
China Institute of Atomic Energy (CIAE)
Committee on Nuclear Chemistry & Radiochemistry, Chinese Nuclear (Chemical) Society(CNRCS)
Committee on Radiation Protection, Chinese Nuclear Society(CRP,CNS)
Beijing Nuclear Society(BNS)
Radiochemistry & Radiation Chemistry Key Laboratory for Fundamental Science(RCKLFS)

Supported by
Migration 2011 is being organized by Peking University and supported by:
- National Natural Science Foundation of China (NSFC)
- Ministry of Education (Through 111 and FRFCU projects), PRC
- Beijing National Laboratory for Molecular Sciences
- Chinese Academy of Engineering Physics (CAEP)
- Institute of High Energy Physics, Chinese Academy of Sciences
- Lanzhou University
- Sichuan University

Migration is also supported by:
European Commission through ACTINET-3
Karlsruhe Institute for Technology (KIT)

230 presentations
(61 oral; 169 poster)

270 participants from
19 countries
Welcome!
Migration 2011

Oral + poster contributions (230)

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<th>Count</th>
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<td>Korea</td>
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<td>Germany</td>
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<td>Sweden</td>
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<td>France</td>
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<td>Czech Republic</td>
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Ju WANG
Beijing Research Institute of Uranium Geology,
China National Nuclear Corporation
Outlines

• Nuclear power plants in China
• Policies and regulations related to geological disposal
• Highlights
• Challenges
Nuclear power plants in China

• 15 reactors in operation in 2012
• 26 reactors under construction in 2012
• although the Fukushima accident happened in 2011, the milestone for NPP development by 2020 remains unchanged:
  - 40 GW in operation
  - 18 GW under construction
Nuclear power plants in Chinese Mainland in 2011: 15 reactors in operation, 26 under construction
2003: Law on Prevention of Radioactive Pollution:

“high level radioactive waste should be disposed in a centralized geological repository”
Policies for nuclear fuel cycle

- A closed nuclear fuel cycle policy
- Spent fuel should be reprocessed
- Waste form for final geological disposal: vitrified waste, CANDU SF
- Deep geological repository is used
- Host rock: granite or clay
- Repository concept:
  - Multi-barrier concept
  - Shaft--tunnel-disposal vault
  - Located in saturated zone

Major contents of the Guidelines

3 main stages for HLW disposal

• 2006--2020:
  Laboratory Study and Site Selection
• 2020--2040
  In Situ R&D in Underground Research Laboratory
• 2040--middle of 21st Century
  Repository construction
A 3-step strategy for HLW disposal

Here we are

Site → URL → Repository

1985 → 2020 → 2050

After SKB
China plans to build an URL before 2020

- **China**: Plans to build an URL before 2020
- **France**: Bure, Tournemire
- **Belgium**: Mol
- **Germany**: Gorleben, Asse
- **Czech**: Joseph
- **Korea**: URT
- **Japan**: Kamaishi, Tono, Mizunami, Honorobe
- **Switzerland**: Grimsel (Switzerland), Mont Terri (Switzerland)
- **Sweden**: Aspö (Sweden)
- **Canada**:
- **USA**:
- **China**: 2020
Goal in 2050:

Construction of China’s National geological repository for high level waste is completed

A multi-barrier concept
• 2007: the Long Term Development Plan for NPP in China (2006-2020) approved by the State Council:

-- The construction of an underground research laboratory (URL) for high level radioactive waste in China should be completed by 2020
• 2012: The Long-term plan for nuclear safety and prevention of radioactive pollution (2012-2020) approved by the State Council, the same words:

-- The construction of an underground research laboratory (URL) for high level radioactive waste in China should be completed by 2020
• 2010: Waste Fund approved by the State Council:
• Rate: 0.026 Yuan/KWh.
• Used for:
  ◆ Geological disposal
  ◆ Spent fuel transportation & storage
  ◆ reprocessing
2011: the new “Regulation of safe management of radioactive waste” approved by the State Council:

- The China Atomic Energy Authority is responsible for implementing R&D, site selection, URL and repository construction.
China National Nuclear Corporation (CNNC)
-- possible implementation body

Organizational structure

Ministry of Environment Protection (MoEP)
National Nuclear Safety Admin. (NNSA)
China Atomic Energy Authority (CAEA)

China National Nuclear Corporation (CNNC)
-- possible implementation body

BRIUG
CNPE
CIAE
CIRP

Universities, Chinese Academy of Science
1986: Site selection started
1989: Six regions selected for high level radioactive waste repository
1990: sub-area selection in Beishan site, Northwest China’s Gansu province
2000: systematical site characterization in Northwest China’s Beishan site
Highlights since 2007---Site selection

• New strategy for Site selection

• Select 12 sites in all China, after comparison, then select 3 sites equally good for repository

• host rock: granite & clay
  priority: granite
Site selection process

12 sites

7-8 sites

3 sites
6 regions selected for repository

1- South China;  2- East China;  3- Southwest China
4- Inner mongolia;  5- Xinjiang;  6- NW China—Beishan area
Highlights since 2007---Site selection

• Beishan site: considered as the first priority site for China’s high level radioactive waste repository
• site characterization continued in the Gibi desert Beishan site in NW China’s Gansu province
• 15 boreholes drilled in the site.
NW China’s Beishan area has been selected as the most potential site.
15 bore holes drilled in Beishan site since 2007

- Jiujing
- Xinchang-Xiangyangshan

- BS03
- BS01
- BS02
- BS05
- BS06
- BS15-16
- BS17-19

3 shallow boreholes
5 shallow boreholes

Yemaquan
Opening Ceremony for borehole BS16 (March 18, 2011)
Surface geophysical survey: to investigation the faults
3-D image of faults in granite

Blocks with less than 700 Ω • m
Groundwater modeling

模拟水头等值线

x:y:z=1:1:30
Beishan site: Preliminary conclusion

- located in Northwestern China’s Gobi desert area
- low population density
- low precipitation: 60--80 mm/a
- high evaporation: 2900-3200 mm/a
- no economical prospect
- no important mineral resources
- convenient transportation
- stable crust
- favorable hydrogeological conditions
- favorable host rock: granite and diorite

the most potential site for China’s HLW repository
A preliminary concept design for China’s high level radioactive waste repository has been proposed. It is a multi-barrier system, with bentonite as buffer material.
Preliminary repository concept

container
canister
buffer

Glass
Engineered barrier system development

- The GMZ bentonite deposit, located in Inner Mongolia, is selected as the most potential supplier for buffer material.
  - tonnage: 160 M ton.
  - A large-scale mock-up established in order to study the behaviour of GMZ bentonite under simulated repository conditions.
Outcrops of the GMZ bentonite deposits

Super large:

160 M T
China-Mock-Up for Bentonite Study
Long-term performance of Engineered Barrier Systems
Workpackage B: China-Mock-Up (2010-2014)
Safety assessment

- Preliminary safety assessment has been conducted for China’s repository concept, by using Beishan site as a reference site.
Safety assessment: case study

- groundwater
- disposal pit
- fracture
- joint belt
- intact rock
- radionuclide migration pathway
- surface
- conceptual model of geological barrier for Beishan site
- GOLDSIM, a PA software
- conceptual model of engineered barrier
- performance assessment process
- North Mountain Pre-Final Site Geological Barrier Concept Model
- conceptual model of geological barrier for Beishan site
- GOLDSIM: a PA software
- performance assessment process
International Exchange and Cooperation

- IAEA
- POSIVA
- SCK•CEN
- SKB
- NAGRA
- BGR, DBE, GRS
- CAD/CEA ANDRA
- KAERI
- JAEA RWMC
- LBL
- CUT, CZ

Flags of participating countries:
CAEA delegation visits Ministry of Economics, Germany, 2007-09
IAEA experts visit Beishan, 9 Sept., 2011
next 5 year

- Site selection for the URL
- Site characterization will be continued at Beishan site
- Other sites in Xinjiang, Inner Mongolia will also be investigated
- Site selection for Underground Research Laboratory will be started soon
- Engineering design and engineered barrier system study will continue
- The behaviour of key radionuclides will further studied
- The safety assessment for the proposed disposal system will continue.
For geological disposal of high level radioactive waste, the following challenges are still facing the Chinese program:

- Social
- Economic
- Public acceptance
- Scientific & technological
- Engineering
Thank you
A new approach for siting a repository for HLW in Germany?

Volkmar Bräuer

Federal Institute for Geosciences and Natural Resources

GEOZENTRUM HANNOVER
Stilleweg 2
30655 Hannover
www.bgr.bund.de
Agenda

1. Political background

2. Scientific background
   • Criteria
   • Host rocks
   • Disposal concepts
   • Retrievability

3. Outlook
Federal Government and State Governments: Roadmap for selection of a repository site, December, 15th 2011

1. Phase to mid 2012
   determination of the decision making process by federal law

2. and 3. Phase from end of 2012 to mid 2013
   development of bases for decisions and decision on the developed proposals by federal law

4. Phase from 2014 to end of 2019
   site selection and above surface exploration

5. Phase to end of 2027 ?
   underground exploration und site decision

6. Phase
   Licensing, construction und operation

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The waste management concept in Germany of 1998

- **Coalition agreement 1998**
  - Doubt about the suitability of the Gorleben site
  - Definition of a new waste management plan

- **Consensus Federal Government / energy supply companies 2000**
  - Moratorium on Gorleben site (max. 3-10 years)
  - Minimisation of transports
    - Last Transport of SF for reprocessing 2005
    - Licensing of interim waste storage facilities at NPP
  - Consensus with utilities regarding life time limits for NPP
  - Adaption of the national atomic act

- **AkEnd 1999 - 2002**
  - Procedure development
    - Development of a site selection procedure for a deep radwaste repository

- **Procedure implementation**
  - Investigation of further sites from 2005 on

---

2nd Chinese-German Workshop, Karlsruhe Oct. 15-16, 2012
Agenda

1. Political background

2. Scientific background
   • Criteria
   • Host rocks
   • Disposal concepts
   • Retrievability

3. Outlook
Factors to be considered for the site selection

- Geology
- Regional development
- Disposal concept
- Hydrogeology
- Seismicity
- Long-term safety
- Public participation
- Protected areas
- Infrastructure
- Tectonics

Disposal site
Definition of criteria for site selection

GEOSCIENCES

Geoscientific minimum requirements
Favourable overall geological setting

SOCIAL SCIENCES

Exclusion criteria
Regional development potential
Evaluation criteria
Willingness to participate

2nd Chinese-German Workshop, Karlsruhe Oct. 15-16, 2012
**Procedure steps**

**STEP 1**
Identification of areas fulfilling specific minimum requirements

**STEP 2**
Selection of partial areas with particularly favourable overall geological setting

**STEP 3**
Identification and selection of site regions for exploration from the surface

**STEP 4**
Determination of sites for underground exploration

**STEP 5**
Decision on a site

---

**StePS**

in the selection procedure

(Dec. 2002)

↑ Step backwards, if required

---

2nd Chinese-German Workshop, Karlsruhe Oct. 15-16, 2012
Procedural step 1

Determination of areas fulfilling specific minimum requirements

Exclusion criteria geoscientific

- Large-area vertical movements
- Active fault zones
- Seismic activity
- Volcanic activity
- Groundwater age

areas

2nd Chinese-German Workshop, Karlsruhe Oct. 15-16, 2012
Procedural step 1

Minimum requirements geoscientific

- **Thickness** of isolating rock zone at least: 100 m
- **Depth** at least: 300 m
- **Mine** no deeper than: 1,500 m
- **Spatial extension:**
  - e.g. salt: 3 km²
  - e.g. clay/granite: 10 km²
- **Rock permeability:**< 10^-10 m/s
- **No findings which give rise to doubt about adherence of rock permeability, thickness and extension for 1 million years**
- **No risk from rock burst**

Determination of areas fulfilling specific minimum requirements

Areas
Agenda

1. Political background

2. Scientific background
   • Criteria
   • Host rocks
   • Disposal concepts
   • Retrievability

3. Outlook
## Repository relevant properties of potential host rocks

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<tr>
<th>Property</th>
<th>Rock salt</th>
<th>Clay/claystone</th>
<th>Crystalline rock (e.g. granite)</th>
</tr>
</thead>
<tbody>
<tr>
<td>heat conductivity</td>
<td>high</td>
<td>low</td>
<td>medium</td>
</tr>
<tr>
<td>permeability</td>
<td>practically impermeable</td>
<td>very low to low</td>
<td>very low (unfractured) to permeable (fractured)</td>
</tr>
<tr>
<td>strength</td>
<td>medium</td>
<td>low to medium</td>
<td>high</td>
</tr>
<tr>
<td>deformation behaviour</td>
<td>visco-plastic (creep)</td>
<td>plastic to brittle</td>
<td>brittle</td>
</tr>
<tr>
<td>stability of cavities</td>
<td>self-supporting</td>
<td>artificial reinforcement required</td>
<td>high (unfractured) to low (strongly fractured)</td>
</tr>
<tr>
<td>in situ stresses</td>
<td>lithostatically isotropic</td>
<td>anisotropic</td>
<td>anisotropic</td>
</tr>
<tr>
<td>dissolution behaviour</td>
<td>high</td>
<td>very low</td>
<td>very low</td>
</tr>
<tr>
<td>sorption behaviour</td>
<td>very low</td>
<td>very high</td>
<td>medium to high</td>
</tr>
<tr>
<td>heat resistance</td>
<td>high</td>
<td>low</td>
<td>high</td>
</tr>
</tbody>
</table>

- **Green** = favorable
- **Red** = unfavorable
- **Yellow** = medium

---

2nd Chinese-German Workshop, Karlsruhe Oct. 15-16, 2012
Regions worthy of investigation for the geologic disposal of heat-generating high-level radioactive waste in Germany
KOCKEL & KRULL 1995, BRÄUER et al. 1994

Comment: Numbering does not indicate any ranking

2nd Chinese-German Workshop, Karlsruhe Oct. 15-16, 2012
Exclusion and selection criteria (Clay study)

1. International fundamental requirements (IAEO, Nagra (CH), Andra (F))
   • long-term geological stability
   • favorable host rock properties
   • sufficient extent of host rock body
   • avoidance of, and insensitivity to, detrimental phenomena and perturbations
   • explorability
   • predictability

2. Exclusion criteria / minimum requirements (AkEnd 2002)

3. Regional restrictions in Germany

4. Specific criterias of argillaceous rock formations
Radioactive Waste Disposal

Argillaceous rock formations in Germany

BGR 2007

BGR-„Clay report“ by order of the German Federal Ministry of Economics and Technology

2nd Chinese-German Workshop, Karlsruhe Oct. 15-16, 2012
Agenda

1. Political background

2. Scientific background
   • Criteria
   • Host rocks
   • Disposal concepts
   • Retrievability

3. Outlook
Disposal concepts (barrier significance)

barrier system
- technical: canister
- geotechnical: backfill
- geological: host rock

Crystalline rock, clay, salt
bentonite, crushed salt
copper (crystalline rock), high grade steal (clay, salt)

increasing significance decreasing significance
## Main criteria for repository concepts in different host rocks

<table>
<thead>
<tr>
<th>Components</th>
<th>Rock salt</th>
<th>Clay/claystone</th>
<th>Crystalline rock</th>
</tr>
</thead>
<tbody>
<tr>
<td>maximum emplacement depth</td>
<td>approx. 900 m</td>
<td>approx. 500 m</td>
<td>500 - 1200 m</td>
</tr>
<tr>
<td>storage technique*</td>
<td>drifts and deep boreholes</td>
<td>drifts and/or short boreholes</td>
<td>boreholes or drifts</td>
</tr>
<tr>
<td>design temperature</td>
<td>max. 200 °C</td>
<td>max. 100 °C</td>
<td>max. 100 °C (bentonite backfill)</td>
</tr>
<tr>
<td>backfill*</td>
<td>crushed salt</td>
<td>bentonite</td>
<td>bentonite</td>
</tr>
<tr>
<td>temporary storage period (fuel rods and HAW coquilles)</td>
<td>min. 15 years</td>
<td>min. 30 - 40 years</td>
<td>min. 30 - 40 years</td>
</tr>
<tr>
<td>drift reinforcement</td>
<td>not necessary</td>
<td>necessary and potentially very complicated</td>
<td>necessary in strongly fractured zones</td>
</tr>
<tr>
<td>container concept</td>
<td>established</td>
<td>new development required for Germany</td>
<td>new development required for Germany</td>
</tr>
<tr>
<td>mining experience</td>
<td>very large (salt mines)</td>
<td>almost none</td>
<td>large (ore mining)</td>
</tr>
</tbody>
</table>

* adapted to each type of host rock

---

2nd Chinese-German Workshop, Karlsruhe Oct. 15-16, 2012
Agenda

1. Political background

2. Scientific background
   - Criteria
   - Host rocks
   - Disposal concepts
   - Retrievability

3. Outlook
Retrievability - Factors to be considered

- Safety
- Ethics
- Acceptance
- Time
- Economy
- Technics
- Proliferation etc.

After ESK 2011

2nd Chinese-German Workshop, Karlsruhe Oct. 15-16, 2012
Retrievability

1. During the operating phase (Reversibility)
   Time: several decades

2. Retrieval (recover) pursuant to BMU safety stipulations (2010)
   – Containers must make it possible to retrieve the waste
   Time: up to 500 years after sealing the repositor

3. Retrievability (s. s.)
   Time: Permanent retrievable emplacement
Retrievability

Pro:

• Retrieval of the waste after water influx, escape of toxins
• Regression feasibility in response to failures in construction, long term forecast deficits
• Flexibility in the light of new scientific-technological developments
• Recycling of the waste
• Permanent control and surveillance capacity (enhancing safety, technical/societal)
• Self-determination by future generations
• Enhancing acceptance by ability to retrieve
Retrievability

Contra:

• Permanent access to the waste must be maintained
• Potential radiation exposure during recovery
• Safety deficits (greater hazard)
  - technical: inflow/outflow of fluids
  - societal: access possible/misuse
• Surveillance/maintenance measures over long periods of time
• Shifting responsibility to future generations
• Long term societal development is not predictable
• Costs of surveillance/maintenance have to be borne over a long period
## Radioactive Waste Disposal (international overview)

<table>
<thead>
<tr>
<th>Country</th>
<th>Repository MAW/LAW</th>
<th>HAW Host rock</th>
<th>est. operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>yes (no operation)</td>
<td>Rock salt, (Alternatives)</td>
<td>approx. 2030 ?</td>
</tr>
<tr>
<td>France</td>
<td>yes</td>
<td>Claystone</td>
<td>2025</td>
</tr>
<tr>
<td>Belgium</td>
<td>no</td>
<td>Clay</td>
<td>approx. 2040</td>
</tr>
<tr>
<td>Finland</td>
<td>yes</td>
<td>Granite</td>
<td>2020</td>
</tr>
<tr>
<td>Great Britain</td>
<td>yes (LLW)</td>
<td>n. d.</td>
<td>approx. 2040</td>
</tr>
<tr>
<td>Sweden</td>
<td>yes</td>
<td>Granite</td>
<td>2023</td>
</tr>
<tr>
<td>Spain</td>
<td>yes</td>
<td>n. d.</td>
<td>Not before 2050</td>
</tr>
<tr>
<td>Netherlands</td>
<td>(yes) 100 years</td>
<td>n. d.</td>
<td>approx. in 100 years</td>
</tr>
<tr>
<td>Italy</td>
<td>no</td>
<td>n. d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>Lithuania</td>
<td>yes</td>
<td>Clay, Anhydrite, Rock salt, Crystalline r.</td>
<td>n.d.</td>
</tr>
<tr>
<td>Slowakia</td>
<td>yes</td>
<td>Granite, Claystone, Clay</td>
<td>n.d.</td>
</tr>
<tr>
<td>Slowenia</td>
<td>no</td>
<td>Sedimentary rocks, Granite</td>
<td>2065</td>
</tr>
<tr>
<td>Czech. Republic</td>
<td>yes</td>
<td>Granite ?</td>
<td>approx. 2065</td>
</tr>
<tr>
<td>Hungary</td>
<td>yes</td>
<td>Claystone, Granite?</td>
<td>approx. 2050</td>
</tr>
<tr>
<td>Switzerland</td>
<td>no</td>
<td>Claystone, (Granite)</td>
<td>2050</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>no</td>
<td>Claystone, Granite?</td>
<td>n.d.</td>
</tr>
<tr>
<td>Romania</td>
<td>yes</td>
<td>Rock salt?</td>
<td>2055</td>
</tr>
<tr>
<td>USA</td>
<td>yes</td>
<td>Tuff?, Rock salt?</td>
<td>n.d.</td>
</tr>
<tr>
<td>Japan</td>
<td>yes</td>
<td>Granite</td>
<td>2030</td>
</tr>
</tbody>
</table>

2nd Chinese-German Workshop, Karlsruhe Oct. 15-16, 2012
Agenda

1. Political background

2. Scientific background
   • Criteria
   • Host rocks
   • Disposal concepts
   • Retrievability

3. Outlook
Federal Government and State Governments: Roadmap for selection of a repository site, December, 15th 2011

<table>
<thead>
<tr>
<th>Phase 1: selection procedure steps</th>
<th>to mid 2012 §</th>
</tr>
</thead>
<tbody>
<tr>
<td>• which procedure steps</td>
<td></td>
</tr>
<tr>
<td>• how are the Federal Government and the State Governments involved</td>
<td></td>
</tr>
<tr>
<td>• who pays</td>
<td></td>
</tr>
<tr>
<td>• which institutions are involved</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Phase 2 + 3: scientific basics</th>
<th>to mid 2013 §</th>
</tr>
</thead>
<tbody>
<tr>
<td>• scientific basis is compiled and specified</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Phase 4: Site selection and surface exploration</th>
<th>to mid 2014</th>
<th>to end of 2014 §</th>
<th>to end of 2019 §</th>
</tr>
</thead>
<tbody>
<tr>
<td>• site regions are localized</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• regions (in different geological formations/host rocks) for surface exploration are selected and specified</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• surface exploration is implemented</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• site for the underground exploration is specified</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Phase 5: Underground exploration and siting</th>
<th>to end of 2027? §</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Assessment of alternatives and site nomination</td>
<td></td>
</tr>
<tr>
<td>• site is confirmed</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Phase 6: Administrative procedure</th>
<th>?</th>
</tr>
</thead>
<tbody>
<tr>
<td>• repository is approved, constructed and under operation</td>
<td></td>
</tr>
</tbody>
</table>

§ legislated/stipulated by federal law

2nd Chinese-German Workshop, Karlsruhe Oct. 15-16, 2012
Thank you!
Monday, October 15

TOPIC: HOST ROCK CHARACTERIZATION (ROCK MECHANICS / HYDROGEOLOGY)
Rock Mass Characterization for the Preselected Beishan area, Gansu, of China’s High-level Radioactive Waste Repository

Wang Guibin

Institute of Rock and Soil Mechanics, the Chinese Academy of Sciences

2012.10.15
CONTENTS

- Introduction
- Field survey and sampling
- Joint characteristics
- Mechanical properties
- In-situ testing results
- Conclusions
Rock mass characterization for the preselected Beishan area

Introduction

The potential areas for China’s HLW repository
Introduction

- Jiujin section, Jijicao quarry and Xinchang are candidates in Beishan-the preselected area (most preferred area) for China’s HLW deep geological disposal

- Since 2002, a series of investigations were performed by Institute of Rock and Soil mechanics, CAS
Rock mass characterization for the preselected Beishan area

Jiujin section

Jijicao quarry

Xinchang
Rock mass characterization for the preselected Beishan area

- Introduction
- Field survey and sampling
- Joint characteristics
- Mechanical properties
- In-situ testing results
- Conclusions
Field Joint Survey

Schematic Joint Survey Method
Rock mass characterization for the preselected Beishan area

Rock Sampling and Test Machines
The lithology is mainly monzonite granite and partially tonalite. Five group of rock sample were chosen from different depth.
Rock mass characterization for the preselected Beishan area

- Introduction
- Field survey and sampling
- Joint characteristics
- Mechanical properties
- In-situ testing results
- Conclusions
Rock mass characterization for the preselected Beishan area
✓ Joints are principally steep shear joints.

✓ Joints, which dip angle greater than 60°, are about 91%.

✓ “X” type shear joints can be observed in some outcrops.

✓ Only one set of joint can be observed for most outcrops.

✓ Joints are flat, smooth, with stable strike and long extension.
Rock mass characterization for the preselected Beishan area

According to the faults, Jijicao quarry (left) and Xinchang (right) are roughly divided into statistical homogeneities and the region which is influenced by the faults.
Rock mass characterization for the preselected Beishan area

Mean trace length and trace midpoint density vs. L in Jiji quarry

\[ y = f(x) = 0.0339 + 0.0671e^{-x/22.182} \]

\[ y = g(x) = 14.17 - 6.852e^{-x/37.428} \]

Mean trace length and trace midpoint density vs. L in Xingchang

\[ \lambda = 0.0469 + 0.1172e^{-0.036L} \]

\[ \nu = 21.027 - 21.027e^{-0.0226L} \]

The boundary of the statistical homogeneities is determined.
Rock mass characterization for the preselected Beishan area

Statistic of joint orientation

Joint polar points and Dip rose diagram of statistical homogeneity II of Jiji quarry

Joint polar points and Dip rose diagram of statistical homogeneity II of Xingchang
Rock mass characterization for the preselected Beishan area

Probability analysis of joint orientation

Fitted dip direction distribution curve and formula of statistical homogeneity II of Jiji quarry

Fitted dip direction distribution curve and formula of statistical homogeneity II of Xingchang

Dip direction can be fitted by Gaussian (normal) distribution
Statistics of joint spacing

Fitted joint space distribution (negative exponential distribution) and formula of statistical homogeneity II of xingchang

Joint spacing of Xingchang

<table>
<thead>
<tr>
<th>SET</th>
<th>ORIENTATION</th>
<th>SPACING (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>1  104.04° /71.34°</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>2  248.95° /71.13°</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td>3  284.04° /71.34°</td>
<td>0.62</td>
</tr>
</tbody>
</table>

According to ISRM suggested method, joint spacing of the 104.04° /71.34° set of Xinchang is moderate spacing and the others are wide spacing.
Estimation of mean trace length and midpoint density

Mean trace length \( \bar{L} \) = \( \frac{\pi (N + N_2 - N_0)}{2(N - N_2 + N_0)} \) 

Midpoint density \( \lambda \) = \( \frac{N - N_2 - N_0}{2\pi c^2} \)
**Estimation of mean trace length and midpoint density (continued)**

**Concentric circles method**

**Results of Concentric circles**

<table>
<thead>
<tr>
<th>窗口半径</th>
<th>窗口编号</th>
<th>各类迹线条数</th>
<th>迹线中点面密度</th>
<th>平均迹长估计值</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.5287</td>
<td>O I</td>
<td>7 16 4</td>
<td>0.0261</td>
<td>17.001</td>
</tr>
<tr>
<td></td>
<td>O II</td>
<td>12 16 3</td>
<td>0.0348</td>
<td>11.688</td>
</tr>
<tr>
<td></td>
<td>O III</td>
<td>5 10 0</td>
<td>0.0174</td>
<td>10.625</td>
</tr>
<tr>
<td>10.1465</td>
<td>O I</td>
<td>0 14 0</td>
<td>0.0216</td>
<td>15.938</td>
</tr>
<tr>
<td></td>
<td>O II</td>
<td>6 13 2</td>
<td>0.0386</td>
<td>10.838</td>
</tr>
<tr>
<td></td>
<td>O III</td>
<td>1 9 0</td>
<td>0.0170</td>
<td>10.140</td>
</tr>
<tr>
<td>6.7644</td>
<td>O I</td>
<td>0 5 0</td>
<td>0.0174</td>
<td>10.625</td>
</tr>
<tr>
<td></td>
<td>O II</td>
<td>6 7 1</td>
<td>0.0661</td>
<td>5.033</td>
</tr>
<tr>
<td></td>
<td>O III</td>
<td>0 3 0</td>
<td>0.0104</td>
<td>10.625</td>
</tr>
</tbody>
</table>

**Tangent circles method**

**Results of tangent circles**

<table>
<thead>
<tr>
<th>窗口半径</th>
<th>窗口编号</th>
<th>各类迹线条数</th>
<th>迹线中点面密度</th>
<th>平均迹长估计值</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.5287</td>
<td>O I</td>
<td>7 16 4</td>
<td>0.0261</td>
<td>17.001</td>
</tr>
<tr>
<td></td>
<td>O II</td>
<td>12 16 3</td>
<td>0.0348</td>
<td>11.688</td>
</tr>
<tr>
<td></td>
<td>O III</td>
<td>5 10 0</td>
<td>0.0174</td>
<td>10.625</td>
</tr>
<tr>
<td>10.1465</td>
<td>O I</td>
<td>4 11 5</td>
<td>0.0294</td>
<td>17.6158</td>
</tr>
<tr>
<td></td>
<td>O II</td>
<td>9 14 3</td>
<td>0.0495</td>
<td>9.9613</td>
</tr>
<tr>
<td></td>
<td>O III</td>
<td>5 10 0</td>
<td>0.0309</td>
<td>7.9691</td>
</tr>
<tr>
<td>6.7644</td>
<td>O I</td>
<td>3 9 6</td>
<td>0.0522</td>
<td>14.8756</td>
</tr>
<tr>
<td></td>
<td>O II</td>
<td>5 8 6</td>
<td>0.0626</td>
<td>11.8060</td>
</tr>
<tr>
<td></td>
<td>O III</td>
<td>3 8 1</td>
<td>0.0487</td>
<td>7.5896</td>
</tr>
</tbody>
</table>

> Stable and reasonable results can be obtained from Tangent Circles Method
Estimation of mean trace length and midpoint density (continued)

Trace length and midpoint density for each statistical homogeneity of Jiji quarry

<table>
<thead>
<tr>
<th>NO.</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>/m^2</td>
<td>0.034</td>
<td>0.0387</td>
<td>0.034</td>
<td>0.0408</td>
<td>0.0414</td>
</tr>
</tbody>
</table>

Trace length and midpoint density for each statistical homogeneity of Xingchang

<table>
<thead>
<tr>
<th>NO.</th>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>/m</td>
<td>14.129</td>
<td>18.671</td>
<td>14.173</td>
</tr>
<tr>
<td>/m^2</td>
<td>0.1058</td>
<td>0.0586</td>
<td>0.0827</td>
</tr>
</tbody>
</table>

Mean trace length is smaller and midpoint density is greater in the region that is influenced by faults than that in statistical homogeneities
**JSR---Jointing Structure Rate**

\[ JSR = W_n \overline{D}_a \overline{L} \]

- \( W_n \) is the weight determined by the joint set number.
- \( \overline{D}_a \) is the weight determined by mean density of trace midpoints
- \( \overline{L} \) is the weight determined by mean trace length

➤ JSR is a general index which can be used for evaluating both the block size and the connectivity of joints networks.
Description and grade for jointing structure characterization according to JSR

<table>
<thead>
<tr>
<th>JSR</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-200</td>
<td>Very slightly jointed</td>
</tr>
<tr>
<td>200-400</td>
<td>Slightly jointed</td>
</tr>
<tr>
<td>400-600</td>
<td>Moderate jointed</td>
</tr>
<tr>
<td>600-800</td>
<td>Strongly jointed</td>
</tr>
<tr>
<td>800-1000</td>
<td>Very Strongly jointed</td>
</tr>
</tbody>
</table>
## Jointing structure characterization for the sections of the Beishan area

<table>
<thead>
<tr>
<th>Section</th>
<th>$W_n$</th>
<th>$R_1$</th>
<th>$R_2$</th>
<th>$JSR$</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS01</td>
<td>2.5</td>
<td>9</td>
<td>5</td>
<td>112.5</td>
<td>Very slightly jointed</td>
</tr>
<tr>
<td>BS03</td>
<td>4</td>
<td>7.5</td>
<td>7</td>
<td>210</td>
<td>slightly jointed</td>
</tr>
<tr>
<td>Jijicao</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>4</td>
<td>10.5</td>
<td>1.5</td>
<td>63</td>
<td>Very slightly jointed</td>
</tr>
<tr>
<td>II</td>
<td>4</td>
<td>10.5</td>
<td>1.5</td>
<td>63</td>
<td>Very slightly jointed</td>
</tr>
<tr>
<td>III</td>
<td>2</td>
<td>11</td>
<td>1.5</td>
<td>33</td>
<td>Very slightly jointed</td>
</tr>
</tbody>
</table>
Rock mass characterization for the preselected Beishan area

Development of 3-D joint simulation system
Development of 3-D joint simulation system (continued)
Rock mass characterization for the preselected Beishan area

- Introduction
- Field survey and sampling
- Joint characteristics
- Mechanical properties
- In-situ testing results
- Conclusions
## Mechanical properties of intact rock

<table>
<thead>
<tr>
<th>Specimen size</th>
<th>Test items</th>
</tr>
</thead>
<tbody>
<tr>
<td>φ50 × 100</td>
<td>Water-content coefficient; Hygroscopic coefficient; Dry density; Acoustic wave measurement; Uniaxial compression strength and deformation; Triaxial strength and deformation</td>
</tr>
<tr>
<td>φ60 × 30</td>
<td>Water-content coefficient; Hygroscopic coefficient; Dry density; Brazilian test</td>
</tr>
<tr>
<td>40 × 40 × 20</td>
<td>Shear strength</td>
</tr>
</tbody>
</table>
Specimen after tests

Uniaxial compression

Triaxial compression

Direct shear

Brazilian splitting
Uniaxial and triaxial compression tests

Uniaxial compression test

Triaxial compression test

\[ \sigma_3 = 30 \text{MPa} \]

\[ \sigma_3 = 20 \text{MPa} \]
Conclusions of rock mechanics characteristics

- Both rock types have high mechanical strength and high stiffness (UCS$_{\text{max}}$ up to 140Mpa).
- Monzonite granite is more homogeneous and has higher mechanical strength.
- Tonalite is inhomogeneous and its mechanical strength is enhanced with depth.
- Rock below 300m has superior homogeneity and its mechanical strength is higher.
Rock mass characterization for the preselected Beishan area

- Introduction
- Field survey and sampling
- Joint characteristics
- Mechanical properties
- In-situ testing results
- Conclusions
Rock mass characterization for the preselected Beishan area

Hydraulic Fracturing and High-pressure Injection Testing were performed in borehole BS03
Geostress characteristic

Geostress measured by hydraulic fracture method

Hypothesis:

1. Host rock is linear, homogeneous, isotropic elastic medium.
2. Injection water flow meet with the Darcy’s law in rock pore.
3. Vertical stress $\sigma_v$ is one of the principal stress.
Results of measurement of geostress

Pressure vs. time curve for depth 283.51~284.51m

The maxim horizontal geostress is 17.52MPa. The moderate geostress range is 10MPa<σ₁<20MPa

➢ The geostress of Borehole 3 is moderate and increases with depth
Seepage characteristic

Permeability coefficient of every sections can be obtained from high pressure injection tests.

The geometric mean value of permeability coefficient for all of the testing sections can be used to describe permeability coefficient of the borehole.

The geometric mean permeability coefficient of borehole BS03 is $4.4 \times 10^{-6}$ cm/s.
Seepage characteristic (continued)

Flow in a single fracture is the basis for the determination of the hydraulic conductivity tensor for fractured medium.

Permeability figure of hydraulic gradient parallel with fracture plane.

Generally, in permeability domain, hydraulic gradient is not parallel to the fracture plane. But water flow velocity in fractures is related to hydraulic gradient which is parallel with fracture plane.

Permeability figure of hydraulic gradient not parallel with fracture plane.

\[
K = \sum_{i=1}^{n} K_{ei} \left[ \begin{array}{ccc}
1 - \cos^2 \beta_i \sin^2 \gamma_i & -\sin \beta_i \cos \beta_i \sin^2 \gamma_i & -\cos \beta_i \sin \gamma_i \cos \gamma_i \\
-\sin \beta_i \cos \beta_i \sin^2 \gamma_i & 1 - \sin^2 \beta_i \sin^2 \gamma_i & -\sin \beta_i \sin \gamma_i \cos \gamma_i \\
-\cos \beta_i \sin \gamma_i \cos \gamma_i & -\sin \beta_i \sin \gamma_i \cos \gamma_i & 1 - \cos^2 \gamma_i 
\end{array} \right]
\]
Initialize array $T(3, 3)$, $V(3, 3)$

Input joint set number, and dip, dip angle, aperture, joint spacing of every set

Calculation of permeability coefficient tensor orientation matrix

Call of main program for calculation of permeability principal values

Simplification of Cardano formula

Cardano discriminator $I$ is less than 0 or not.

Permeability coefficient tensor

Flow chart for determination of permeability tensor

Plot the permeability ellipse

Output permeability tensor, eigenvector, eigenvalue, principal permeability orientation

Call subprogram of permeability principal vector orientation

Call subprogram of eigenvector for multi-set joint

Call subprogram of eigenvector for only one set joint

Joint set number is equal to one or not.

Exit

Yes

No
Rock mass characterization for the preselected Beishan area

Seepage characteristic (continued)

Hydraulic parameters of 4 set joint:

1st: dip 43.19°, dip angle 70.58°, spacing 2.75m
2nd: dip 141.75°, dip angle 60.75°, spacing 5.03m
3rd: dip 223.23°, dip angle 67.05°, spacing 2.11m
4th: dip 348.03°, dip angle 68.14°, spacing 8.64m

Hydraulic conductivity tensor

\[
K = \begin{bmatrix}
0.823 \times 10^{-5} & -0.763 \times 10^{-5} & 0.194 \times 10^{-5} \\
-0.763 \times 10^{-5} & 1.070 \times 10^{-5} & -0.016 \times 10^{-5} \\
0.194 \times 10^{-5} & -0.016 \times 10^{-5} & 1.390 \times 10^{-5}
\end{bmatrix}
\]

Permeability principal value

0.157 \times 10^{-5} \quad 0.135 \times 10^{-4} \quad 0.177 \times 10^{-4}

Permeability principal vector

\(\alpha_1(-0.763, -0.637, 0.112)\)

\(\alpha_2(0.146, -0.338, -0.930)\)

\(\alpha_3(0.630, -0.692, 0.351)\)

3 permeability principal orientation:

1. dip 230.12°, dip angle 6.42°
2. dip 336.61°, dip angle 68.36°
3. dip 137.70°, dip angle 20.57°
Rock mass characterization for the preselected Beishan area

- Introduction
- Field survey and sampling
- Joint characteristics
- Mechanical properties
- In-situ testing results
- Conclusions
Conclusions

- The quantitative parameters describing joint characteristics have been obtained. Rock mass of Beishan are very slightly jointed.

- Rock in the research area is high density, low water-content, low porosity, low permeability.

- Rock in the research area is high mechanical strength, high stiffness \((\text{UCS}_{\text{max}} \text{ up to } 140 \text{ MPa}. \text{ Very hard & brittle.})\)

- The geostress of bohole BS03 is moderate and increases with depth. The mean permeability coefficient is only \(4.4 \times 10^{-6} \text{ cm/s} \).
Thanks for your attention!
Multi-scale Applications of Electrical Resistivity Tomography in the Site Characterization for HLW Disposal

Qi You ZHOU

Department of Hydrosciences, School of Earth Sciences and Engineering Nanjing University, Nanjing 210093, China

October 15, 2012
OUTLINE

1 Introduction
2 Objectives of this study
3 Applications of ERT at sample scale in the lab
4 Applications of ERT at block scale in the lab
5 Applications of ERT at meters scale in the field
6 Applications of ERT at hundreds of meters scale in the field
7 A site characterization concept with multi-scale and multi-dimensional ERT
8 Conclusions
The difficulties we are facing in the site characterization for HLW disposal

Main Conventional Approaches:
1. Geological and geophysical prospecting and surveying from ground surface
2. Hydraulic and tracer transport tests within boreholes
3. Isotope analysis and inversion methods based on water and core sampling

Difficulties:
1. The extremely high heterogeneity and anisotropy of the site
2. The scale effects of parameters
3. The data obtained at points or along lines isn't enough in describing the 3-D structure of the site
The difficulties we are facing in the site characterization for HLW disposal

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3. The data obtained at points or along lines isn’t enough in describing the 3-D structure of the site
The extremely high heterogeneity and anisotropy of the site
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The extremely high heterogeneity and anisotropy of the site
The fractal structure and scale effects in dispersivity

from Wheatcraft and Tyler [1988]
The fractal structure and scale effects in dispersivity

from Wheatcraft and Tyler [1988]  
from Gelhar et al. [1992]
Currently available geophysical methods and the advantages of ERT
Currently available geophysical methods and the advantages of ERT

1. Seismic surveying
2. Gravity Surveying
3. Electromagnetic Surveying, VLF, Slingram, EH4
4. High density electrical resistivity tomography, ERT
Currently available geophysical methods and the advantages of ERT

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Currently available geophysical methods and the advantages of ERT

1. Seismic surveying
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4. High density electrical resistivity tomography, ERT

Advantages of ERT
- with robust theoretical foundation
- sensitive to water flow and solute transport
- can be used for test monitoring
- multi-scale and multi-dimensional surveying possible
Why is it possible for ERT to be used at multiscales?

Its measurement range is determined by electrode interval, which can be easily adapted to different scales of centimeters to kilometers.
Why is it possible for ERT to be used at multi-scales?

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- The method may be used at sample scale in the lab to kilometers scale in the field.
Why is it possible for ERT to be used at multiscales?

Its measurement range is determined by electrode interval, which can be easily adapted to different scales of centimeters to kilometers.

- The method may be used at sample scale in the lab to kilometers scale in the field
- Even at the same site, it may be used at different scales
Objectives of this study

By example applications of ERT

To demonstrate the capabilities of ERT in site characterization for HLW disposal at multi-scales.
Objectives of this study

By example applications of ERT

1. at sample scale in the lab
Objectives of this study

By example applications of ERT

1. at sample scale in the lab
2. at block scale in the lab
Objectives of this study

By example applications of ERT

1. at sample scale in the lab
2. at block scale in the lab
3. at meters scale in the field
Objectives of this study

By example applications of ERT

1. at sample scale in the lab
2. at block scale in the lab
3. at meters scale in the field
4. at hundreds of meters scale in the field
Objectives of this study

By example applications of ERT

1. at sample scale in the lab
2. at block scale in the lab
3. at meters scale in the field
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By example applications of ERT

1. at sample scale in the lab
2. at block scale in the lab
3. at meters scale in the field
4. at hundreds of meters scale in the field

To demonstrate the capabilities of ERT in the site characterization for HLW disposal at multi-scales.
Applications of ERT at sample scale in the lab
The **ERT** at sample scale sandstone block

Coverage range: $10 cm \times 10 cm \times 2 cm$

Total electrode number: 121

Electrode spacing: 1cm

$$\rho^t_a(x, y, z) - \rho^{t=0}_a(x, y, z)$$
The ERT at sample scale sandstone block

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\[ \rho_a^t(x, y, z) - \rho_a^{t=0}(x, y, z) \]
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$$\rho^t_a(x, y, z) - \rho_{a=0}^t(x, y, z)$$
Applications of ERT at block scale in the lab
The **ERT** at a **tuff** block with fracture

Total electrode number: 64
Block size: $40\text{cm} \times 40\text{cm} \times 20\text{cm}$
Electrode spacing: 5cm
The ERT at a tuff block with fracture

Total electrode number: 64
Block size: $40\,cm \times 40\,cm \times 20\,cm$
Electrode spacing: 5cm

19 minutes before infiltration
The ERT at a tuff block with fracture

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19 minutes before infiltration

At the end of the infiltration
The ERT at a tuff block with fracture

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At the end of the infiltration
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Block size: 40cm × 40cm × 20cm
Electrode spacing: 5cm

Infiltration

19 minutes before infiltration

At the end of the infiltration
Applications of ERT at meters scale in the field
The 3-D infiltration and ERT monitoring experiments on fractured granite rocks

Date: 2009.8.13-9.13, Monitored range: 3.5m × 3.5m
Resistivity variations in planes during the water infiltration.
A visualization for the 3-D water flow process in fractures
In situ infiltration and ERT monitoring experiments on low permeability granite rock

Monitored range: 1.0m × 1.0m

October 15, 2012
The infiltration process in planes revealed by ERT -1/2
The infiltration process in planes revealed by ERT -2/2
The infiltration process in sections revealed by ERT -1/2
The infiltration process in sections revealed by ERT -2/2
Applications of ERT at hundreds of meters scale in the field
The 2-D ERT surveying lines around borehole 5# in the field

Measurement date: 2008.8.13-31; Total length: 3120m with south 720m, north 720m, east 880m and west 800m respectively.
The 2-D resistivity distributions obtained around borehole 5#. Borehole 5# is at 932m in E-W section and 620m in S-N section. Borehole 7# is at 730m in the S-N section.
A comparison of the simulated 2-D ERT images with known resistivity models
Thus constructed psuedo 3-D resistivity distribution for the site.
The fault interpretation in the north and south resistivity sections

beta=62

beta=57
The fault interpretation in the east and west resistivity sections
The flow system at the near surface
The possible flow system deep in the site
A site characterization concept based on multi-scale and multi-dimensional ERT

1. With electrodes at the surface and in boreholes
2. Resistivity surveying based on surface ERT
A site characterization concept based on multi-scale and multi-dimensional ERT

3. Deep resistivity surveying around boreholes
A site characterization concept based on multi-scale and multi-dimensional ERT

4. Characterize the site with multiple sections
A site characterization concept based on multi-scale and multi-dimensional ERT

5. With electrodes installed in the tunnels
6. Resistivity surveying based on tunnel ERT
The 2D ERT measurement line from Borehole #18 to #13 conducted at Xinchang site.
The three 2D ERT measurement sections crossing fault F4 at different positions.
The apparent resistivity section obtained at the north side of Fault F4
The tent setup in the Gobi field
Our ERT measurement team in the field
What did I look like when working in the field?
Conclusions

1. In the site characterization for RWD, high density electrical resistivity tomography has great potential applications.

It can be conducted not only in multi-scales ranging from rock samples in the lab to ground surface and boreholes in the field,

but also in multi-dimensions at the ground surface, in the boreholes and in underground excavated cavities.

Thus a detailed ERT surveying together with other methods may provide us with a wealth of information about the subsurface resistivity, thus help us understand the 3-D structure of the site.
Conclusions

A even more promising application of ERT for RWD lies in its capability and versatility of process monitoring.

Although this usage may be limited to small spatial scales, a sequence of resistivity images at different time would help us understand the physical processes occurred and even evaluate parameters as permeability, thermal conductivity and dispersivity in multi-dimensions and multi-scales.

This certainly would be useful in the input parameter constraint for repository security assessment.
THANKS!
Characterization of fracture networks at different scales

Prof. Xiaozhao Li

Institute for Underground Space and Geo-environment,
Nanjing University

For the 2nd Chinese-German Workshop on Radioactive Waste Disposal
October 15-16, 2012,
Karlsruhe Institute of Technology (KIT), Germany
OUTLINE

- Kinematic concept and fracture patterns at different scales
- Identification of permeability of fault and fracture zones
- Measurement, analysis method and non-uniform distribution of fracture trace
- Stability-controlling modes and preferential structural plane
- Simulation analysis on permeability parameters and flow path
Kinematic concept and fracture patterns at different scales

In order to build up fracture system model and identify flow pathways, a good understanding of the deformation mechanism and kinematic relations is crucial.
Kinematic concept and fracture patterns at different scales

R-and T-fractures at small scale co-exist in a same location
From field observation and structural analysis, we find that:

- The low angle fractures (e.g. R-fracture in NE orientation) are more developed.

In contrast, the high angle fractures (e.g. X-fracture in NW orientation) are just in initial formation stage.

- The low angle fractures are predominant and well developed. The developments of different type of fractures depend on stress and kinematic boundary conditions.
Kinematic concept and fracture patterns at different scales
Identification of permeability of fault and fracture zones

- Internal composition and fracture architecture
- Opening and filling condition
- Stress regime
Identification of permeability of fault and fracture zones

- Internal composition and fracture architecture

**Fault core:** Both thickness and compositions of fault core are related to the length, amount slip of faults.
Identification of permeability of fault and fracture zones

- **Internal composition and fracture architecture**

  - **Shiyuejing Fault** – *the main boundary of Jiujing Section*

  - Left lateral tenso-slip fault
  - Recent activity (*cutting relation; TL dating*)

  - A single permeable zone?
  - Combined **Conduit-Barrier** (due to the clay fault gouge)

Ground water level in BS02 in the fault is 0.5m, while the level 100m away is 15.4 m, the ground water gradient reaches 15%. (by *Guo Y.H.*)
Identification of permeability of fault and fracture zones

- Internal composition and fracture architecture
  - Fracture zone near the *Shiyuejing Fault*

Dualistic model:
Fault (*Boundary*) + Stochastic joints (*inside*)?
Identification of permeability of fault and fracture zones

 grote composition and fracture architecture

 Fault core of F4

The Jijicao domain boundary fault F4 belongs to the 2nd class in length. Its fault core comprises major slip surfaces, comminuted fault rocks and intensively fractured rocks. Most of the faulted rocks are made up of angular-to-subrounded survivor clasts embedded in fine grained matrix. The grayish white and brown-red bands within the comminuted fault rocks are sub-parallel to the major slip surfaces. According to the structures and compositions, five different structural domains are distinguished within the fault core.
Identification of permeability of fault and fracture zones

- Internal composition and fracture architecture

- The fracture patterns and densities in different fault architectural components have been identified and documented in detail.

- The intrinsic permeabilities of the fault architectural components in fault F4 were measured individually. Then permeability data can be assigned to each architectural component to simulate the detailed flow through fault zone, or to estimate the bulk hydraulic behaviour of the fault zone.
Identification of permeability of fault and fracture zones

Opening and sealing condition

All the large faults, not only the NE-trending reversed faults, but also the NW normal faults are impermeable.

The large fault (regional fault):
- NE reversed fault
- NW normal fault

NW normal faults passed by the tunnel, impermeable
Identification of permeability of fault and fracture zones

Opening and sealing condition

Instead, the smaller NNW- and NWW-trending faults and fracture zones are permeable.

These faults and fracture zones are neotectonic structures. They are too young to be sealed.

X.Z. Li et al, China Communications press, 2006; ISGSR2007
Identification of permeability of fault and fracture zones

Opening and sealing condition

Determination of sealing condition is usually quite difficult. Analysis of structure evolution and identification of neotectonic structures may be helpful.
Identification of permeability of fault and fracture zones

Stress regime - Compressive or extensional?

Large fault, compressive, impermeable

Fracture zone, in extensional regime, high conductive corridor
Identification of permeability of fault and fracture zones

- **Stress regime - Compressive or extensional?**

- **Project 1** - Laoshan highway tunnel
  *Inverted anticline with intensive compressive structural stress regime, inflow into tunnel is very few*

- **Project 2** - A survey tunnel, pumped storage power station in Liyang
  *Maoshan - langxi thrust-nappe belt. After thrusting, the stress had been released. Inflow into tunnel like a heavy rain.*
Identification of permeability of fault and fracture zones

Stress regime - tectonic evolution

Original tectonic stress $\sigma^o_1$

Current stress $\sigma_1$

NW- normal fault: Permeability decrease

NNE sinistral compressive-shear fault: Adding dextral movement → opening of secondary fractures → permeability increase

1. Conductive channel: NW fault-major fault plane; NNE fault – secondary fractures due to reverse movement
2. $K_{NW} > K_{NNE}$

Monitoring Results:
1. 160 l/min passed through NW fault; stable
2. 40 l/min through NNE fault; unstable; Outflow varies greatly from different probing boreholes in a single working face.
Identification of permeability of fault and fracture zones

- Stress regime

Stress regime has significant influence on the permeability of structural planes.

During tectonic evolution, especially reverse movement, the opening and permeability of fault plane and its secondary fractures will change.
Measurement, analysis method and non-uniform distribution of fracture trace


The bias in estimation of mean trace length decreases as the sampling range increases. When the range is large enough, the bias is very small.
Measurement, analysis method and non-uniform distribution of fracture trace

The effect of non-uniformity of trace distribution on mean trace length estimation

At some locations, the bias increases, instead of decreases, when the sampling range reaches to some extent.

The non-uniformity of trace distribution may be a main reason.

→ To reduce bias in estimation, multiple windows at different locations, rather than one window, should be used.

Measurement, analysis method and non-uniform distribution of fracture trace


- The accurately measured distribution of fractures inside the Jijicao section

GIS-based analysis:

- The Semivariogram & covariance of fracture area density present rhythmic variations.
- The correlation distance in EW direction < that in NS direction.

(P. Wang, X.Z. Li et al, J. Eng. Geology, 2012.)
Measurement, analysis method and non-uniform distribution of fracture trace

- Structural patterns of fractures inside the sections
  - Parent-Daughter Structure

- Structural patterns: even though the current simulated distributions show some preferential anisotropic directions, the structural pattern is distinct from real situation

- Hydrogeological significance: although the secondary fractures are so many, the main conductive channel is the major plane.

- It is still a challenge.
Measurement, analysis method and non-uniform distribution of fracture trace

- Structural patterns of fractures inside the sections
  - Conjugate shear joint sets of different periods in Beishan

![Conjugate shear joints](image1)

![Measurement, analysis method and non-uniform distribution of fracture trace](image2)
Measurement, analysis method and non-uniform distribution of fracture trace

- Structural patterns of fractures inside the sections

  - **Step Structure**
    - different permeability in different directions

  ![Step Structure Example](image)

  - Sheared offset surface
    - left lateral

  ![Sheared Offset Surface Example](image)
Measurement, analysis method and non-uniform distribution of fracture trace

- Structural patterns of fractures inside the sections
  - Shear fracture zone

*A dense tenso-shear fracture zone, formed when the major shear planes are close to each other. It forms an unified conductive channel again.*
Different grades of structural planes play different roles in stability, therefore, different evaluation methods should be taken.

Tectonic stability
- Grade I → earthquake → earthquake resistant evaluation
- Grade II → slip, creep → measures for tectonic deformation

Eng. stability
- Grade III → deformation boundary → Geo. Model for stability analysis
- Grade IV → weaken rocks → rockmass quality rating

The activity time of some faults maybe relatively new, but because of it's limited scale, don’t worry too much about the induced earthquake. But it’s tectonic deformation merits attention when tunnel has to pass through them.

Some structural planes may act as the deformation boundary, or controlling the failure mode, they shouldn’t be dealt simply in rockmass quality evaluation.

X.Z. Li, Keynote of 3rd National conf. Waste Disposal, 2010
Stability-controlling modes and preferential structural plane

Geometrical combination and Preferential Structural Plane

Just small joints oblique to tunnel surface – Heavily damage

Small joints parallel to the working face

Small joints oblique to the working face - rugged surface

Even a fault, no obvious influence

Taken from Jinping Hydropower Station
A heavy accident in Sep, 2009: 3 deaths, 7 injuries

Due to the falling of a block formed by several steep and one gentle structural plane
Stability-controlling modes and preferential structural plane

Geometrical combination and Preferential Structural Plane

Outcrops around BS03

Outcrops around BS03 + BS03 boreholes
Stability-controlling modes and preferential structural plane

Geometrical combination and Preferential Structural Plane

Frequency of fracture in different dip angles in BS03

Frequency of gentle structural planes in different depth
Stability-controlling modes and preferential structural plane

- Geometrical combination and Preferential Structural Plane

Y.S. Zhang & X.Z. Li 2010
Simulation analysis on permeability parameters and flow path

- Back analysis of fracture transmissivity and fractured rockmass permeability

**Stochastic fracture network model** created on the basis of statistics of over 800 fractures around borehole BS03

**Deterministic fractures passed by borehole observed by BT (Borehole Televiewer)**

**Deterministic fracture observed by BT placed in the stochastic fracture network**

** Deterministic-stochastic model**

- Injection water pressure $P$
- Giving initial transmissivity $T_0$
- Calculate the injection flow $F_c$
- Compared with observed flow in Paker Test: $F_c = F_p$?
  - *yes* stop
  - *no* continue

Calibrated transmissivity of the model ($m^2/s$) vs. block size ($m$)

**Back analysis (Wang M 2000)**
Simulation analysis on permeability parameters and flow path

- Back analysis of fracture transmissivity and fractured rockmass permeability

空间方向渗透系数变化

341 /21

209 /19

7 /31
Simulation analysis on permeability parameters and flow path

- Back analysis of fracture transmissivity and fractured rockmass permeability

Variation of hydraulic conductivity on vertical planes in different directions

<table>
<thead>
<tr>
<th>Strike map</th>
<th>K_1</th>
<th>2.08</th>
<th>110.3</th>
<th>80.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>K_2</td>
<td>1.71</td>
<td>349.6</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td>K_3</td>
<td>0.47</td>
<td>258.9</td>
<td>8.6</td>
<td></td>
</tr>
</tbody>
</table>
Simulation analysis on permeability parameters and flow path

Back analysis of fracture transmissivity and fractured rockmass permeability

Simulation analysis on permeability parameters and flow path

Simulation on flow path of fracture system

OUTCROP3826

Identification of significant orientation sets

X.Z. Li & Q. Liu 2008
Simulation analysis on permeability parameters and flow path

- Simulation on flow path of fracture system

- Trace length statistics in each set
  - significant exponential-distribution

- OUTCROP3826

 ecdf and exp distribution

 QQ-Plot

 Outcrop 3826 Set 1

 Trace Length of Set 1

 Density

 Outcrop 3826 Set 1

 Trace Length of Set 1

 Abs. Frequency

 X.Z. Li & Q. Liu 2008
Simulation analysis on permeability parameters and flow path

- Simulation on flow path of fracture system

Network: Shortest length, as an example between two virtual boreholes of Bon12 and Bon 63

Network: Highest Conductance, as an example between two virtual boreholes of Bon12 and Bon 63

A tensional fracture with comparatively strong weathering

Total 3D DFM

OUTCROP3826

X.Z. Li & Q. Liu 2008
Conclusions

- In order to build up fracture system model and identify flow pathways, a good understanding of their deformation and kinematic relations is crucial. From field observation and structural analysis, we find that the low angle fractures are more developed, while the high angle fractures are just initial development stage in the study area. The developments of different type of fractures depend on stress and kinematic boundary conditions.

- The internal composition and fracture architecture, their opening and sealing condition and stress regime are three crucial factors affecting the permeability of fault zones.

- Both thickness and compositions of fault core are related to the length, amount slip of faults. The fracture patterns and densities in different fault architectural components should be identified and documented in detail.

- An understanding of tectonic evolution is helpful for the characterization of these factors. The identification of the main active periods maybe helpful for analysis of the opening and filling condition. During tectonic evolution, especially reverse movement, the opening and permeability of fault plane and its secondary plane will change.

- The GPS and GIS technique are very helpful for the measurement and analysis of fracture distribution. The non-uniformity of locations is one of the main reasons for the bias in estimation of fracture intersection situation and mean trace length. Even though the current simulated distributions show some preferential anisotropic directions, the structural pattern is distinct from real situation.
Conclusions

- Different grades of structural planes play different roles in stability, therefore, different evaluation methods should be taken.

- Due to the geometrical combination of structural planes and tunnel, there maybe preferential structural plane which controls the failure modes and probability of intersecting tunnel and forming blocks.

- Deterministic-stochastic model combining with packer test and back analysis can be used for estimation of transmissivity of fracture and spatial variation of fractured rockmass.

- On the basis of 3D fracture network simulation, the flow path with shortest length or highest conductance can be searched out. But, how to comprehensively consider the geometrical connection and the preference of geological properties in a model needs to be further studied.
Acknowledgements

The work is supported by National Key Basic Research Program of China (973 Program), National Natural Science Foundation of China (NSFC) and Key projects of National Foundation for Disposal of Radioactive Waste. The field work is supported by the Beijing Research Institute of Uranium Geology.
Thanks a lot for your attention!
German experience and investigations in the characterisation of potential host rocks

SHAO, H. & SÖNNKE, J.

Federal Institute for Geosciences and Natural Resources (BGR)
Stilleweg 2, D-30655 Hanover, Germany
Introduction

1. Objectives of international cooperations
2. Objectives of projects in claystone
3. Examples of German projects in argillaceous rocks
4. Examples of main tasks in different host rocks
5. Results of some investigations in crystalline rocks
6. Outlook
BGR ACTIVITIES IN RADIOACTIVE WASTE DISPOSAL

• Research since more than 25 years
• Site specific investigations
  Gorleben, Morsleben, Konrad
• Research and development
  Host rocks,
  geotechnical barriers,
  scenario analyses
• International co-operation
  International URLs,
  bilateral agreements
BGR Research Programs in URL’s

Envisaged for a repository
• Opalinus Clay in Switzerland
• Callovo-Oxfordian in France
• Boom Clay in Belgium

Site characterisation

Crystalline rocks
Argillaceous rocks
International Cooperation

Objectives:

• Information exchange on storage facilities

• Selection and characterisation methodologies for disposal sites

• Information exchange on disposal concepts

• Safety assessment of disposal facilities during the operating and post-closure phases

• Participation in experimental programmes carried out in underground laboratories or facilities

• Participation in demonstration programmes

• Characterisation of the behaviour of waste under repository conditions
Argillaceous rocks as host rock
for the disposal of radioactive waste

**BGR-Projects**

- Konrad-Mine (D)
  - Characterisation of argillaceous rock formations in the overburden of a repository

**R & D**

- Tournemire (F)
- Grimsel (CH), Äspö (S)
- Mont Terri (CH)
- Bure (Meuse, Haute-Marne) (F)
Objectives of R&D in argillaceous rock formations

• Properties and effectiveness of bentonite in geotechnical barriers
• Development and tests of methods for the characterisation of argillaceous rock formations

Studies for argillaceous rock formations in Germany

• Site selection criteria
• Site characterisation
• Longterm safety analysis (incl. scenarios and FEPs) for a repository in argillaceous rocks
Project: AnSichT

Argillaceous rock formations in Germany

Stratigraphic position

formation with high proportions of shales and claystone
regionally distributed formation of argillaceous rocks with good spatial characterizability - possible host rock for nuclear waste repositories
regionally distributed formation of argillaceous rocks with significantly restricted spatial characterizability
formation with sandstone and siltstone facies
Project: AnSichT

Methodik und Anwendungsbezug eines Sicherheitsnachweiskonzeptes für ein HAW-Endlager im Tonstein

„AnSichT“

Methodology and application of a safety case concept for a HAW-repository in argillaceous rock formations
Project: AnSichT

Objectives:

• Evaluation of the instruments for safety assessment of HAW repositories in argillaceous rock formations in Germany (North and South-Germany)

• Development of methods for the proof of the integrity of technical, geotechnical and geological barriers

• Conceptual geological model, repository and safety concepts for a model site

• Compilation of representative data

• Development of a specific FEP-catalogue for two model-sites in argillaceous rocks

• Methodology for scenario development and analysis

• Recommendation for future works
• Geological exploration
• Geotechnical investigations
  Permeability
  Deformation
  Stress
• Geophysical investigation
  Temperature
  Ultrasonic
  Electromagnetic Reflection (EMR)
• Current focus: hydrocarbons in salt
Argillaceous rock formations

Special tasks
• Transport processes & reactions
• Diffusion & retention
• Geochemistry & microbiology
• Gas migration & pore pressure
• Rock mechanics

Connected processes (THMC)
• Rock specific
• Concept specific (materials)

• Scale dependant tasks and methods
  (From regional to micro scale)

• Demonstration experiments

Illustration d'un découplage des installations

GEOLOGICAL SECTION OF PARIS BASIN

Special methods are to be developed

Quelle ANDRA
Granitic rocks

Main projects (Grimsel Test Site & Äspö URL)

Processes and long-term behaviour of the engineered barriers
- Full scale experiments
- Gas migration
- Sealing tests of the EB

Radionuclide transport interactions between waste, engineered and geological barriers

Characterisation of the geological barriers
- Diffusion
- Hydrogeological, geomechanical and geological characterisation of the rock & the fracture system

Technical and operational aspects of repository constructions

Quelle NAGRA
Investigations in Crystalline Rock

- Development & Application of methods and models

Fractured rock characterisation:
- BK, GS, EFP (Grimsel Test Site)
- TURE, TASK 5 (Hard Rock Laboratory Äspö)

Near-field characterisation:
- ZPK, CTN (Grimsel Test Site)
- TPF (Hard Rock Laboratory Äspö)

Geological and geotechnical barriers:
- GMT, FEBEX, GAST (Grimsel Test Site)
- PR, EBS, LASGIT (Hard Rock Laboratory Äspö)
Small Scale Solute Transport in Fractured Rock

Single fracture model

Small Scale ( < 10 m) Single Feature Model Flow and Advection in Fracture
2nd Chinese-German Workshop on Radioactive Waste Disposal

Block Scale Solute Transport in Fractured Rock

Transport pathway

Injection

Direct distance

10 m
50 m
100 m

Intermediate Scale
(< 50 m)
Fracture Network Model
Flow and Advection
in Fracture System

fracture network model

Pressure [E5 Pa]

Start: 26.2.1991, 12.00 h

Elapsed time [h]

Elapsed time [h]

Pressure [E5 Pa]

BoBK 9, d=15,50 m
BoBK 9, d=21,50 m
BoBK 9, d=35,50 m
BoBK 13, d=5,50 m
BoBK 14, d=16,00 m
Large Scale Solute Transport in Fractured Rock

Large Scale
(> 100 m)
Coupled Fracture and Matrix model
Flow and Advection in Fracture System
Diffusion and Sorption in Matrix

Conceptual model
Scale Dependency of Solute Transport in Fractured Rock

Coupled fracture and matrix model
Near-field Characterisation

Thin section photo: micro fissure network marked with the fluoresced resin (picture 1.2 mm)
Near-field Hydraulic Properties

Granite:
\[ k < 10^{-18} \text{ m}^2 \]
EDZ: 0.03 – 0.5 m
Fracture

Clay:
\[ k < 10^{-19} \text{ m}^2 \]
EDZ: 1.0 - 2.5 m
Anisotropy

Salt rock:
\[ k \ll 10^{-20} \text{ m}^2 \]
EDZ: k. A.

Grimsel (CH)
Mont Terri (CH)
Bure (F)
Äspö (S)

since 2011 Gorleben (D)
Geological and Geotechnical Barriers

Radial displacement of Point 1 in borehole SH1
TM - calculation with bentonite swelling
variation of parameter values

- $a = 1.2 \times 10^{-5}$, $E = 53.3 \text{ GPa}$
- $a = 0.8 \times 10^{-5}$, $E = 64.3 \text{ GPa}$
- $a = 0.8 \times 10^{-5}$, $E = 53.3 \text{ GPa}$
- $a = 0.5 \times 10^{-5}$, $E = 53.3 \text{ GPa}$
- measured

Temperature [°C]
- calculated at $t = 1000 \text{ d}$
- measured at $t = 1000 \text{ d}$
- calculated at $t = 300 \text{ d}$
- measured at $t = 300 \text{ d}$
- calculated at $t = 180 \text{ d}$
- measured at $t = 180 \text{ d}$
- calculated at $t = 90 \text{ d}$
- measured at $t = 90 \text{ d}$

Bundesanstalt für Geowissenschaften und Rohstoffe

2nd Chinese-German Workshop on Radioactive Waste Disposal
Cooperation between BGR and BRIUUG

Thermal and hydraulic properties comparison
GMZ Bentonite, MX-80, and FEBEX-Bentonite.

<table>
<thead>
<tr>
<th>Porosity (-)</th>
<th>GMZ</th>
<th>MX-80</th>
<th>FEBEX</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0.39</td>
<td>0.41</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Permeability (m²)</th>
<th>GMZ</th>
<th>MX-80</th>
<th>FEBEX</th>
</tr>
</thead>
<tbody>
<tr>
<td>9e-21</td>
<td>4e-21</td>
<td>6e-21</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thermal conductivity (dry – wet) (W/mK)</th>
<th>GMZ</th>
<th>MX-80</th>
<th>FEBEX</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3-1.5</td>
<td>0.3-1.3</td>
<td>0.4-1.5</td>
<td></td>
</tr>
</tbody>
</table>

Heat capacity (J/kgK) 1200 800 1600

Backfill:: bentonite 80%, host rock 20%
Granite
Bentonite
Canister
Vitrified HLW

Backfill
Granite
Bentonite
Carbon Steel overpack

SINOROCK2009, Hongkong

ISRM2011, Beijing
## BGR Current & Future Activities

<table>
<thead>
<tr>
<th>R+D</th>
<th>Salt</th>
<th>Argillaceous rock formations</th>
<th>Granite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characterisation of potential host rocks</td>
<td>✖</td>
<td>✖</td>
<td>(✖)</td>
</tr>
<tr>
<td>Geotechnical barriers, Excav. Disturbed Zone</td>
<td>✖</td>
<td>✖</td>
<td>✖</td>
</tr>
<tr>
<td>Siting of potential host rocks in Germany</td>
<td>✖</td>
<td>✖</td>
<td>✖</td>
</tr>
<tr>
<td>Safety assessment</td>
<td>✖</td>
<td>✖</td>
<td>(✖)</td>
</tr>
</tbody>
</table>
Thank you for your attention!
Radionuclide transport in crystalline formations: laboratory and field experiments

Thorsten Schäfer

- KIT-INE Grimsel Test Site entrance fee and CFM participation (KOLLORADO-2 project) funded by BMWi/PtKA
- FP 7 CP CROCK “Crystalline Rock Retention Processes”
- FP 7 CP BELBaR “Bentonite Erosion: effects on the Long term performance of the engineered Barrier and Radionuclide transport”
Acknowledgement (CFM Partners)

Min-Hoon Baik  Korea Atomic Energy Research Institute (KAERI)
Kazuki Iijima  Japan Atomic Energy Agency (JAEA)
Kotaro Nakata  Central Research Institute of Electric Power Industry (CRIEPI)
Undaria Yamada  National Institute of Advanced Industrial Science and Technology
Masaya Suzuki

Ursula Alonso  The Centre for Energy-Related, Environmental & Technological Research
Tiziana Missana

Susanna Wold  Royal Institute of Technology, representative for SKB
Vladimir Cvetkovic

Pirrko Hölttä  University of Helsinki, POSIVA
Kari Koskinen

Paul Reimus  Los Alamos National Laboratory (LANL)

Bill Lanyon  Fracture-Systems Ltd.

Thomas Trick, Karam Kontar  SOLEXPERTS AG, Swiss precision monitoring

Ingo Blechschmidt  NAGRA
Andrew Martin

Claude Degueldre  PSI, Laboratory for Waste Management (LES)

Ulrich Noseck, Judith Flügge  Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH

Outline

■ INTRODUCTION
  ■ Conceptual Approach
  ■ Normal evolution Scenario (KBS-3 concept)
  ■ Colloid Radionuclide Retardation & Colloid Formation & Migration projects

■ RESULTS & DISCUSSION
  ■ Bentonite Erosion / Colloid Formation (Laboratory studies)
  ■ Colloid associated radionuclide transport
    ■ Hydraulics at Grimsel Test Site
    ■ Migration Experiments
    ■ Comparison of Laboratory and Field data

■ SUMMARY & FUTURE ACTIVITIES
Institute for Nuclear Waste Disposal (INE)

Conceptual Approach

- Research is dedicated to study
  - Colloid formation/bentonite erosion
  - Groundwater/porewater mixing zone
  - Colloid migration (filtration)
  - Colloid associated RN transport

Laboratory Studies
- Colloid-RN interaction
- Colloid Generation
- Field test analysis

Field Experiments
- In situ test: formation & migration
- Migration: colloids, homologues, RN tracers

Modelling Studies
- Solute, colloid and associated RN transport
- Colloid generation

Expected Outputs
- Significant increase in process understanding related to colloid formation at the bentonite/ host rock interface
- Provide PA relevant information on the colloid influence on RN migration/ retardation
- Gain experience in long term monitoring for repository surveillance.
Normal evolution scenario for Sweden's KBS-3 repository

- Dilute water intrusion from melt waters during the glaciation stage will impact groundwater compositions at repository depth.

  Deglaciation during the partly brackish Yoldia Sea period 11 500 to 10 800 BP

  Water depth at Forsmark 190 m

  Continental Ice sheet

  Water depth at Forsmark 190 m

  Forsmark

  Dilute glacial melt water transported to depth by strong hydraulic gradients

  Brackish to saline water?

  Fracture intersecting a deposition hole

- Buffer erosion part of the normal evolution scenario (SKB report TR-06-09)
- Calculations of buffer material losses could lead to advective flow conditions in some deposition holes.
- By regression fit to erosion rate calculations 50 deposition holes will see advective conditions by 1 million year (SSM report 2011:8)
Where do we find glacial melt water conditions? Grimsel Test Site (GTS)

<table>
<thead>
<tr>
<th>GTS groundwater</th>
<th>Na-Ca-HCO$_3$ type</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pressure (bar)</strong></td>
<td>1.4 – 33</td>
</tr>
<tr>
<td><strong>pH</strong></td>
<td>9.6 ± 0.2</td>
</tr>
<tr>
<td><strong>Ionic strength (mol/L)</strong></td>
<td>0.0012</td>
</tr>
<tr>
<td><strong>$E_H$(mV)</strong></td>
<td>≤ -200</td>
</tr>
<tr>
<td>(Na$^+$, K$^+$, Rb$^+$, Cs$^+$)</td>
<td>0.7 mmol/L</td>
</tr>
<tr>
<td>$\Sigma$(Ca$^{2+}$,Mg$^{2+}$,Sr$^{2+}$)</td>
<td>0.14 mmol/L</td>
</tr>
<tr>
<td><strong>Fe$_{ToT}$(µmol/L)</strong></td>
<td>0.003$^+$</td>
</tr>
<tr>
<td><strong>Total cell number (cells/mL)</strong></td>
<td>4.0 ± 0.4·10$^3$*</td>
</tr>
<tr>
<td><strong>DOC (mg/L)</strong></td>
<td>0.4 – 1.4</td>
</tr>
</tbody>
</table>

*Frick et al. (1992); * Gillow et al. (1999)

GTS ideal site to investigate experimentally effects of glacial melt water on buffer integrity & colloidal transport

low ionic strength charge repulsion prevails

high ionic strength attraction (van der Waals) prevails

Glacial melt water

Thorsten Schäfer- "Radionuclide transport in crystalline rocks"
Interaction of strongly sorbing radionuclides with colloids in low mineralized groundwaters

The Colloid & Radionuclide Retardation Experiment

Möri et al., Colloids and Surfaces A 2003, 217(1-3), 33-47.

Project duration: 1997-2004

Colloid Formation and Migration

Project duration: 2004-2015
Outline

INTRODUCTION
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SUMMARY & FUTURE ACTIVITIES
Colloid Formation/ Bentonite erosion (Mock-up)

Compacted Febex bentonite ring provided by CIEMAT

Aperture: 1mm, 
GGW \( v_{\text{init}} \approx 1 \times 10^{-5} \text{ m/s} \)

Experimental details:
- Plexiglas set-up
- Aperture 1mm
- Compacted bentonite 1650 kg/m³
- \( v_{\text{init}} \approx 1 \times 10^{-5} \text{ m/sec} \)
- Grimsel GW
Colloid Formation/ Bentonite erosion (Mock-up)

SKB TR-10-64 (Bentonite erosion model)
- Fracture aperture \( (2b) \) 1mm
- Water velocity \( (v) \) varied
- Cylindrical deposition borehole \( (Ø 1.75\text{m}) \)

Graph showing:
- Erosion rate \( [\text{kg a}^{-1} \text{m}^{-2}] \)
- Water velocity \( (\text{m a}^{-1}) \)

Equations:
- BACKFILL: \( r = 20.7 \times 2b \times v^{0.568} \)
- BUFFER: \( r = 27.2 \times 2b \times v^{0.41} \)
Migration (MI) shear zone (GTS, Switzerland)
(1730 m a.s.l., depth 450 m)

(1) Grimsel Test Site, (2) Rätherichsbodensee,
(3) Grimselsee and (4) Juchlistock.

- A zone with many discontinuities
- Signs of **ductile** and **brittle** deformation
- Some water inflow into the tunnel
- Core sample for lab experiments
Micro-scale CFD on real fracture geometries


- Procon X-Ray Alpha 160 kV max. Flat panel-detector, max. 2048 x 2048 px, max. resolution ~ 1 µm / px.

- µCT @ BAM (Berlin) core scanned with 900 projections over 360° rotation of the sample at 220 kV voxel resolution 80 µm

**Methological approach**

- **µXCT**
  - Geometry reconstruction
- **Preprocessing**
- **Postprocessing**

• Min. aperture [mm]: 0.0
• Max. aperture [mm]: 1.5309
• Mean aperture [mm]: 0.4503
• Std. deviation [mm]: 0.1385
• Variance [mm]: 0.0192
• Total volume [mm³]: 2702

Thorsten Schäfer- "Radionuclide transport in crystalline rocks"
Full 3D computational fluid dynamic (CFD)


Velocity distribution

Particle Tracing

**Full 3D model** ~ 10.5 Mio elements

Wedge shaped fracture geometry

Pressure inlet and outlet (pressure = 0); Step input (C = 1 for t > 0)
Colloid associated RN transport

Fast dissociating/ ion exchangeable (outer sphere)

Slow dissociating (inner sphere) or incorporated

\[ M \quad \text{Ex} \quad M_{\text{slow}} \quad M \quad \text{aq} \]

\[ k_3 \quad k_4 \quad k_2 \]

Flow path heterogeneity

M = metal ion
\( k_n = \text{reaction rate} \)

Surface roughness (protrusions) 3 \( \mu \text{m} \)
What did we know after CRR at the start of CFM?


1) NAGRA Report
2) Hauser et al. 2000,
3) Möri et al. 2002/Geckeis et al. 2004
4) Missana et al. 2003,
5) Schäfer et al. 2004

Data needed
Tunnel sealing system and flow control

- Schematic of the site of the CFM in-situ experiment
- Schematic of the “megapacker” with its key elements and functionalities

Isolated pressurised annulus provide mechanical support to resin. Approximate volume 10m³.
Hydraulic conditions established

- Hydraulics of shear zone controlled by outflow from “Pinkel” surface packer.
- Under constant flow conditions:
  - Head varies by ~1m over year due to influence of lake levels
  - Head difference/gradient is very stable <10mm
  - Gradient ~60mm/6m ~1%
- Unique opportunity to study flow and transport at near repository conditions
CFM project: Tracer Test Runs

- With different combinations of homologues or RN’s, colloids and conservative tracers
- Injection into the MI shear zone in borehole CFM 06.002-i2 and extraction at the Pinkel surface packer

**Run 08-01**: direct tracer injection with 10 mL-min⁻¹; extraction flowrate 160 mL-min⁻¹ (CRR configuration)

**Run 10-01**: tracer recirculation and 50 mL-min⁻¹ extraction flowrate.

**Run 10-03**: tracer recirculation and 10 mL-min⁻¹ extraction flowrate.

**Run 12-02**: tracer recirculation and 25 mL-min⁻¹ extraction flowrate, slight injection with 0.33 mL-min⁻¹
Injection Radionuclide cocktail: Run 12-02

- **Bentonite concentration:**
  - Total: 101.4 ± 2.5 mg/L
  - 8.9 ± 0.4 mg/L Ni-montmorillonite, rest Febex derived colloids

- **Conservative tracer Amino-G:**
  - 1646± 8 ppb

- **ICP-MS & gamma- spectrometry data**

- **Colloid association:**
  - Na-22: 0-3%, Cs-137: 97%, Ba-133: 24-34%
  - Am(III):100%, Th(IV):95-97%, Pu(IV):100%, Np(V):0%
Breakthrough curves: Run 12-02

- Quantitative conservative tracer recovery (Amino-G)
- Dilution factor: $\sim 137$
- Very good match between PSI-LES and KIT-INE data for gamma spectrometry
HR-ICP-MS results: Run 12-02 (first results)

$^{242}$Pu:
Recovery: $\sim 124$ng
Injected: 1266ng

$\Rightarrow \sim 10\%$ recovery
Units to deal with:

- **Mass units:**
  - **dilution:**
  - (milligram) mg/L or 1000 mg/m³ or ppm (1 parts per million, 1/1000g per 1000g solution = 1/1,000,000) $10^{-6}$
  - (microgram) µg/L or 1mg/m³ or ppb (1 parts per billion, 1/1,000,000,000) $10^{-9}$
  - (nanogram) ng/L or 1µg/m³ or ppt (1 parts per trillion, 1/1,000,000,000,000) $10^{-12}$
  - (picogram) pg/L or ppt (1 part per quadrillion, 1/1,000,000,000,000,000) $10^{-15}$

What does ppq mean in reality?

$\Rightarrow$ 1ppq means **10 Swiss sugar cube (~4.4g each) homogeneously diluted in the volume of Lake Constance ~44g/48km³.**

Water volume Lake Constance 48 km³
On-site in-line LIBD measurements

The INE mobile LIBD system (MOB2)

Laser-induced Breakdown Detection (LIBD)

Single solid particles are ionized in the focus of a laser beam;
Breakdown plasma formation;
Breakdown probability \( \sim f(N, d) \)
Laser energy dependency \( \sim f(d) \)

Pulsed Laser Beam
Focusing lens
Colloids
Solution
Sample cuvette

Breakdown

BDP
Lg(N)

Puls energy
Lg(d)
Colloid detection sites

Forsmark (sampling cylinder)

INE (laboratory)

Grimsel Test Site (in-situ)

Laxemar (sampling cylinder)

Äspö Underground Laboratory (in-situ)

Ruprechtov (remote operated sampling cylinder)
On-site in-line LIBD measurements

- Colloid mass recovery
- Mobile LIBD (MOB2)

\[ \text{~66% colloid mass recovery} \]

![Graph showing particle concentration and average colloid diameter over time.](image)

- LIBD Laser Pulse Energy:
  - 203 mV
  - 156 mV
  - 122 mV

- Grimsel background colloids
- Run 12-02 cocktail colloids
- Run 12-02 eluted colloids
Synopsis of migration experiments

Colloid filtration observed
RN-colloid desorption kinetics

2) Hauser et al. 2000,
3) Möri et al. 2002/Geckeis et al. 2004
4) Missana et al. 2003,
5) Schäfer et al. 2004
Does the field migration data fit to laboratory desorption experiments?  

**From binary system data**  
(Nota: No colloid – FFM interaction)

\[ R_{d,\text{tot}} = \frac{K_{d,\text{FFM}}}{1 + C_C \cdot K_{d,\text{coll}}} \]

*Binary data from NTB 03-02*

---

**Pu(IV) Bentonite desorption**

- \( k_{3,\text{average}} = 0.0014 \text{h}^{-1} \)
- \( k = 0.0085 \text{h}^{-1} \)

---

From binary system data

Modelling of tracer tests: Comparison RN reversibility

- Modelling of tracer migration tests
  - GRS, KIT, LANL, Nagra, SKB/KTH
- Homologue tracer tests 08-01, 10-01, 10-03 + conservative tracer tests
- Model showing consistency in homologue sorption/desorption and colloid filtration parameters between laboratory and in situ data.

<table>
<thead>
<tr>
<th></th>
<th>Pu(IV)/Th(IV)</th>
<th>Am(III)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_3$ &quot;high C&quot;</td>
<td>0.0014 hr$^{-1}$</td>
<td>0.0037 hr$^{-1}$</td>
</tr>
<tr>
<td>$k_3$, &quot;low C&quot;</td>
<td>0.0085 hr$^{-1}$</td>
<td>0.009 hr$^{-1}$</td>
</tr>
</tbody>
</table>

RELAP-Model Test 10-03

Laboratory experiment derived desorption rate

Eu $k_r = 0.023$ hr$^{-1}$
Tb $k_r = 0.037$ hr$^{-1}$
Hf $k_r = 0.0007$ hr$^{-1}$
Th $k_r = 0.0018$ hr$^{-1}$
Conclusions (1/2)

- Control of the hydraulic system has allowed further decrease in gradients and consequent increase in travel time. The megapacker sealing system works well and is ready for the long-term in-situ experiment! 😊😊

- Flow velocity and gradient in shear zone more relevant to post-closure situation: 1% gradient and ~10^{-5} m/s while maintaining high recovery.

- Reduction in hydraulic gradients has resulted in
  - Detection of influence of distant boundary conditions
  - Identification of cyclic flow and transport processes in shear zone
  - A conservative tracer has always to be added!

- In situ colloid/homologue tracer tests demonstrate:
  - Radionuclide/homologue colloid associated transport over increasing residence time detectable.
  - Colloid mobility highly sensitive to fracture geometry (flow path) and fracture surface roughness.
  - Radionuclide/Homologue recovery is in-line with batch data on bentonite sorption/reversibility studies.
Conclusions (2/2)

- **URL activities on radionuclide migration** (matrix diffusion & colloid migration) constitute an up-scaling of laboratory experiments and is an important part of the confidence building and uncertainty reduction.

- **Testing and development of conceptual and numerical models** of processes potentially relevant to radionuclide transport through rock.

- **Experiments related to long-term processes**, post-operational phases, e.g. bentonite buffer/backfill stability are necessary to obtain mechanistic understanding of empirical correlations currently used in conceptual models under realistic conditions.

- **Instrumentation experience** gained under real-site conditions especially on the reliability of long-term monitoring systems will foster technical innovation and will therefore improve monitoring.
thank you for your attention
A fractional derivative approach to creep of salt rock

H. W. Zhou et al

State Key Laboratory of Coal Resources and Safe Mining
China University of Mining and Technology (Beijing)

Email: zhw@cumtb.edu.cn
1. Motivation

2. Fractional derivative approach: constant-viscosity

3. Laboratory experiments of salt rock creep

4. Fractional derivative approach: variable-viscosity

5. Conclusions

6. Furthermore works
1. Motivation: engineering background

- Oil & gas storage
- Nuclear waste disposal
- CO$_2$ emission

Salt rock: An ideal medium for the underground energy storage, for disposal of CO2 and high-level radioactive...
1. Motivation: problem

How we predict the large deformation of salt rock in a long term service: Time-dependent behavior of salt rock?

- Variation of the internal pressures
- Time-dependent behavior of salt rock

Decrease of effective storage volume

Eminence in USA
Kiel in Germany
Tersanne in France

(Berest and Brouard, 2003)
1. Motivation: experimental study

Laboratory experiment of salt rock creep

(Hou et al, 2004) (Yang et al, 1999)

How we get a modeling?
1. Motivation: modeling

- **Empirical models**: fewer parameters but long experimental time.

- **Component models**: the advantage of flexible description of different creep deformations and the disadvantage of a mathematical complexity of a creep constitutive equation, such as Maxwell, Kelvin, Bingham, ...

- **Mechanism-based creep constitutive models**: cracking and damage growth at the micro-scale such as Urai, Chris Spiers, Hendrik, Zwart, Lister. Nature 324, 1986
1. Motivation: modeling

Change our channel: the application of fractional calculus to viscoelastic and viscoplastic relations?

Component models + Fractional derivative

Fractional derivative approach: constant-viscosity

Creep damage + Fractional derivative

Fractional derivative approach: variable-viscosity
1. Introduction: meaning of derivative

The first order integer derivative with respect to $x$ may be tangent direction geometrically or speed physically.

\[ f'(x) = \frac{df(x)}{dx} \]

What if the order will be 1/2?
1. Motivation: beginning of fractional derivative

① What if the order will be 1/2?
② It will lead to a paradox, from which one day useful consequences will be drawn (September 30th, 1695)

Can the meaning of derivatives with integer order be generalized to derivatives with non-integer orders?
1. Motivation: remarkable contributions

\[
\frac{d^{1/2} f(t)}{dt^{1/2}} = \frac{1}{\sqrt{\pi}} \frac{d}{dt} \int_0^t \frac{f(\tau)}{(t-\tau)^{1/2}} d\tau
\]

which definition of a $1/2$-order was introduced by Laplace in 1812.
The first use of fractional operation was given by Abel in 1823.

In 1823, Abel wrote a paper in French. It was "a general representation of the possibility to integrate all differential formulas" (Norwegian: en alminnelig Fremstilling af Muligheten at integrere alle mulige Differential-Formler). Because of it, Abel’s work was regarded as the first use of fractional calculus.
1. Motivation: recent publications


\[ \sigma = G \lambda^\xi \frac{d^\xi \varepsilon}{dt^\xi}, \quad (0 \leq \xi \leq 1) \]

1000 papers (more or less) in journal and proceedings per year.

Herrmann, R. Fractional Calculus: An Introduction for Physicists (2011)
Ortigueira, M.D. Fractional Calculus for Scientists and Engineers (2011)
Mainardi, F. Fractional Calculus and Waves in Linear Viscoelasticity (2010)
Podlubny, I. Fractional Differential Equations (1999)
2. Fractional derivative approach: the Abel dashpot

The constitutive relation: \[ \sigma(t) = \eta^\gamma D^\gamma [\varepsilon(t)] \quad (0 \leq \gamma \leq 1) \]

Special cases:

① \( \gamma = 0 \quad \Rightarrow \quad \sigma(t) = C \)  
Hooke body, an ideal solid.

② \( \gamma = 1 \quad \Rightarrow \quad \sigma(t) = \eta \varepsilon'(t) \)  
Newtonian body, an ideal fluid.

The Abel dashpot describe a material between an ideal solid and an ideal fluid.
Let \( \sigma(t) = \sigma = \text{const} \), then \( \varepsilon(t) = \frac{\sigma}{\eta} \frac{t^\gamma}{\Gamma(1+\gamma)} \), \( 0 \leq \gamma \leq 1 \).

\[ \sigma = 20 \text{Mpa} \quad \eta = 0.8 \text{Gpa} \cdot \text{h} \]
2. Fractional derivative approach: a new model

(a) Nishihara model

(b) Fractional derivative model

\[ \varepsilon(t) = \begin{cases} \frac{\sigma}{E_0} + \frac{\sigma}{E_1} \left( 1 - e^{-\frac{E_1 t}{\eta_1}} \right), & \sigma < \sigma_s \\ \frac{\sigma}{E_0} + \frac{\sigma}{E_1} \left( 1 - e^{-\frac{E_1 t}{\eta_1}} \right) + \frac{\sigma - \sigma_s}{\eta_2} t, & \sigma \geq \sigma_s \end{cases} \]
2. Fractional derivative approach: parameter determination

**Least-square analysis**

Using the experimental data of time-dependent deformation of salt rock under uniaxial compression (Hou, 1997), we determine the parameters of the fractional model data.

\[
\varepsilon(t) = \frac{\sigma}{E_0} + \frac{\sigma}{E_1} - \frac{\sigma}{E_1} E_\gamma \left( - \frac{E_1}{\eta_1} t^\gamma \right) + \frac{\sigma - \sigma_s}{\eta_2} \frac{t^\gamma}{\Gamma(1+\gamma)}
\]

Mittag-Leffler function:

\[
E_\gamma(x) = \sum_{n=0}^{\infty} \frac{x^n}{\Gamma(1+\gamma n)}
\]

\( E_0, E_1, \eta_1, \eta_2, \gamma \) can be determined by a least-squares function, i.e.,

\[
\varepsilon_{LS}(E_0, E_1, \eta_1, \eta_2, \gamma) = \sum_{i=1}^{N} \left( \varepsilon_i - \varepsilon(t_i) \right)^2
\]
The fractional model adequately represents the time-dependent deformation of salt rock.

Parameters determined by fitting analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_0$</td>
<td>22.98 (Gpa)</td>
</tr>
<tr>
<td>$E_1$</td>
<td>9.88 (Gpa)</td>
</tr>
<tr>
<td>$\eta_1^\gamma$</td>
<td>1.23 (Gpa-h$^\gamma$)</td>
</tr>
<tr>
<td>$\eta_2^\gamma$</td>
<td>13.76 (Gpa-h$^\gamma$)</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Least-squares error: $4.31 \times 10^{-5}$

Laboratory experimental conditions of salt rock: uniaxial load: 14.1 Mpa, temperature: room, period: 1256 days (Hou, 1997)
2. Fractional derivative approach: sensitivity study

- **Effect of the fractional derivative order**

\[
\sigma \geq \sigma_s, \quad \sigma = 14.1 \text{Mpa}, \sigma_s = 8.46 \text{Mpa}, \quad E_0 = 22.98 \text{Gpa}
\]

\[
\eta_1^\gamma = 1.23 \text{Gpa} \bullet h^\gamma, \quad E_1 = 9.88 \text{Gpa}, \quad \eta_2^\gamma = 13.76
\]

The higher the fractional derivative order, the higher the creep strain.

- **Effect of the stress level**

\[
\sigma_s = 8.46 \text{Mpa}, \quad E_0 = 22.98 \text{Gpa}, \quad E_1 = 9.88 \text{Gpa}
\]

\[
\eta_1^\gamma = 1.23 \text{Gpa} \bullet h^\gamma, \quad \eta_2^\gamma = 13.76, \quad \gamma = 0.31
\]

The higher the stress level, the higher the creep strain.
2. Fractional derivative approach: a special case

**Discussion:** fractional Nishihara model in the case of $\gamma = 1$

$$
\varepsilon(t) = \begin{cases} 
\frac{\sigma}{E_0} + \frac{\sigma}{E_1} \sum_{k=1}^{\infty} \frac{(-1)^{k+1} \left( \frac{E_1}{\eta_1} \right)^k}{k!}, & \sigma < \sigma_s \\
\frac{\sigma}{E_0} + \frac{\sigma}{E_1} \sum_{k=1}^{\infty} \frac{(-1)^{k+1} \left( \frac{E_1}{\eta_1} \right)^k}{k!} + \frac{\sigma - \sigma_s}{\eta_2} t, & \sigma \geq \sigma_s
\end{cases}
$$

$\gamma = 1$

Fractional derivative model

Nishihara model

Nishihara model is a special case of the fractional model.
A creep constitutive model for salt rock based on fractional derivatives

H.W. Zhou *, C.P. Wang, B.B. Han, Z.Q. Duan

State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology, Beijing 100083, China

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Nishihara model
Parameter fit analysis

ABSTRACT

By replacing a Newtonian dashpot in the classical Nishihara model with the fractional derivative Abel dashpot, a new creep constitutive model is proposed on the basis of time-based fractional derivative. The analytic solution for the fractional derivative time-dependent constitutive model is given. The parameters of the fractional derivative model and the Nishihara model are determined by fitting to existing experimental results of time-dependent deformation of salt rock. The results estimated by the fractional derivative model proposed in the paper are in better agreement with the experimental data than the results estimated by the Nishihara model. A sensitivity study for the analytic solution of the time-based fractional derivative model is carried out, showing the effects of fractional derivative order and stress level on creep strain of salt rock. It is shown that the time-based fractional derivative model can be simplified to the Nishihara model for the special case of fractional derivative order equal to 1.0.

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3. Laboratory experiments of salt rock creep: sampling

Chuwang Well No. 1 at depth of 1982 m from ground surface, Jianghan Oilfield, Hubei Province, Central China

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Weight/g</th>
<th>Diameter/mm</th>
<th>Height/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS01a</td>
<td>1430.35</td>
<td>75.01</td>
<td>150.14</td>
</tr>
<tr>
<td>RS02a</td>
<td>1473.83</td>
<td>75.03</td>
<td>149.98</td>
</tr>
<tr>
<td>RS05a</td>
<td>1447.25</td>
<td>75.22</td>
<td>150.22</td>
</tr>
</tbody>
</table>
3. Laboratory experiments of salt rock creep: setup

- Uniaxial loading: stress level at 4Mpa, 6Mpa, 8Mpa ...
- Measurement of axial displacement: displacement sensor

(at Sichuan University, Chengdu, China)
3. Laboratory experiments of salt rock creep

RS01a (140 days)  RS02a (157 days)  RS05a (136 days)
3. Laboratory experiments of salt rock creep

RS05a (136 days)
3. Laboratory experiments of salt rock creep: CT setup

CT setup at CUMTB

Before

After
4. Fractional derivative approach: variable-viscosity

Experimental conditions: uniaxial load-18MPa, temperature-22°C, and period-140 days
4. Fractional derivative approach: variable-viscosity

Before

\[ \sigma(t) = \eta^\beta D_t^\beta [\varepsilon(t)] \]

Variable-viscosity

\[ \sigma(t) = \eta'^\beta D_t^\beta [\varepsilon(t)] \]

\[ \eta'^\beta = (1 - d) \cdot \eta^\beta \]

\( d \) is the damage variable \( 0 \leq d < 1 \)

4. Fractional derivative approach: variable-viscosity

The ultrasonic wave speed of salt rock during creep test

(Hou et al 2003) \[ d = 1 - \frac{1}{1 + \varepsilon_v} \frac{v_p}{v_0} \]

Increase of damage variable with time

\[ d = 1 - e^{-\alpha t} \]

\[ \eta^{\beta'} = (1 - d) \cdot \eta^\beta \]

\[ \sigma(t) = (\eta^\beta e^{-\alpha t}) D_t^\beta [\varepsilon(t)] \quad (0 \leq \beta \leq 1) \]
4. Fractional derivative approach: variable-viscosity

\[\sigma(t) = (\eta^\beta e^{-\alpha t})D_t^\beta [\varepsilon(t)] \quad (0 \leq \beta \leq 1)\]

\[\varepsilon(t) = \frac{\sigma}{\eta^\beta} t^\beta \sum_{k=0}^{\infty} \frac{(\alpha t)^k}{\Gamma(k+1+\beta)}\]

Creep strain described by the variable-viscosity Abel dashpot

\[\text{Nondimensional Time } = \frac{t}{\eta}\]

\[\text{strain(%) }\]

\[\beta=0.1, \alpha=0.03\]
\[\beta=0.5, \alpha=0.03\]
\[\beta=0.9, \alpha=0.03\]
\[\beta=0.3, \alpha=0.01\]
\[\beta=0.3, \alpha=0.05\]
\[\beta=0.3, \alpha=0.09\]
4. Fractional derivative approach: variable-viscosity

The variable-viscosity fractional derivative model

\[
\varepsilon(t) = \frac{\sigma}{E_0} + \frac{\sigma}{\eta_1^\beta} \sum_{k=0}^{\infty} \left( \frac{-E_1}{\eta_1^\beta} \right)^k t^{(1+k)\beta} + \frac{\sigma - \sigma_s}{\eta_2^\beta} t^\beta \sum_{k=0}^{\infty} \frac{(\alpha t)^k}{\Gamma(k+1+\beta)} \quad (\sigma \geq \sigma_s)
\]

\[
\varepsilon(t) = \frac{\sigma}{E_0} + \frac{\sigma}{E_1} - \frac{\sigma}{E_1 E_{\beta,1}} \left[ -E_1 \left( \frac{t}{\eta_1} \right)^\beta \right] + (\sigma - \sigma_s) \left( \frac{t}{\eta_2} \right)^\beta E_{1,1+\beta}(\alpha t)
\]
4. Fractional derivative approach: variable-viscosity

<table>
<thead>
<tr>
<th></th>
<th>$E_0$ (GPa)</th>
<th>$E_1$ (GPa)</th>
<th>$\eta_1^\beta$ (GPa·h$^\beta$)</th>
<th>$\eta_2^\beta$ (GPa·h$^\beta$)</th>
<th>$\beta$</th>
<th>$\alpha$ (h$^{-1}$)</th>
<th>LSF errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fractional derivative model</td>
<td>5.73</td>
<td>27.59</td>
<td>1.40</td>
<td>178.63</td>
<td>0.3</td>
<td>0.0021</td>
<td>4.2 × 10$^{-5}$</td>
</tr>
</tbody>
</table>
4. Fractional derivative approach: variable-viscosity

- Sensitivity of the creep strain to the stress level

*Fig. 6* Sensitivity of the creep strain to the stress level $\sigma$
($\sigma_s = 16$ MPa, $E_0 = 5.37$ GPa, $E_1 = 27.59$ GPa,
$\eta_1^B = 1.4$ GPa h$^B$,
$\eta_2^B = 178.63$ GPa h$^B$, $\beta = 0.3$
and $\alpha = 0.0021$ h$^{-1}$)
4. Fractional derivative approach: variable-viscosity

- Sensitivity of the creep strain to the fractional derivative order

\[ \eta_1^\beta = 1.4 \text{ GPa} \cdot h^\beta, \]
\[ \eta_2^\beta = 178.63 \text{ GPa} \cdot h^\beta, \]
\[ \sigma = 18 \text{ MPa}, \alpha = 0.0021 \text{ h}^{-1} \]
4. Fractional derivative approach: variable-viscosity

- Sensitivity of the creep strain to the parameter $\alpha$

\[\text{Fig. 8} \quad \text{Sensitivity of the creep strain to the exponent } \alpha \ (\sigma_s = 16 \text{ MPa}, \ E_0 = 5.37 \text{ GPa}, \ E_1 = 27.59 \text{ GPa}, \ \eta_1^B = 1.4 \text{ GPa h}^\beta, \ \eta_2^B = 178.63 \text{ GPa h}^\beta, \ \sigma = 18 \text{ MPa}, \ \beta = 0.3)\]
A fractional derivative approach to full creep regions in salt rock

H.W. Zhou · C.P. Wang · L. Mishnaevsky Jr. · Z.Q. Duan · J.Y. Ding

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Abstract Based on the definition of the constant-viscosity Abel dashpot, a new creep element, referred to as the variable-viscosity Abel dashpot, is proposed to characterize damage growth in salt rock samples during creep tests. Ultrasonic testing is employed to determine a formula of the variable viscosity coefficient, indicating that the change of the variable viscosity coefficient with the time meets a negative exponent law. In addition, by replacing the Newtonian dashpot in the classical Nishihara model with the variable-viscosity Abel dashpot, a damage-mechanism-based creep constitutive model is proposed on the basis of time-based fractional derivative. The analytic solution for the fractional-derivative creep constitutive model is presented. The parameters of the fractional derivative creep model are determined by the Levenberg–Marquardt method on the basis of the experimental results of creep tests on salt rock. Furthermore, a sensitivity study is carried out, showing the effects of stress level, fractional derivative order and viscosity coefficient exponent on creep strain of salt rock. It is indicated that the fractional derivative creep model proposed in the paper provides a precise description of full creep regions in salt rock, i.e., the transient creep region (the primary region), the steady-state creep region (the secondary region) and the accelerated creep region (the tertiary region).

Keywords Salt rock · Abel dashpot · Variable viscosity coefficient · Fractional derivative · Creep constitutive model

5. Conclusion remarks

- The variable viscosity Abel dashpot, characterized by damage growth of salt rocks during the creep tests, is available in description of the non-steady creep process or the accelerated creep region.

- The new fractional derivative creep model proposed in the paper is capable of giving a precise approach to full creep regions in salt rock.
6. Furthermore works

- Further research on the physical meaning of the derivative order is important and necessary.
- Application of fractional derivative model to numerical simulation of creep deformation of salt cavities is still a big task.
Thank you for your attention

H. W. Zhou

State Key Laboratory of Coal Resources and Safe Mining
China University of Mining and Technology (Beijing)

Email: zhw@cumtb.edu.cn
2nd Chinese-German Workshop on Radioactive Waste Disposal

Oct. 15 – 16, 2012  Karlsruhe, Germany
Basic Principles of Waste Disposal in Rock Salt Mass

- Some Selected Remarks

Univ. Prof. Dr.-Ing. habil K.-H. Lux
Overview

1. Underground Waste Disposal in Germany

2. Specialized Safety Analysis as well as Safety Criteria with Respect to Rock Salt

3. Contributions of Department of Waste Disposal and Geomechanics to Safety Analysis

4. Some Concluding Remarks
Overview

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Underground Waste Disposal in Germany – Hazardous Waste

Chemotoxic Waste

Hazardous Waste

Radioactive Waste

Underground waste Disposal

Waste Isolation from Biosphere

Waste Utilisation for Backfilling

Waste Isolation from Biosphere

Waste Utilisation for Backfilling

! Long Term Protection of Environment against Remigration of Waste !
Activities for Underground Rad-Waste Disposal in the World
Underground Waste Disposal in Germany – Chemotoxic-Waste

Underground Emplacement Activities in Saliniferous Rock Mass:
- 4 Disposal Facilities
- 12 Backfill facilities (Salt Mine)
- 1 Backfill Facility (Salt Cavern)

Thermal plants (WTE plants and RDF power plants) in European States by capacity in Mio t
**Situation in Germany with Respect to Radioactive Waste Disposal**

**Current Status of Site Activities:**

- Morsleben (rock salt)
  * to be closed
- Asse (rock salt)
  * waste recovery under investigation
- Konrad (claystone)
  * operation prepared
- Gorleben (rock salt)
  * exploration at low intensity
  * preliminary safety assessment

**Legal Activities:**


Federal Government Law (?) → New Site Identification and Site Characterisation Procedure (including / excluding Gorleben site ?) ⇒ precondition: no preselected host rock mass type
Underground Waste Disposal in Germany

Identified Geotectonic Systems for Underground Waste Disposal

- **Future**
  - Crystalline Formations (granite)
  - Sedimentary Formations (claystone, clay)

- **Past, Presence**
  - Evaporitic Formations (rock salt)
Saliniferous Structures – Bedded Salt
Saliniferous Structures – Domal Salt
Basic Principles with Respect to Safety

Basic Principles for Radwaste Disposal:
- national disposal
- protection of human beings and the environment against radiation
- protection of human beings against chemotoxic harmful substances
- disposal in deep underground formations
- complete isolation of waste in rock mass (CC)
- multibarrier system against release of hazardous substances back to biosphere
- time of prognosis > 1 Mio. years
- no design for retrieval of waste after end of disposal operation and sealing
- maintenance-free disposal → after repository closure no monitoring as well as no repair work

Final disposal – basic objectives:
safe, without time limit, maintenance-free
as well as
accepted by public

How may it work?
Overview

1. Underground Waste Disposal in Germany

2. Specialized Safety Analysis as well as Safety Criteria with Respect to Rock Salt

3. Contributions of Department of Waste Disposal and Geomechanics to Safety Analysis

4. Some Concluding Remarks
Specialized Safety Analysis with Respect to Rock Salt

**Basic Demand:**

Protection of the Environment Against

→ Hazardous Waste (acc. to Waste Law)

→ Radioactive Waste (acc. to Atomic Law)

→ Mining Waste (acc. to Mining Law)

Resulting from Human Activities

**Basic Safety Principle:**

- Isolation of Hazardous Waste from Biosphere – CC

**Additional Demands:**

- long term (> 1 Mio years, permanent)

- safe

- maintenance-free

- no necessity regarding retrievability after abandonment

**Basic Public Principle:**

May be Necessary but … NIMBY ⇒
General Demand with Respect to Underground Waste Disposal ⇒

**Principally No Return of Hazardous Particles to Biosphere**

Additional Specified Demands ⇒
- long term / permanent
- safe
- maintenance-free
- no necessity regarding retrievability after abandonment

Current Procedure:

**Documentation of Isolation of Waste from Biosphere in Deep Underground Rock Mass Formations**
- Safety well documented acc. to International State of the Art
+ Participation of Public in Process

**Detailed Procedure of Realisation ⇒**

1. Development of Excellent Knowledge
2. Selection of a Basically Suitable Site based on Preliminary Prognostic Safety Analysis as well as on Public Participation
3. Site-Specific Repository Design
4. First Prognostic Safety Analysis / Licencing Procedure, Public Participation
5. Extensive Monitoring during Construction and Operation
6. Updated Prognostic Safety Analysis, during Operation, Public Participation
7. Final Prognostic Safety Analysis before Closure, Public Participation
8. Closure of Repository

Participation of Public in Process
Specialized Safety Analysis with Respect to Rock Salt

(1/1) Legal Demand: Isolation of Chemotoxic Waste in Rock Salt Formations

(1/2) Legal Demand: Isolation of Radioactive Waste in Suitable Underground Formations

- long term – safe - no necessity retrievability after abandonment - maintenance-free

(2) Engineering Realisation ⇒ Creation of a Multibarrier System against Radionuclide / Toxic Waste Mobilisation / Migration

consisting of ⇒

Geologic Barrier(s) Geotechnical Barrier(s) Technical Barrier(s)

Barrier = physical element of repository preventing hazardous / radioactive waste mobilization / migration

during construction, operation, after closure during long term during operation

as well as in the long term (repository in rock salt mass)

Underground Waste Repositories:

Where to dispose off? How to dispose off? Who is responsible? When should final disposal takes place?
THMC – Analysis of Physicochemical Processes in Near Field

\[ M \rightarrow \tilde{M}/T \rightarrow \tilde{T}/H \rightarrow \tilde{H}/C \rightarrow \tilde{C} \]

Construction – Operation – Closure

geogenic system

farfield

nearfield

excavation / waste disposal

no permeability

Probability of Occurrence of Possible Future Developments of Site

- developments with high probability ⇒ complete isolation!
- developments with low probability ⇒ admissible release! (=safe isolation)
Specialized Safety Analysis with Respect to Rock Salt


Basic Rock salt mass properties with Respect to Waste Disposal:

- excellent hydraulic properties (impermeable = tight → no natural pathways for fluids)
- good mechanical properties regarding strength (no destrengthening joint system, sufficient load bearing capacity)
- good mechanical properties regarding deformability (ductile behaviour, plastic-viscous / creep → reclosure of underground holes)
- good thermal properties (→ relativ high heat conductivity)
- good mechanical properties regarding fissure closure (→ self-sealing / self-healing)

but:

- worse geochemical properties regarding sorption (less / no sorption capacity)
- worse geochemical properties regarding rock material stability (→ soluble in fresh water)

⇒ Documentation of Geochemical Stability of Site Specific Saliniferous Rock Mass System Obligatorily Necessary! (in past and presence as well as in future including waste disposal impacts)
Specialized Safety Analysis with Respect to Rock Salt

Geological Barrier(s) in Saliniferous Geosystems

Alternative Thesis:

- just one intact geologic barrier necessary ⇒
  rock salt mass

- two intact geologic barriers necessary ⇒
  rock salt mass (main barrier)
  +
  non rock salt formation (to protect rock salt formation against groundwater access and to realize some sorption capacity at site as well as to give some kind of redundancy and diversity)

General Properties / Criteria

(a) before repository construction
→ impermeable rock salt mass
  (tight crystalline fabric as well as no naturally induced pathways for fluid flow)

⇒ Documentation of Existing Geological Barrier Integrity (site selection process)

(b) after repository construction and disposal of waste in the long term
→ impermeable rock salt mass too
  (no technically induced pathways during construction, operation, abandonment)

⇒ Documentation of (absolute or sufficient?) Preservation of Pre-Existing Geological Barrier Integrity (during Exploration, Construction, Operation and Abandonment Phase as well as in the Long Term)
Specialized Safety Analysis with Respect to Rock Salt


**Basic Criteria with Respect to Guarantee Long Term Safety**

(1) Appropriate Site with Intact Geologic Barrier System →

(2) Maintenance of Naturally Existing Geologic Barrier Integrity

(2/1) - mechanical integrity:
   no damage

(2/2) - hydraulic integrity:
   no fluid infiltration

(2/3) - chemical integrity:
   limited temperature change

Documentation of maintenance of *pre-existing barrier integrity* or just documentation of *sufficient barrier integrity*?

→ some local / zonal loss of barrier integrity perhaps
   only temporarily may be tolerable if guaranteeing long term safety of repository at any time

**Identifying as well as Determining**

**Isolating Rock Mass Area Around Repository**

acc. to AKEnd (2002)
Specialized Safety Analysis with Respect to Rock Salt

How to Demonstrate Safety at Repository Site for the (Unknown) Long Term Development (> 1 Mio Years ?)

Fundamentals:

(1) Reliable geoscientific understanding of geotectonic development of the site in the past (> 10 Mio years)

(2) Geoscientific based extrapolation of geotectonical possible developments of the site with high or less degree of probability of occurrence in the future considering all possible impacts and processes (time scale > 1 Mio years) – acc. to State of the Art

Precondition:

(3) Good and complete understanding of site-specific T-H-M-C-B-(Tr) processes relevant to selected site with respect to site-specific conditions taking into account

⇒ rock mass system
⇒ mine system (shafts, drifts, chambers)
⇒ disposed off waste properties
⇒ sealing system
**Specialized Safety Analysis with Respect to Rock Salt**

**How to Demonstrate Safety at Site for the (Unknown) Long Term Development**

(> 1 Mio Years ?)

(4) **Physicochemical Modelling** of relevant processes and their interaction (T-H-M-C)

(5) **Numerical Simulation** of possible disposal system developments considering

- site developments with high degree of probability to occur in order to demonstrate complete isolation of waste (!)
- site developments with low degree of probability to occur in order to analyse possible mobilisation / migration of waste towards biosphere

(6) **Proof of safety** for numerically determined results

- proof of complete isolation of waste (criteria? necessary safety margins?)
- proof of limited as well as tolerable release of harmful particles with respect to waste specific environmental protection criteria → chemotoxic waste – (deep) groundwater → radiotoxic waste - biosphere

including **Sensitivity Analysis**
Specialized Safety Analysis with Respect to Rock Salt

How to Demonstrate Safety at Site for the (Unknown) Long Term Development

(> 1 Mio Years ?)

Key Elements for Safety Analysis
- Documentation of Isolation
- Analysis of Mobilisation / ETI

⇒ T

M

H processes - individual as well as
- coupled (one side / two sides - if necessary with respect
to safety aspects)

C

- Identifikation
- Understanding
- Modelling (Formula)
- Characterisation (Site-Specific)
Overview

1. Underground Waste Disposal in Germany
2. Specialized Safety Analysis as well as Safety Criteria with Respect to Rock Salt
3. Contributions of Department of Waste Disposal and Geomechanics to Safety Analysis
4. Some Concluding Remarks
Contributions of Department of Waste Disposal and Geomechanics

(1/1) Laboratory Investigations

- strength properties
- deformation properties (elastic-viscous behaviour)
- damage properties
- healing properties
- hydraulic properties (1-/2-phase flow)
- infiltration properties

with respect to

- rock materials
- backfill materials
- geotectonic barrier materials
- waste materials

Rock Mechanical Lab of TUC
(1/1) **Strength Properties as well as Damage Properties**

\[ D = 1 - \frac{1}{1 - \varepsilon_{vol}} \left( \frac{v_p}{v_p^0} \right)^2 \]
Contributions of Department of Waste Disposal and Geomechanics

(1/2) **Deformation / Creep Properties as well as damage properties**

Creep Phases: (I) Transient Creep, (II) Stationary Creep, (III) Accelerated Creep, (IV) Creep Failure

*Lab Investigations → Physical Modelling*
(1/3) Deformation / Creep Properties – Recreation of Damage / Healing

Back-formation of Damage

\[ \dot{\varepsilon}_{ij}^h = -\varepsilon_{vol} \cdot \left( \frac{1}{f_{c1}} \cdot \dot{F}_h + \frac{I_1}{f_{s1}} + \frac{1}{f_h} \right) \cdot \frac{\partial Q^h}{\partial \sigma_{ij}} \]

\[ \dot{D} = -D \cdot \left( \frac{\dot{F}_h}{f_{c1} \cdot f_{c2} + \frac{I_1}{f_{s1} \cdot f_{s2}} + \frac{1}{f_h}} \right) \]

Secondary porosity \( \rightarrow H(K^S, P_F) \)

Damage intensity \( \rightarrow M(\beta, \dot{\varepsilon}) \)
Contributions of Department of Waste Disposal and Geomechanics

(1/4) Infiltration Properties

Lab test experience

Salt rock sample with infiltration of liquid

\[-\bar{v}_{\text{inf}} = a \cdot \exp(b \cdot \Delta p_{FI})\]
\[-\Delta p_{FI} \uparrow = \beta \cdot \Delta K\]
\[-\Delta p_{FI} \downarrow = \beta \cdot \Delta \phi\]

Flow related to Darcy

Infiltration phase

Basic mechanisms

Physical Model

Pressure-dependent representation of the average rate of infiltration $\bar{v}_{\text{inf}}$
Contributions of Department of Waste Disposal and Geomechanics

(2) Physical Modelling Development of Constitutive Model Lux/Wolters
(2/1) Creep Process without Damage

\[ \dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^p + \dot{\varepsilon}_{ij}^c \]

\[ \dot{\varepsilon}_{ij}^c = \dot{\varepsilon}_{ij}^p \]

modLubby2: \( \sigma \rightarrow \sigma_f \left( 1 - D \right) \), mod \( G_k \), mod \( \eta_m \)

\[ \dot{\varepsilon}_{ij}^p = \frac{3}{2} \left[ \frac{1}{\eta_k(\sigma)} \left\{ 1 - \frac{\sigma_{ij}}{\sigma_f} \right\} (1-D) \right] + \frac{1}{\eta_m(\sigma, T)} \cdot s_{ij} \]

\[ D = 1 - \frac{1}{1 - \varepsilon_{\text{vol}}} \cdot \left( \frac{\varepsilon_{\text{ip}}}{\varepsilon_{\text{ip}}^0} \right)^2 \]

\[ D = 0 \text{ if no damage} \]

modLubby2 without damage

\[ \dot{\varepsilon}_{ij}^p = - \frac{3}{2} \left[ \frac{1}{\eta_k(\sigma)} \left\{ 1 - \frac{\sigma_{ij}}{\sigma_f} \right\} + \frac{1}{\eta_m(\sigma, T)} \cdot s_{ij} \right] \]

\[ \varepsilon_{\text{max}} = \frac{1}{G} \cdot \sigma_f \]

\[ \eta_k(\sigma) = \eta_k^* \cdot \exp(k_2 \cdot \sigma_f) \]

\[ G_k(\sigma) = G_k^* \cdot \exp(k_1 \cdot \sigma_f) \cdot \left( \frac{\sigma}{\sigma_f} \right)^\gamma \]

\[ \eta_m(\sigma, T) = \eta_m^* \cdot \exp(m \cdot \sigma_f) \cdot \exp(l \cdot T) \cdot \left( \frac{\sigma}{\sigma_f} \right)^\gamma \]
Contributions of Department of Waste Disposal and Geomechanics

(2) Physical Modelling Development of Constitutive Model Lux/Wolters
(2/2) Creep Process with Damage

Modellansatz
\[ \dot{\varepsilon}_y = \dot{\varepsilon}_y^p + \dot{\varepsilon}_y^d \]

\[ \dot{\varepsilon}_y^p = \varepsilon_y^p + \dot{\varepsilon}_y^d \]

Damage of Rock Fabric

\text{micro-}\text{/\text{macrofissurisation}} \rightarrow \text{dilatancy / destrengthening} \rightarrow \text{damage}

Damage Intensity Factor:

\[ D = 1 - \left( \frac{1}{1 - \varepsilon_{vol}} \left( \frac{v_p}{v_{p0}} \right)^2 \right) \]

\[ D \approx |\varepsilon_{vol}| \]

Implementation of Damage D as well as Damage-induced Creep in the Constitutive Model LUBBY2

\[ \Delta \sigma = \frac{\partial \sigma}{\partial \sigma_y} \frac{\partial Q}{\partial \sigma} + a_1 \left( \frac{F^d}{F^e} \right)^{\alpha_1} \frac{\partial Q}{\partial \sigma} \left( \frac{1 - D}{1 - D} \right)^{\alpha_1} \]

Modifiziertes LUBBY2:

\[ \varepsilon_y^p = \frac{1}{2} \left( 1 - \frac{\eta_{\sigma}}{\eta_{\sigma}} \left( \frac{1 - D}{1 - D} \right) \right) + \frac{1}{2} \eta_{\sigma} (1-D)^{\alpha_1} \]

Dilatanzgrenze

\[ F_{ds}^{\alpha} = \sqrt{3J_2 - \eta_{\sigma}} \cdot \beta(\sigma, \theta) \]

\[ F_{dz}^{\alpha} \leq 0 \]

\[ F_{ds}^{\alpha} > 0 \text{ oder } F_{dz}^{\alpha} > 0 \]

\[ D = 0 \text{ keine weitere Schädigung} \]

\[ D_{vol} \approx \sigma_y \]

\[ \dot{D} = a_{11} \left( \frac{F^d}{F^e} \right)^{\alpha_1} + a_1 \left( \frac{F^d}{F^e} \right)^{\alpha_1} \frac{\partial Q}{\partial \sigma} \left( \frac{1 - D}{1 - D} \right)^{\alpha_1} \frac{\partial Q}{\partial \sigma} \]
Contributions of Department of Waste Disposal and Geomechanics

(2) Physical Modelling Development of Constitutive Model Lux/Wolters
(2/3) Creep Process with Damage and Recreation of Damage (Healing)

**Recreation of Rock Fabric Quality**
- fissure closure
- fissure sealing
- fissure healing

→ Reduction of Damage (Healing)

**Implementation of Reduction of Damage (Healing) in the Constitutive Model LUBBY2**

**Modellansatz**
\[
\dot{\varepsilon}_{ij} = \dot{\varepsilon}^{\text{phys}}_{ij} + \dot{\varepsilon}^{\text{dam}}_{ij}
\]

**Modifiziertes LUBBY2: \( \sigma \rightarrow \sigma/(1-D) \)**
\[
\dot{\varepsilon}^{\text{phys}}_{ij} = \frac{3}{2} \left( \frac{1}{\eta_{\infty}} \right) \left( 1 - \frac{\sigma_{ij}}{\sigma_{\infty}} (1-D) \right) + \frac{1}{\eta_{\sigma}(\epsilon_{\sigma})} s_{ij} (1-D)
\]

**Dilatanzgrenze**
\[
F^a = \sqrt{3} J_2 - \eta(\sigma) \cdot \mu(\sigma, \theta)
\]

**Schädigungsrate**
\[
D = a_{\alpha_1} \left( \frac{F^a_{\alpha_1}}{F_{\alpha_1}} + \frac{F^b_{\alpha_1}}{F_{\alpha_1}} \right)^{\alpha_1}
\]

**Verheilungsgrenze**
\[
F^a \leq 0 \quad \text{und} \quad F^b \leq 0
\]

**Verheilungsrate**
\[
D = 0 \quad \text{keine weitere Schädigung und Verheilung}
\]

**Dilatanzrate in geschädigten Bereichen**
\[
\dot{\varepsilon}_{ij}^d = \dot{\varepsilon}^{\text{phys}}_{ij} + \dot{\varepsilon}^{\text{dam}}_{ij} = a_{\alpha_1} \frac{F^a_{\alpha_1}}{(1-D)} \frac{\partial Q^{a_1}}{\partial \sigma_{ij}} + a_{\alpha_1} \frac{F^b_{\alpha_1}}{(1-D)} \frac{\partial Q^{b_1}}{\partial \sigma_{ij}}
\]

**Verheilungsrate in geschädigten Bereichen**
\[
\dot{\varepsilon}_{ij}^h = - \epsilon_{\text{vol}} \left( \frac{1}{f_{\text{c1}} F^a + f_{\text{b1}} F^b + f_{\text{h}} Q^h} \right) \frac{\partial Q^h}{\partial \sigma_{ij}}
\]
Contributions of Department of Waste Disposal and Geomechanics

(2/4) Physical Modelling Development of Constitutive Model Lux/Wolters

Mechanical Processes coupled with Hydraulic Processes

General Demands
- Mechanical Stability
- Tightness
- Acceptable surface subsidence
- Environmental safe abandonment

Salt Cavern – Rock Mass Behaviour after Abandonment

still impermeable salt rock mass

Further infiltration front developing?

\[ p_{Hr} \quad (\text{roof}) \]

infiltration front \((x,t)\)

specific infiltration volume

time-dependent pressure increase (infiltration process, convergence process)

infiltration rate

impermeable salt rock mass

pHy (roof)

[Diagram showing the process of infiltration front development and its impact on rock mass behavior after abandonment]
Contributions of Department of Waste Disposal and Geomechanics

(3) Numerical Simulations – Validation / Prognosis
(3/1) Morsleben Repository – Abandonment / Barrier Integrity
Contributions of Department of Waste Disposal and Geomechanics

(3) Numerical Simulations – Validation / Prognosis
(3/2a) Asse Repository – Mine Behaviour / Dry Conditions

Pillar Deformation Rate in Dependence of Time

Validation        Prognosis →
Contributions of Department of Waste Disposal and Geomechanics

(3) Numerical Simulations – Validation / Prognosis
(3/2b) Asse Repository – Mine Behaviour / Wet Conditions

Estimation of Efflux Rate of Brine after Flooding due to Convergence as well as Gas Generation Rate
Contributions of Department of Waste Disposal and Geomechanics

(3) Numerical Simulations – Validation / Prognosis
(3/3) Infiltration Process with Respect to Convergence and Gas Generation
Contributions of Department of Waste Disposal and Geomechanics

(3) **Numerical Simulations – Validation / Prognosis**

(3/4a) **Geotecnical Barriers – Analysis of Drift Sealing System**

<table>
<thead>
<tr>
<th>Zeit, [a] x10^4</th>
<th>Hauptspannungen, [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-9.0</td>
<td>-8.0</td>
</tr>
<tr>
<td>-7.0</td>
<td>-6.0</td>
</tr>
<tr>
<td>-5.0</td>
<td>-4.0</td>
</tr>
<tr>
<td>-3.0</td>
<td>-2.0</td>
</tr>
<tr>
<td>-1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>1.4</td>
<td>1.6</td>
</tr>
<tr>
<td>1.8</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Pressure Build-up in Contract Zone

Static Stability?

Functionability?
Contributions of Department of Waste Disposal and Geomechanics

(3) Numerical Simulations – Validation / Prognosis
(3/4b) Geotechnical Barriers – Analysis of Shaft Sealing System

Pore-Pressure in EDZ

Efflux-Rate through EDZ

Static Stability?
Functionality?
Overview

1. Underground Waste Disposal in Germany

2. Specialized Safety Analysis as well as Safety Criteria with Respect to Rock Salt

3. Contributions of Department of Waste Disposal and Geomechanics to Safety Analysis

4. Some Concluding Remarks
What do we have to do?

The human has three ways of acting wisely:

first through contemplation
  – this is the noblest

second by mimicking
  – this is the easiest

third by experience
  – this is the bitter

Konfuzius
Some Concluding Remarks

Thanks for your Attention
Tuesday, October 16, 2012

TOPIC: TECHNICAL / GEOTECHNICAL BARRIERS
THMC Testing of Three bentonites of Potential Use for HLW Repository

Liu Xiaodong

East China Institute of Technology

10/15/2012
1 Test samples

Sample A: GMZ (Na-bentonite from Gaomiaozi deposit, China)
initial water content: 5\% ±

Sample B: MX-80 (virgin MX-80 Na-bentonite, USA)
initial water content: 6\% ±

Sample C: FIM (virgin Friedland Ton bentonite, German)
initial water content: 2\% ±
2 THMC testing design and the installations

C: cooling pipes;  H: heater with the temperature from 90°C to 95°C;  
F: sintered filter;  P: pump for the circulation of 3.5% CaCl$_2$ solution
**Cells**: stainless cell 40mm high with the diameter of 30 mm. Stainless cell was connected with the copper bottom.

**Heater**: the temperature can be adjust in 2°C.

**Thermal Sensor**: digital thermal sensor with the measurement range of -50°C to 150°C.
Circulation Solution:

3.5% CaCl₂ (stimulate the underground water)

Duration of the test:

continuously running in 3 weeks

Thermal gradient:

about 10°C per cm in the cells and a maximum temperature of 95°C at the bottom of the cells
Analyses specimens:

At the end of the thermal/hydrothermal treatment, the compacted bentonite in the cell will be cut into three parts for chemical, microstructure analyses etc.

- Sampling for microstructure analyses - “cold end”
- Sampling for microstructure analyses
- Sampling for microstructure analyses - “hot end”

MX-80

At the end of the thermal/hydrothermal treatment, the compacted bentonite in the cell will be cut into three parts for chemical, microstructure analyses etc.
Purpose of the test:

To reveal the possible changes of
The three bentonites in hydraulic conductivity, expandability, compressibility, microstructural constitution, and mineralogical Compositions.
3 Results of the test

3.1 Chemical changes

Chemical analysis of bentonite individual particles from the cold and hot ends, and the virgin samples were performed by use of EPMA techniques.
Analyses of individual particles of smectite by JXA-8100 EPMA at Key Laboratory of Nuclear Resources and Environment of MIE, ECIT.
<table>
<thead>
<tr>
<th>Sample</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃ (FeO)</th>
<th>CaO</th>
<th>MgO</th>
<th>K₂O</th>
<th>Na₂O</th>
<th>MnO</th>
<th>TiO₂</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMZ “cold-end”</td>
<td>71.16</td>
<td>15.63</td>
<td>2.18</td>
<td>2.35</td>
<td>4.10</td>
<td>0.18</td>
<td>0.91</td>
<td>0.01</td>
<td>0.06</td>
<td>97.18</td>
</tr>
<tr>
<td>GMZ “hot-end”</td>
<td>68.44</td>
<td>19.58</td>
<td>1.90</td>
<td>1.97</td>
<td>4.80</td>
<td>0.10</td>
<td>1.03</td>
<td>0.05</td>
<td>0.00</td>
<td>98.37</td>
</tr>
<tr>
<td>GMZ “virgin”</td>
<td>68.40</td>
<td>21.13</td>
<td>1.41</td>
<td>0.54</td>
<td>4.97</td>
<td>0.02</td>
<td>1.01</td>
<td>0.01</td>
<td>0.02</td>
<td>97.40</td>
</tr>
<tr>
<td>MX-80 “cold-end”</td>
<td>63.58</td>
<td>21.75</td>
<td>3.29</td>
<td>1.31</td>
<td>2.57</td>
<td>0.05</td>
<td>0.66</td>
<td>0.02</td>
<td>0.14</td>
<td>94.15</td>
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<tr>
<td>MX-80 “hot-end”</td>
<td>60.63</td>
<td>20.09</td>
<td>2.77</td>
<td>0.89</td>
<td>3.53</td>
<td>0.06</td>
<td>0.77</td>
<td>0.03</td>
<td>0.10</td>
<td>90.76</td>
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<tr>
<td>MX-80 “virgin”</td>
<td>61.69</td>
<td>22.36</td>
<td>3.50</td>
<td>0.31</td>
<td>2.29</td>
<td>0.20</td>
<td>0.68</td>
<td>0.02</td>
<td>0.10</td>
<td>91.14</td>
</tr>
<tr>
<td>FIM “cold-end”</td>
<td>57.18</td>
<td>27.12</td>
<td>6.56</td>
<td>0.60</td>
<td>2.30</td>
<td>3.87</td>
<td>0.46</td>
<td>0.01</td>
<td>0.14</td>
<td>98.55</td>
</tr>
<tr>
<td>FIM “hot-end”</td>
<td>58.70</td>
<td>26.98</td>
<td>4.71</td>
<td>0.75</td>
<td>1.88</td>
<td>2.43</td>
<td>0.53</td>
<td>0.01</td>
<td>0.31</td>
<td>97.33</td>
</tr>
<tr>
<td>FIM “virgin”</td>
<td>57.59</td>
<td>27.89</td>
<td>4.76</td>
<td>0.16</td>
<td>2.25</td>
<td>2.86</td>
<td>0.40</td>
<td>0.01</td>
<td>0.28</td>
<td>96.20</td>
</tr>
</tbody>
</table>

Chemical Composition of the clay samples by EPMA Analyses (weight %)
- SiO$_2$ increased at the cold and hot ends of GMZ and at the cold end of MX-80
- CaO increased significantly in the cold ends (due to the circulation of 3.5% CaCl$_2$ solution at the cold end of the cells)
- Na$_2$O increased in the hot ends of the samples by migration of Na from the colder clay where Ca$^{2+}$ replaced Na$^+$ as adsorbed cation.
- Fe accumulated in the cold parts of all the clays.
3.2 Minerals and microstructure changes

X-ray diffraction, infrared spectroscopy (FTIR spectroscopy) analyses and the SEM imaging indicated the changes in microstructure and in mineral compositions of the three bentonites.
*neoformed kaolinite with well-pronounced 001 reflection occurred in the interlamellar space of montmorillonite in the hot-end specimen of GMZ

*presence of neoformed illite
fine silica particles precipitated on smectite (montmorillonite) of GMZ, corresponding to the SiO₂ increase by chemical analyses
Neoformed aggregated gypsum (Gyp) crystals precipitated in the void between of montmorillonite particles.
-FIM

• formation of gypsum was indicated by XRD analyses
• Precipitation of silica was documented by FTIR spectroscopy

V = “virgin” material; H = “hot-end” specimen
C = “cold-end” specimen
3.3 Physical properties changes

3.3.1 Hydraulic conductivity and swelling pressure

<table>
<thead>
<tr>
<th>Property</th>
<th>GMZ</th>
<th>MX-80</th>
<th>FIM</th>
</tr>
</thead>
<tbody>
<tr>
<td>ρ/ρd (kg/m³)</td>
<td>1871/1232</td>
<td>1788/1233</td>
<td>1951/1375</td>
</tr>
<tr>
<td>K (m/s)</td>
<td>2.6E-11</td>
<td>2.8E-11</td>
<td>1.2E-11</td>
</tr>
<tr>
<td>ps (MPa)</td>
<td>0.11</td>
<td>0.53</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Hydraulic conductivity and swelling pressure for the hot and cold end specimens for their respective densities after saturation and percolation with 3.5 % CaCl₂ solution for 14 days.

- The hot samples are denser than the “cold” ones
- Significant changes in swelling pressure of hot end samples of GMZ and MX-80
3.3.2. Stress-strain behaviour

Uniaxial loading tests were made of the “hot-end” specimens and of the “virgin” clays with approximately the same density as the “hot-end” specimens.
the “hot-end” specimens appear stiffer than the virgin clay samples and exhibited brittle behaviour at failure
4 Discussion

4.1 Mineralogical changes

Gypsum formed in all three bentonite specimens, kaolinite only appeared in GMZ.

But mineralogical changes were small or moderate in “hot-end” specimens in contrast to the virgin samples.
4.2 Physical properties

The hot-end specimens of all three bentonites become significantly stiffer and more brittle than those of the virgin clays while the compressive strength had dropped. The loss in strength is believed to be related to fissures that did not self-heal.
The drop in swelling pressure of the hot-end specimens can be explained by the precipitation of siliceous components and illite that might welded the montmorillonite lamellae.
Published paper:

Liu Xiaodong, Richard Prikryl and Roland Pusch

Applied Clay Science

Vol. 52, 419-427
Acknowledgements

Experimental hydrothermal treatment, hydraulic conductivity, swelling pressure and uniaxial loading tests for three bentonites were conducted in Lund under the kind guidance of Prof. Roland Pusch.
Thank you!
Experimental investigations on the thermo-hydraulic behaviour of GMZ01 bentonite

Weimin YE
Tongji University
2012. KIT/ Germany
Acknowledgements

Yu C., 2006; Qian L.X, 2007; Niu W.J., 2008; Wan M., 2010;
Pan H., 2010; Wang Q.  

The authors are grateful to the National Natural Science Foundation of China (Projects No. 41030748) and China Atomic Energy Authority (Project [2007]831).
Outline

1 Introduction
2 GMZ bentonite
3 Temperature effects on hydraulic conductivities
   3.1 Saturated hydraulic conductivity
   3.2 Unsaturated hydraulic conductivity
4 Conclusion
1 Introduction (Multi-barrier)

- Parent Rock
- Bentonite
- Canister
- Underground Gellary
- Shaft and tunnel

Parent Rock: 500~1000m
Outline

1 Introduction

2 GMZ bentonite

3 Temperature effects on hydraulic conductivities
   3.1 Saturated hydraulic conductivity
   3.2 Unsaturated hydraulic conductivity

4 Conclusion
2 GMZ bentonite

Xinghe county, the Inner Mongolia Autonomous Region with a distribution of 72 km².

Deposit >160 (120) million t

(Wen Zhijian, 2005)
## GMZ bentonite

### Mineralogical composition of some bentonite (wt %)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Montmorillonite</th>
<th>Quartz</th>
<th>Cristobalite</th>
<th>Feldspar</th>
<th>Plagioclase</th>
<th>Kaolinite</th>
<th>Chalcedony</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMZ</td>
<td>75.4</td>
<td>11.7</td>
<td>7.3</td>
<td>4.3</td>
<td>--</td>
<td>0.8</td>
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<tr>
<td>FEBEX</td>
<td>92 ± 3</td>
<td>2 ± 1</td>
<td>--</td>
<td>2 ± 1</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>MX-80</td>
<td>65-82</td>
<td>4-12</td>
<td>5-8</td>
<td>8.2 ± 2.7</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Kunigel-V1</td>
<td>47</td>
<td>0.6</td>
<td>--</td>
<td>4</td>
<td>--</td>
<td>37</td>
<td></td>
</tr>
</tbody>
</table>

## 2 GMZ bentonite

### Mineralogical composition of some bentonite (wt %)

<table>
<thead>
<tr>
<th>Clay</th>
<th>Montmorillonite</th>
<th>Quartz</th>
<th>Cristobalite</th>
<th>Feldspar</th>
<th>Plagioclase</th>
<th>Kaolinite</th>
<th>Chalcedony</th>
</tr>
</thead>
<tbody>
<tr>
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<td>7.3</td>
<td>4.3</td>
<td>--</td>
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<td></td>
</tr>
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<td>--</td>
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<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>MX-80</td>
<td>65-82</td>
<td>4-12</td>
<td>5-8</td>
<td>8.2 ± 2.7</td>
<td>--</td>
<td>--</td>
<td></td>
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<tr>
<td>Kunigel-V1</td>
<td>47</td>
<td>0.6</td>
<td>--</td>
<td>4</td>
<td>--</td>
<td>37</td>
<td></td>
</tr>
</tbody>
</table>

## Cation Exchange Capacity of some bentonite

<table>
<thead>
<tr>
<th>Clay</th>
<th>CEC (meq/100 g)</th>
<th>E(K+)</th>
<th>E(Na⁺)</th>
<th>E(1/2Ca²⁺)</th>
<th>E(1/2Mg²⁺)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMZ</td>
<td>77.30</td>
<td>2.51</td>
<td>43.36</td>
<td>29.14</td>
<td>12.33</td>
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<tr>
<td>FEBEX</td>
<td>111 ± 9</td>
<td>22.2 ± 1.8</td>
<td>25.53 ± 2.07</td>
<td>42.18 ± 3.42</td>
<td>31.08 ± 2.52</td>
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<tr>
<td>MX-80</td>
<td>78.7 ± 4.8</td>
<td>1.3 ± 0.2</td>
<td>66.8 ± 4</td>
<td>6.6 ± 0.33</td>
<td>4 ± 0.3</td>
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<tr>
<td>Kunigel-V1</td>
<td>73.2</td>
<td>0.9</td>
<td>40.5</td>
<td>28.7</td>
<td>3.0</td>
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</table>

## GMZ bentonite

### Main physical properties of some bentonite

<table>
<thead>
<tr>
<th>Clay</th>
<th>Gs</th>
<th>$w_L$(%)</th>
<th>$w_p$(%)</th>
<th>Ip</th>
<th>S (m$^2$/g)</th>
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</thead>
<tbody>
<tr>
<td>GMZ</td>
<td>2.66</td>
<td>313</td>
<td>38</td>
<td>275</td>
<td>570</td>
</tr>
<tr>
<td>FEBEX</td>
<td>2.7</td>
<td>102±4</td>
<td>53±3</td>
<td>42±7</td>
<td>725</td>
</tr>
<tr>
<td>MX-80</td>
<td>2.76</td>
<td>520</td>
<td>42</td>
<td>478</td>
<td>562</td>
</tr>
<tr>
<td>Kunigel-V1</td>
<td>2.79</td>
<td>415</td>
<td>32</td>
<td>383</td>
<td>687</td>
</tr>
</tbody>
</table>

**First choice in China** (Ye et al, 2010)

Outline

1 Introduction

2 GMZ bentonite

3 Temperature effects on hydraulic conductivities
   3.1 Saturated hydraulic conductivity
   3.2 Unsaturated hydraulic conductivity

4 Conclusion
3.1.1 Saturated hydraulic conductivity

**Apparatus**

- Screw cap
- Sealing ring
- Porous stone
- Valve A
- Valve B
- Sample
- GDS controller
- Oven (Resolution: ±0.1°C)
- Pressure transducer
- Data Logger

A cylindrical specimen with a height of 10 mm, diameter of 50 mm
3.1.2 Test procedures

- GMZ01 bentonite with an initial water content of 10.6%.
- Cylindrical specimens were compacted to dry density of 1.70 Mg/m³ for swelling pressure tests at temperatures.
- After swelling pressure test at 40 °C, saturated permeability tests at temperature path 50→60→50→20 °C were conducted.
3.1.3 Results and discussion

1) Temperature influence on swelling pressure

Evolution of swelling pressure with time at different temperatures

FEBEX bentonite (Villar, 2008)

Cui et al. (2002) and Tang et al. (2008)
2) Temperature influences on saturated hydraulic conductivity

Evolution of hydraulic conductivity with time of GMZ01 bentonite

(Villar and Lloret, 2008)
3) A hydraulic conductivity model considering temperature effects

- The influences of temperature mainly depend on the influences of temperature on $\eta$ (Philip, 1963; Hopmans, 1986).

$$k_s = k_{in} \rho_w g / \eta(T)$$

where $k_{in}$ is intrinsic hydraulic conductivity, $\rho_w$ water density, $g$ acceleration of gravity and $\eta(T)$ water viscosity as a function of temperature.
3) A hydraulic conductivity model considering temperature effects

- the influences of temperature mainly depends on the influences of temperature on $\eta$ (Philip, 1963; Hopmans, 1986).

$$k_s = k_{in} \rho_w g / \eta(T)$$

- where $k_{in}$ is intrinsic hydraulic conductivity, $\rho_w$ water density, $g$ acceleration of gravity and $\eta(T)$ water viscosity as a function of temperature.
3) A hydraulic conductivity model considering temperature effects

Water kinematic viscosity versus temperature

\[ \eta(T) = 0.0002601 + 0.001517 \exp[-0.034688 \times (T - 273)] \]
3) A hydraulic conductivity model considering temperature effects

\[ k_s = \frac{1.58 \times 10^{-20} \rho_w g}{0.0002601 + 0.001517 \exp\left[-0.034688 \times (T - 273)\right]} \]
3) A hydraulic conductivity model considering temperature effects

\[
k_s = \frac{1.58 \times 10^{-20} \rho_w g}{0.0002601 + 0.001517 \exp\left[-0.034688 \times (T - 273)\right]}
\]

Experiment values

Increase predicted by change in water viscosity

FEBEX bentonite at 1.38 Mg/m³ (Villar, 2004)
3) A hydraulic conductivity model considering temperature effects

\[ k_s = k_{in} \rho_w g / \eta(T) \]

- Temperature effects on the intrinsic hydraulic conductivity should be considered.
- Under confined conditions, the microstructure of the saturated GMZ01 bentonite changes little with temperature (Wan, 2010).
- Heating may cause movement of high-density adsorbed water to large pores where it becomes free water (Villar, 2004).
3) A hydraulic conductivity model considering temperature effects

\[ y = -0.0049x - 42.65 \quad R^2 = 0.9859 \]

\[ y = -0.0048x - 44.502 \quad R^2 = 0.957 \]

\[ y = 0.0079x - 45.252 \quad R^2 = 0.7833 \]

- 1.4 kg/cm³ (Cho, 1999)
- 1.6 kg/cm³ (Cho, 1999)
- 1.4 kg/cm³ (Rivas, 1991)
3) A hydraulic conductivity model considering temperature effects

- Villar (2001) proposed a relationship:

\[ k_{in} = \exp(-52.94 + 7.6e) \]

\[ k_{in} = \exp(\alpha + \beta \times (T - 273)) \]

\[ k_s = \frac{k_{in}(T) \rho_w g}{\eta(T)} = \frac{\exp(\alpha + \beta \times (T - 273)) \rho_w g}{0.0002601 + 0.001517 \exp[-0.034688 \times (T - 273)]} \]
3) A hydraulic conductivity model considering temperature effects

With the saturated hydraulic conductivity values measured at 20 and 40°C, \( \alpha = -45.703 \) and \( \beta = 0.0054 \).

\[
k_s = \frac{k_{in}(T)\rho_w g}{\eta(T)} = \frac{\exp(-45.703 + 0.0054 \times (T - 273))\rho_w g}{0.0002601 + 0.001517 \exp[-0.034688 \times (T - 273)]}
\]

With this equation, the values at 50 and 60°C can be calculated.
3) A hydraulic conductivity model considering temperature effects

Outline

1 Introduction
2 GMZ bentonite
3 Temperature effects on hydraulic conductivities
   3.1 Saturated hydraulic conductivity
   3.2 Unsaturated hydraulic conductivity
4 Conclusion
3.2 Unsaturated hydraulic conductivity

- The instantaneous profile method (Ye et al., 2009) was adopted in this study.

- Tests at 40 and 60 °C were performed and results were analyzed with results at 20 °C*

- **Determination of WRCs** at various temperatures

3.2.1 Determination SWRCs at various temperatures

For high suctions:

Oven (temperature control ± 0.1°C)

Salt solution

Sample

Salt

Air pump
## Solutions and corresponding suctions /MPa (Tang et al, 2005)

<table>
<thead>
<tr>
<th></th>
<th>20°C</th>
<th>40°C</th>
<th>80°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiCl₂</td>
<td>309</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MgCl₂</td>
<td>150</td>
<td>155</td>
<td>181</td>
</tr>
<tr>
<td>K₂CO₃</td>
<td>113</td>
<td>117</td>
<td>139.8</td>
</tr>
<tr>
<td>Mg(NO₃)₂</td>
<td>82</td>
<td>98</td>
<td></td>
</tr>
<tr>
<td>NaNO₂</td>
<td>57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NaCl</td>
<td>38</td>
<td>38.8</td>
<td>39.7</td>
</tr>
<tr>
<td>(NH₄)₂SO₄</td>
<td>24.9</td>
<td>30.8</td>
<td></td>
</tr>
<tr>
<td>KCl</td>
<td>21</td>
<td>26.8</td>
<td>31.8</td>
</tr>
<tr>
<td>ZnSO₄</td>
<td>12.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KNO₃</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K₂SO₄</td>
<td>4.2</td>
<td>5.1</td>
<td>5.8</td>
</tr>
</tbody>
</table>
3.2.1 Determination SWRCs at various temperatures

For low suctions:

- Oven (temperature control ±0.1°C)
- Polyethylene Membrane
- Semi-permeable Membrane
- Porous Stone
- Specimen
- Rubber Ring
- Steel Bracket
- Magnetic Stirrer
- PEG20000 Solution
Constraint conditions and temperature control

Digital oven

20, 40 and 80 °C were selected

unconfined

confined
Hysteresis behaviors of unconfined compacted GMZ01 bentonite following different dry/wet path at 40°C
Water Retention Curves at 20°C (Chen et al, 2006)

- At suctions higher than 4 MPa, the WRC under confined and unconfined conditions are almost the same.
- At suctions lower than 4.2 MPa, the confined condition gave much lower water content.
Hysteresis behavior of GMZ01 Bentonite (40°C)

Hysteresis becomes larger in low suctions
Hysteresis behavior of GMZ Bentonite

Hysteresis loop of SWRC at 20°C is larger than that at 40°C.

Hysteresis deviates as temperature rises.

Ye et al, J of Central South University of Tech., 2009, Vol. 16(1): 143-148
3.2.1 Determination SWRCs at various temperatures

- Water retention capacity decreases as temperature rises.
- Temperature influence depends on suction.
3.2.2 Infiltration tests at various temperatures

Schematic layout of the temperature controlled infiltration test
3.2.2 Infiltration tests at various temperatures

Evolution of the relative humidity of confined GMZ01 with time at 40°C
3.2.2 Infiltration tests at various temperatures


Change of unsaturated hydraulic conductivity with suction for the confined GMZ01 at 60°C
3.2.2 Infiltration tests at various temperatures

As in the first stage, water transfer is primarily governed by the network of large pores and these large pores are progressively decreasing in quantity and in size, resulting in hydraulic conductivity decreases. After completion of this large-pore clogging by gel creation, a normal conductivity increase with suction decrease is observed (Ye et al., 2009).
3.2.2 Infiltration tests at various temperatures

Hydraulic conductivity increases as temperature rises.

Temperature influence depends on suction

Outline

1 Introduction
2 GMZ bentonite
3 Temperature effects on hydraulic conductivities
   3.1 Saturated hydraulic conductivity
   3.2 Unsaturated hydraulic conductivity
4 Conclusion
4 Conclusion

- The swelling pressure of the compacted GMZ01 bentonite increases with temperature rise.
- The saturated hydraulic conductivity of the compacted GMZ01 bentonite increases with temperature rise. Temperature changing paths (heating or cooling) have little impact on the saturated hydraulic conductivity.
4 Conclusion

- The revised model accounts for both the water viscosity and effective flow cross area of porous channels can well reflect the temperature influences on saturated flow.

- For all the temperatures considered, the unsaturated hydraulic conductivity decreases slightly in the first stage of hydration. The value of the hydraulic conductivity becomes constant as hydration progresses. Finally, the hydraulic conductivity increases rapidly with suction decreases when saturation is approached.
Under confined conditions, the hydraulic conductivity increases as temperature increases, at a rate that decreases with temperature rises. Also, the influence of temperature on the hydraulic conductivity is quite suction-dependant.
7-10 July 2013, Shanghai,

http://www.unsat-waste2013.cn
Many thanks for your attention!
Initial Results on Stability of natural GMZ Ca-Bentonite & modified Na- Bentonite under Thermal/Radiation Aging

By: Yang Zhongtian

China Institute for Radiation Protection (CIRP, CNNC)

E-mail: ztyang@263.net
Mobile phone: 13934546499
Contents

1 Introduction
2 Experimental
3 Results
4 Initial conclusion
5 Recent work
1 Introduction

- GMZ Bentonite from inner Mongolia has been recommended as potential buffer material in China.
- Its stability under near field condition should be investigated.
Requirements

• near field condition

dose rate: 0.2~2 Gy/h (γ, n)
temp.: 90°C

thermal period lasted: hundreds ~ thousands years
temp.: 90°C → disposal Environment temp.
total dose in thermal period: 0.7 MGy ~ ? MGy

(Applied Clay Science 43 (2009)143-149)

what will happen?
how to simulate and validate?
Methodology

- **Problem:** Have to make predictions of time-temperature-dose rate superposition at experimentally inaccessible times

- **How to solve:** mainly two experiment methods
  1. **Simulating method**
     - similar to real disposal condition (low temp., low dose rate, short time) → extrapolate to hundreds ~ thousands years
  2. **Accelerating method**
     - adopting accelerated condition (high temp., high dose rate, short time) → results stand for the long term effect

How to verify the methods and results with sufficient confidence?
Which one would be better?
2 Experimental

2.1 Material

- **Ca-bentinote**: exploited directly from GMZ mine and prepared by xinghe county dope factory
  - Apparent density: 0.51 g/cm³

- **Modified-Na-bentonite**: prepared by reaction of Ca-bentinote with Na₂CO₃ solution by xinghe county dope factory
  - Apparent density: 0.46 g/cm³
  - Water content: 7.3%

- Bentonite be used as got without any further processing.
2 Experimental

2.2 Thermal treatment

- Ca-bentinite \( \text{M-Na-bentonite} \) was put in PTFE bottles and sealed
- Temp.: 120°C, 150 °C, 180 °C
- Duration: 3000h, 6000h, 9000h
2 Experimental

2.3 Irradiation treatment

- **M-Na-bentonite** was put in canister made of stainless steel (thickness: 1mm; diam.: 10cm; Height: 60cm) and sealed

- **γirradiation** at R.T.
  - Dose rate: 1.7 kGy/h
  - Cumulative dose: 1000kGy, 2000kGy, 3000kGy, 4000kGy, 5000kGy
2 Experimental

2.4 Irradiation- Thermal sequential treatment

After γ irradiation, canister with M-Na-bentonite were put into an oven and treated at following condition

Temp.: 120℃, 150 ℃, 180 ℃

Time: 3000h, 6000h, 9000h
2 Experimental

2.5 Analysis

XRD

- qualitative analysis: by both CIRP and Zhejiang University
- quantitative analysis: Zhejiang University

DX-2700 in CIRP
3 Results

3.1 Comparison of thermal treatment results for M-Na-bentonite & Ca-bentonite

XRD spectrum of M-Na-bentonite aging at 180°C
Conclusion: **Na-bentonite** is more stable than **Ca-bentonite** under thermal aging.
3 Results

3.2 Thermal treatment of M-Na-bentonite

- For 120°C, 150°C, 180°C--3000h: small change
- For 120°C, 150°C, 180°C--6000h: obvious change
- For 120°C, 150°C, 180°C--9000h: new diffraction peak of illite

Conclusion:
- Temperature effect is small during this interval
- Time effect is more obvious
3 Results

3.3 γ Irradiation treatment of Na-bentonite

(1) qualitative analysis

- almost no change
3 Results

(2) Quantitative analysis

- Similar result as for that of thermal treatment,
- Small change of 2-Theta & d value
- Decrease of crystal size

<table>
<thead>
<tr>
<th>No.</th>
<th>condition</th>
<th>2-Theta (°)</th>
<th>d (Å)</th>
<th>Height</th>
<th>Area(a1)</th>
<th>FWHM</th>
<th>XS (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>blank</td>
<td>7.074</td>
<td>12.4858</td>
<td>7401</td>
<td>139996</td>
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<td>158</td>
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<tr>
<td>2</td>
<td>1000 kGy</td>
<td>7.053</td>
<td>12.5229</td>
<td>6792</td>
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<td>3</td>
<td>2000 kGy</td>
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<td>12.4032</td>
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<td>4</td>
<td>3000 kGy</td>
<td>7.085</td>
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<td>5</td>
<td>4000 kGy</td>
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<td>12.4433</td>
<td>7778</td>
<td>160334</td>
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<td>146</td>
</tr>
</tbody>
</table>
3 Results

3.4 Irradiation- Thermal sequential treatment of M-Na-bentonite

(1) qualitative analysis

- 1000kGy-180℃-6000h
  - 5000kGy-180℃-6000h:
    - Obvious change of smectite diffraction peak

- 1000kGy-120℃-9000h
  - 5000kGy-180℃-9000h:
    - Disappear of smectite diffraction peak;
    - Formation of new diffraction peak of illite.
## (2) quantitative analysis

<table>
<thead>
<tr>
<th>No.</th>
<th>Condition</th>
<th>2-Theta衍射角</th>
<th>d (Å) 层间距</th>
<th>FWHM</th>
<th>XS (Å)晶胞尺寸</th>
</tr>
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<tbody>
<tr>
<td>1</td>
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<td>12.4858</td>
<td>0.551</td>
<td>158</td>
</tr>
<tr>
<td>2</td>
<td>1000 kGy</td>
<td>7.053</td>
<td>12.5229</td>
<td>0.625</td>
<td>137</td>
</tr>
<tr>
<td>3</td>
<td>1000KGY-120℃-6000h</td>
<td>7.131</td>
<td>12.3869</td>
<td>0.726</td>
<td>116</td>
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<td>4</td>
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<td>11.5953</td>
<td>1.367</td>
<td>60</td>
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<tr>
<td>5</td>
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<td>7.370</td>
<td>11.9849</td>
<td>1.454</td>
<td>56</td>
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<tr>
<td>6</td>
<td>5000 kGy</td>
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<td>12.4433</td>
<td>0.590</td>
<td>146</td>
</tr>
<tr>
<td>7</td>
<td>5000KGY-120℃-6000h</td>
<td>7.084</td>
<td>12.4676</td>
<td>0.592</td>
<td>146</td>
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<tr>
<td>8</td>
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<td>12.0363</td>
<td>1.208</td>
<td>68</td>
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<tr>
<td>9</td>
<td>5000KGY-180℃-9000h</td>
<td>7.315</td>
<td>12.0745</td>
<td>1.407</td>
<td>58</td>
</tr>
</tbody>
</table>
4 Initial conclusions

(1) General effects: γ irradiation-thermal sequential treatment > thermal treatment > γ irradiation.

(2) During irradiation-thermal sequential treatment, crystal size decreases with the increase of time and temperature; but the temperature effect is small; time effect is more obvious.

(3) Even for weak aging condition: 1000kGy-120°C, diffraction peak of smectite disappear absolutely after 9000h (only more than 1 year) treatment, it means that modified-GMZ Na-bentonite is not stable under such condition.
5 Plan for future work

- **Guess**: effects of simultaneous γ irradiation / thermal treatment ≥ γ irradiation-thermal sequential treatment
New Experiment: Dose rate effect
simultaneous γ irradiation / thermal treatment (~90°C)
# Detailed irradiation condition

<table>
<thead>
<tr>
<th>Cumulative Dose</th>
<th>Dose Rate</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>610 Gy/h</td>
<td>170 Gy/h</td>
<td>85 Gy/h</td>
<td></td>
</tr>
<tr>
<td>0.28 MGy</td>
<td>time</td>
<td></td>
<td></td>
<td>3401 h</td>
</tr>
<tr>
<td>Sample No.</td>
<td></td>
<td></td>
<td></td>
<td>1 #</td>
</tr>
<tr>
<td>0.37 MGy</td>
<td>time</td>
<td>608 h</td>
<td>2180 h</td>
<td>4360 h</td>
</tr>
<tr>
<td>Sample No.</td>
<td></td>
<td>11 #</td>
<td>5 #</td>
<td>2 #</td>
</tr>
<tr>
<td>0.74 MGy</td>
<td>time</td>
<td></td>
<td></td>
<td>4360 h</td>
</tr>
<tr>
<td>Sample No.</td>
<td></td>
<td></td>
<td></td>
<td>3 #</td>
</tr>
</tbody>
</table>
Diffraction pattern : 0.37MGy

(11#-610Gy/h, 5#-170Gy/h, 2#-85Gy/h)
<table>
<thead>
<tr>
<th>No.</th>
<th>condition</th>
<th>2-Theta (度)</th>
<th>d value (Å)</th>
<th>FWHM</th>
<th>XS (Å)</th>
<th>Area</th>
<th>Height</th>
<th>Peak Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>blank</td>
<td>—</td>
<td>7.096</td>
<td>12.4469</td>
<td>0.632</td>
<td>136</td>
<td>27252</td>
<td></td>
<td>1042</td>
</tr>
<tr>
<td>11#</td>
<td>610Gy/h-623h-0.37MGy</td>
<td>7.054</td>
<td>12.5215</td>
<td>0.561</td>
<td>155</td>
<td>28485</td>
<td></td>
<td>1205</td>
</tr>
<tr>
<td>5#</td>
<td>170Gy/h-2180h-0.37MGy</td>
<td>7.194</td>
<td>12.2781</td>
<td>1.008</td>
<td>82</td>
<td>22289</td>
<td></td>
<td>541</td>
</tr>
<tr>
<td>2#</td>
<td>85Gy/h-4360h-0.37MGy</td>
<td>7.252</td>
<td>12.1798</td>
<td>1.038</td>
<td>80</td>
<td>23290</td>
<td></td>
<td>548</td>
</tr>
</tbody>
</table>

With dose rate ↓: 2-Theta ↑, d value ↓, XS (Å) ↓.

Concl.: There exist dose rate effect.
Diffraction pattern:
85 Gy/h (1#-0.28 MGy / 2#-0.37 MGy)
<table>
<thead>
<tr>
<th>No.</th>
<th>condition</th>
<th>2-Theta (度)</th>
<th>d value (Å)</th>
<th>FWHM</th>
<th>XS (Å) 冉胞尺寸</th>
<th>Area</th>
<th>Height 峰高</th>
</tr>
</thead>
<tbody>
<tr>
<td>blank</td>
<td>—</td>
<td>7.096</td>
<td>12.4469</td>
<td>0.632</td>
<td>136</td>
<td>27252</td>
<td>1042</td>
</tr>
<tr>
<td>1#</td>
<td>85Gy/h-3401h-0.28MGy</td>
<td>7.199</td>
<td>12.2700</td>
<td>0.888</td>
<td>94</td>
<td>23113</td>
<td>643</td>
</tr>
<tr>
<td>2#</td>
<td>85Gy/h-4360h-0.37MGy</td>
<td>7.252</td>
<td>12.1798</td>
<td>1.038</td>
<td>80</td>
<td>23290</td>
<td>548</td>
</tr>
</tbody>
</table>
Diffraction pattern:
170 Gy/h-（5#-0.37MGy/3#-0.74MGy）
<table>
<thead>
<tr>
<th>No.</th>
<th>condition</th>
<th>2-Theta (度)</th>
<th>d value (Å)</th>
<th>FWHM</th>
<th>XS (Å) 晶胞尺寸</th>
<th>Area</th>
<th>Height 峰高</th>
</tr>
</thead>
<tbody>
<tr>
<td>blank</td>
<td>－</td>
<td>7.096</td>
<td>12.4469</td>
<td>0.632</td>
<td>136</td>
<td>27252</td>
<td>1042</td>
</tr>
<tr>
<td>5#</td>
<td>170Gy/h-2180h-0.37MGy</td>
<td>7.194</td>
<td>12.2781</td>
<td>1.008</td>
<td>82</td>
<td>22289</td>
<td>541</td>
</tr>
<tr>
<td>3#</td>
<td>170Gy/h-4360h-0.74MGy</td>
<td>7.612</td>
<td>11.6040</td>
<td>1.176</td>
<td>70</td>
<td>1101</td>
<td>26</td>
</tr>
</tbody>
</table>

With dose ↑: 2-Theta ↑, d value ↓, XS (Å) ↓.

Concl.: There exist dose effect.
At condition:  
90°C-170Gy/h-0.74MGy, after 4360h (6 months) there appears an transition diffraction peak  
This proves that: GMZ bentonite is not stable under combined radiation/thermal aging, and montmorillonite will transform to illite in short time.

Results: IR、STA、Kd(Cs-137), till 2013
Thanks for your Attention!
THM Behaviour of Clay Host Rocks for Disposal of Radioactive Waste

Chun-Liang Zhang
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS)
Repository Safety Research Division
Braunschweig, Germany
URLs in clay formations

**Callovo-Oxfordian Argillite** at Bure in France

- **clay content**: 40 – 45 %
- **water content**: 7.7 %
- **dry density**: 2.30 g/cm³
- **porosity**: 16.0 %
- **uniaxial strength**: 20 – 30 MPa
- **permeability**: < 10⁻²⁰ m²

**Opalinus Clay** at Mont Terri in Switzerland

- **clay content**: 58 – 76 %
- **water content**: 6.7 %
- **dry density**: 2.35 g/cm³
- **porosity**: 15.0 %
- **uniaxial strength**: 10 – 15 MPa
- **permeability**: < 10⁻²⁰ m²
<table>
<thead>
<tr>
<th>Project</th>
<th>Investigations of</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODEX-REP</td>
<td>HM behaviour of the COX argillite at Bure</td>
</tr>
<tr>
<td>Pre-Project Bure</td>
<td>THM behaviour of the COX argillite at Bure</td>
</tr>
<tr>
<td>HED Experiment</td>
<td>Thermal effects on the Opalinus clay at Mont Terri</td>
</tr>
<tr>
<td>VE Experiment</td>
<td>Ventilation effects on the Opalinus clay at Mont Terri</td>
</tr>
<tr>
<td>NP-PRO</td>
<td>Damage and self-sealing of clay rocks</td>
</tr>
<tr>
<td>TIMODAZ</td>
<td>Thermal impact on long-term development of EDZ</td>
</tr>
<tr>
<td>BET / HG-C</td>
<td>Gas migration in clay formation</td>
</tr>
<tr>
<td>THM-TON</td>
<td>THM-Processes in the COX argillite around HLW</td>
</tr>
<tr>
<td>FEBEX</td>
<td>THM behaviour of bentonite buffer around HLW</td>
</tr>
<tr>
<td>EBS</td>
<td>Hydration of bentonites as sealing material</td>
</tr>
<tr>
<td>SWELLING</td>
<td>Swelling of bentonites under saline conditions</td>
</tr>
<tr>
<td>KENTON</td>
<td>Water/gas two-phase-flow in clay-based mixtures</td>
</tr>
<tr>
<td>SB Experiment</td>
<td>Self-sealing barriers of clay-based mixtures</td>
</tr>
</tbody>
</table>

Field observations ↔ Laboratory tests ↔ Numerical modelling
MODEX-REP: GRS lab tests on drilling cores

- Physical properties
- Permeability
- Short-term behaviour
- Long-term behaviour
Ventilation Experiment (VE): In-situ measurements

**VE Geoelectrics: Electrode Array**

- **SA**: Mini-Piezometers
- **SB**: Humidity sensors
- **SC**: TDRs
- **SD**: Extensometers
- **SE**: Geoelectric

![Diagram of electrode array with measurements and colors indicating different values.]

- **BORDER AREA**
- **Forward door**
- **MI**
- **MTM 55,54 m**
- **7 m**
- **2,30 m**
- **2,40 m**
- **2,30 m**
- **Rear door**
- **DI**
- **MTM 45,54 m**

![Images of workers at the site.]

![Close-up image of equipment setup.]

---

Change1-25/8

- **(2D)**
- **19 May 2004**
- **0 0.5 1 x / m**
- **-0.5 0 1 z / m**
- **3.0**
- **2.8**
- **2.6**
- **2.4**
- **2.2**
- **2.0**
- **1.8**
- **1.6**
- **1.4**
- **1.2**
- **1.0**

---
Ventilation Experiment (VE): Lab tests

Opalinus clay at Mont Terri

- Relative humidity of airflow (%)
  - Test data: 98%
  - Model: relative humidity
- Water content (%)
  - Test data: 90%
- Model: water content

Strain (%)
- Test data: compression, extension
- Model:
  - Axial
  - Radial
  - Volume

Time (day)

Images of test samples.
SB Experiment: Self-sealing of clay-based barriers

Distance to bottom (m):

- 0
- 0.2
- 0.4
- 0.6
- 0.8
- 1

35clay/65sand mixture

Water injection pressure = 1 MPa

Degree of water saturation [%]
Re-saturation of Clay/Sand Mixtures

Test data obtained on MX-80 bentonite

Modelling results for FEBEX bentonite (code: CODE-BRIGHT)
HE-D heating experiment

**HE-D Experiment at URL Mont Terri**

- **Objective:** Understanding of THM processes in clay
- **Measurement:**
  - Temperature
  - Pore-water pressure
  - Gas migration
  - Deformation
- **Modelling**

Heater borehole: D = 30 cm, L = 14 m
24 boreholes
more than 80 instruments
HE-D Experiment: temperature and pore-water pressure

![Graph showing temperature and pore-water pressure over time]

- Temperature (°C) vs. Time (day)
- Pore water pressure (MPa) vs. Time (day)

Legend:
- A = borehole
- B = packer
- C = steel
- D = test interval
- E = Opalinus Clay
- F = filled with resin

- Initial state
- Power interruption
- Cooling
- Heater/rock interface
- Failure of heater-packer
- Borehole drilling
- Power interruption

Parameters:
- Heater 2
- Initial state
- Power interruption
- Cooling
HE-D Experiment: Large-scale heating test

Sample: D=260mm, L=700mm

GRS-mini-packers
(D=10mm, L=30mm)

Temperature sensors
PT100

Confining stress = 8 MPa
Heater temperature = 80°C, Boundary temperature = 30°C
Water pressure at top = 0 MPa, Water pressure at bottom = 1 MPa
Results of the large-scale heating test

Thermal conductivity
Specific heat capacity
Thermal expansion coefficient of the solid grains
Thermal expansion coefficient of the pore water
Thermal expansion coefficient of the rock mass
Elastic modulus
Poisson’s ratio
Intrinsic permeability

\[ \lambda = 1.7 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1} \]
\[ C = 800 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1} \]
\[ \alpha_s = 1.5 \cdot 10^{-6} \text{ K}^{-1} \]
\[ \alpha_w = 3.4 \cdot 10^{-4} \text{ K}^{-1} \]
\[ \alpha_m = 1.7 \cdot 10^{-5} \text{ K}^{-1} \]
\[ E = 6680 \text{ MPa} \]
\[ \nu = 0.33 \]
\[ k = 2 \cdot 10^{-20} \text{ m}^2 \]
Coupled THM Modelling (CODE-BRIGHT)

- **Balance of energy:**

\[
\frac{\partial}{\partial t}\left[E_s \rho_s (1 - \phi) + E_l \rho_l S_l \phi + E_g \rho_g S_g \phi \right] + \nabla \cdot \left( i_c + j_{Es} + j_{El} + j_{Es} \right) = f^E
\]

- **Balance of water mass:**

\[
\frac{\partial}{\partial t} \left( \theta^w S_c \phi + \theta^w S_g \phi \right) + \nabla \cdot \left( \hat{j}^w + \hat{j}^w \right) = f^w
\]

- **Balance of air mass:**

\[
\frac{\partial}{\partial t} \left( \theta^a S_c \phi + \theta^a S_g \phi \right) + \nabla \cdot \left( \hat{j}^a + \hat{j}^a \right) = f^a
\]

- **Balance of solid mass:**

\[
\frac{\partial \theta^{s}}{\partial t} (1 - \phi) + \nabla \cdot (\hat{j}^s) = 0
\]

- **Stress equilibrium:**

\[
\nabla \cdot \sigma + b = 0
\]

- **Heat transport:**

  - conduction, advection with water/vapour flow
  - Water flow: advection and vapour diffusion
  - Air flow: advection and dissolution in liquid water
  - Thermo-elasto-plastic model: thermal expansion/consolidation, swelling/shrinking
Modelling of the HE-D Heating Experiment
Damage tests

Triaxial compression test

- Deviatoric stress (MPa)
- Axial strain (%)
- Volumetric strain (%)

- \( \sigma_3 = 8 \text{ MPa} \)
- Onset of dilatancy
- Failure

Opalinus clay samples after failure

EDZ evolution

Far-field < 2 m
Long-term creep tests

Callovo-Oxfordian specimens

Axial strain (%)

Time (day)

Axial stress (MPa):

creep rate: \(6.7 \times 10^{-11} \text{ 1/s}\)

4.4 \times 10^{-11} \text{ 1/s}

Long-term deformation

\rightarrow \text{drift convergence}

\rightarrow \text{compaction of barriers}

\rightarrow \text{re-healing of EDZ}

Creep deformation

EDZ

barrier

0.0
0.1
0.2
0.3
0.4
0.0
0.1
0.2
0.3
0.4
50
100
150
200
250

0.0
0.2
0.4
0.6
0.8
2
4.95
463.4 m
474.2 m
487.1 m
505.7 m

0.0
0.2
0.4
0.6
0.8
2
4.95
463.4 m
474.2 m
487.1 m
505.7 m
Sealing tests on damaged samples by re-compaction

Sealing / healing

Callovo-Oxfordian argillite at Bure

\[ \sigma_1 = \sigma_2 = \sigma_3 \]

\[ \sigma_1 \neq \sigma_3 = 3\text{MPa} \]

\[ \sigma_1 = 3.3 \cdot \sigma_3 \]

\[ \sigma_1 = 6.5 \cdot \sigma_3 \]

Re-loading

Water re-saturation
Sealing tests by water re-saturation

Callovo-Oxfordian argillite at Bure

Test conditions:
- confining stress = 1.5 MPa
- injection pressure = 0.75 bar
- before water injection

Test conditions:
- confining stress = 2.4 MPa
- injection pressure = 20 bar
- after water injection

Sample 1
Sample 2

Re-sealed samples show the same permeability as that of intact clay rock

\[ K = 10^{-21} \text{ m}^2 \]
Conclusions

The studied clay rocks exhibit that

- The deformation is dominated by elasto-plasticity with dilatancy at high stresses
- Above the damage boundary, shear and tensile fracturing leads to failure
- The damage-induced permeability increase occurs only at low confining stresses
- The fracture closure & permeability decrease is dominated by the normal stress
- The effective stress is dominated by the swelling pressure acting in bound porewater
- The swelling pressure & strain depends on water saturation & confining conditions
- The sealing fractures is strongly enhanced by water flow and can be resealed to the intact rock state under the repository conditions
- Only positive rather than negative thermal effects are observed with respect to the integrity and stability of the clay host formations
Bentonites in HLRW systems

Stephan Kaufhold
Reiner Dohrmann
One of today's big challenges:

- Corrosion
- Erosion

+ Stability: cement water
+ Stability: drying
+ Stability: salt solutions
+ Stability: radiation

+ Sealing (swelling capacity)

+ T conductivity (radionuclide adsorption)
+ Retention (radionuclide adsorption)

Safe disposal of high level radioactive waste (HLRW) option: Bentonite barrier
Introduction – aim of BGR bentonite study

Bentonites are rather different!!!!!!

Bentonites cannot be generalized,
   e.g. the corrosion rate determined with one bentonite does not apply to all others.

For the determination of the actual ranges of e.g. corrosion rates (or whatever) different bentonites have to be compared.

Therefore, BGR established a significant sample set which is used to compare performance and properties

   e.g.: compare Fe content with a specific performance parameter (e.g. temperature stability)
Introduction - Sample base

USA
Brazil
Argentina
Indonesia
India
Russia
Georgia
Armenia
Europe:
Spain
Italy
Greece
Slovakia
Germany
Romania
England
Hungary
CzechR.
Morocco
Introduction - Sample base

All samples (except for 4) were available as raw materials.
Characterisation– mineralogical composition (charge 1)

kaolinite

3

3

4

3

4

5

chlorite
3

cristobalite

0

1

1

2

1

2 17 5

2

1

6

1
0

ilmenite

1

0

2

3

1

1

1

1

goethite
1

0

0

5

0

1

2

2

3

7

7

heulandite

1

1

analcime

1

1

1

2 10 2

1

4 10 1 13 1

1 12

3

8

2

6 23 7

0

3 16 22 11 6 11

5

8

9

0

1

3

2

2

3

4

1

4

1

1

1

0

0

1

1

1

2

18 19 7

5

2

8

4

1

3

2

0

0

1

1

0

0

0

1

3

2

2

5

8

5 18 8 10 12 5

4

5

1

1

1
1

1

0

4

0

4

1

2

1

5

7

4

0
1

1

1


1
1

1

1
1

0
1

17

pyrite

1

1

1

0

2

6

7
1

8

8

8

n.d. B-38

n.d. B-37

63 B-38

75 B-36

41 B-35

77 B-34

88 B-33

92 B-32

4

clinopt

fluorapatite

2
0

1
9

gypsum

4

9

2

1
8

barite

3

6

6

dolomite
feldspars

6

2
1

0

1

6

hematite

calcite

31

2

quartz

rutile+ anatase

81 B-31

29

80 B-37

4 17

37 B-30

89 B-29

69 B-28

84 B-27

86 B-26

61 B-25

80 B-24

80 B-23

3

76 B-22

4

80 B-21

86 B-20

19 5

75 B-19

92 B-18

88 B-17

70 B-16

79 B-15

88 B-14

84 B-13

91 B-12

2

89 B-11

2

89 B-10

74 B-9

91 B-7

91 B-6

88 B-5

91 B-4

89 B-3

3

67 B-8

musc./illite

77 B-2

smectite

78 B-1

Common minor components: quartz, feldspar, carbonates
often: kaolinite, cristob., gypsum, musc/illite, dolom., TiO2
Rarely: apatite, baryte, pyrite, zeolite, chlorite, hem/ilm/goe,


Characterisation – chemical composition (charge 2), XRF
SiO2

TiO2

Al2O3

Fe2O3

MnO

MgO

CaO

Na2O

K2O

P2O5

LOI

sum

[mass%] [mass%] [mass%] [mass%] [mass%] [mass%] [mass%] [mass%] [mass%] [mass%] [mass%] [mass%]

B1
B2
B3
B4
B5
B6
B7
B8
B9
B10
B11
B12
B13
B14
B15
B16
B17
B18
B19
B20
B21
B22
B23
B24
B25
B26
B27
B28
B29
B30
B31
B32
B33
B34
B35
B36
B37
B38
B39
B40

53.3
52.0
52.1
49.4
47.6
52.8
54.8
66.8
59.6
49.4
46.1
47.9
44.6
45.8
38.3
51.5
54.5
53.6
54.1
60.8
54.2
62.4
58.7
53.2
55.0
62.3
59.2
58.8
49.8
58.9
59.7
52.1
58.6
57.9
59.8
61.7
63.3
54.6
69.1
51.7

0.2
0.6
0.7
0.7
0.7
0.7
0.3
0.1
0.1
1.9
2.4
0.6
2.0
2.1
1.7
0.4
0.3
0.2
0.2
0.1
0.2
0.2
0.2
0.2
0.5
0.1
0.2
0.2
1.2
0.9
0.7
0.4
0.1
0.6
1.1
0.8
0.1
0.7
0.2
0.4

16.6
15.4
16.6
15.6
15.9
18.0
17.0
15.7
14.7
13.9
14.4
13.6
16.2
16.8
13.8
20.1
17.4
16.7
15.5
19.0
20.7
15.0
17.5
21.2
18.1
14.0
19.2
13.5
21.0
17.9
13.7
12.8
19.5
15.5
16.7
17.5
20.1
16.0
15.6
20.2

2.8
5.0
4.9
8.0
6.0
3.4
3.2
3.1
3.0
11.4
15.7
9.8
10.1
9.9
8.8
5.9
3.2
3.1
3.4
3.6
2.2
1.1
1.1
2.0
5.8
1.1
3.7
2.1
5.4
6.3
4.7
8.4
3.6
7.2
5.9
8.1
2.4
3.1
1.9
7.6

0.1
0.1
0.1
0.0
0.0
0.0
0.1
0.0
0.3
0.0
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99.7
99.7
99.7
99.5
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99.7
99.7
99.6
99.7
99.8
99.7

SiO2: quartz/cristob
Al/Mg/Fe: variable
smectite composition
and minor components
as kaolinite, goethite
Ca/Na/K: variable
interlayer composition
and minor components
as feldspar/illite


Characterisation – LECO analysis (C, S)

<table>
<thead>
<tr>
<th></th>
<th>organic C [mass%]</th>
<th>inorganic C [mass%]</th>
<th>total C [mass%]</th>
<th>total S [mass%]</th>
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<td>0.0</td>
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</tbody>
</table>

$C_{\text{org}}$ is commonly low (0.1 or lower, largest content in VolclaySPV (Wyo-product))

Approximately half of the bentonites are free of $C_{\text{inorg}}$ (below 0.0 mass%)

Approximately 70% of the bentonites are free of S (below 0.0 mass%)
Results – variability of the BGR bentonite sample set

Smectite content: 60 – 95 mass% (without ill/smt clays)
LCD: 0.18 – 0.38 eq/FU
CEC: 65 – 110 meq/100 g
% Na: 0 – 100 %
pH: 4 - 10
%tet charge: 10 – 65 %
Fe content: 1 – 16 mass%
Carbonates: 0 – 10 mass% (Cc-eq)
SSA: 7 – 130 m²/g
Different smectite morphology (sample with fibrous smt)
Different submicron particle size distribution
1 - drying

Kaufhold & Dohrmann (2010): all samples dried at 90° and 120°C up to 4.5 years!

CEC decreased by ca. 10%

Process is limited
Ca/Mg decreased from 90°C to 120°C. Na did not change to the same extent. 90°C (1.5a) -> 120°C (4.5a)

A model for explaining this was developed.

Bivalent cations migrate towards sites where they are bound more strongly – possibly opposing charges?

Conclusions: loss of swelling capacity upon drying only is a limited process.
## Batch experiments with different conditions

(60 – 90°C, with and without excess of Ca(OH)$_2$, different shaking intensity; Kaufhold & Dohrmann, 2011)

<table>
<thead>
<tr>
<th>Reference</th>
<th>Sample</th>
<th>Solution</th>
<th>pH</th>
<th>T [°C]</th>
<th>t [months]</th>
<th>Type of Experiment</th>
<th>Conclusions</th>
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<tbody>
<tr>
<td>Cuevas et al., 2007</td>
<td>Mg-FEBEX</td>
<td>K$_2$, Na$_x$, Ca(OH)$_2$</td>
<td>12.5/13.5</td>
<td>60</td>
<td>6-12</td>
<td>batch</td>
<td>At pH 12.5, 60°C no significant reaction, alteration products at pH 13.5</td>
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<tr>
<td>Bauer et al., 2006</td>
<td>Na-SAz-1</td>
<td>1 M KOH</td>
<td>12.4</td>
<td>80</td>
<td>6</td>
<td>batch</td>
<td>KOH induces solid state transformation towards illite (high charged smectite)</td>
</tr>
<tr>
<td>Turrero et al., 2007</td>
<td>FEBEX</td>
<td>mixed</td>
<td>13.5</td>
<td>100</td>
<td>6-12</td>
<td>column, incl. cement block</td>
<td>Formation of cement minerals (portlandite, CSH, ...) at cement block contact</td>
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<tr>
<td>Cuisinier et al., 2008</td>
<td>COX</td>
<td>portland cement sol</td>
<td>12.4</td>
<td>60</td>
<td>6-12</td>
<td>column</td>
<td>Microstructure is affected (macroporosity increased)</td>
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<tr>
<td>Kämmland et al., 2007</td>
<td>MX80</td>
<td>Na$_2$OH/Ca(OH)$_2$</td>
<td>12.4-13.8</td>
<td>RT</td>
<td>1.5</td>
<td>column</td>
<td>pH &lt; 13 has no effect on swelling pressure</td>
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<tr>
<td>Melkior et al., 2004</td>
<td>COX+MX80</td>
<td>mixed</td>
<td>12.5</td>
<td>RT</td>
<td>1-12</td>
<td>diffusion</td>
<td>Alkaline solution increases the diffusion coefficients</td>
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<tr>
<td>Mosser-Ruck &amp; Cathelineux, 2004</td>
<td>Wycm + Texas</td>
<td>K$_2$, Na$_x$, Ca(OH)$_2$</td>
<td>12-12</td>
<td>150</td>
<td>2</td>
<td>batch</td>
<td>Smectite alteration and precipitation of secondary minerals in case of KOH/CO$_3$</td>
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<tr>
<td>Clare et al., 2002</td>
<td>COX</td>
<td>SYF</td>
<td>13.2</td>
<td>60</td>
<td>12</td>
<td>batch</td>
<td>Smectite is altered (towards mixed layer minerals) and organic matter might preserve some smectites</td>
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<tr>
<td>Pusch et al., 2003</td>
<td>Friedland</td>
<td>extracted cement water</td>
<td>8-9.4</td>
<td>RT</td>
<td>5</td>
<td>batch</td>
<td>Hydraulic conductivity slightly increased</td>
</tr>
<tr>
<td>Ramírez et al., 2002</td>
<td>Almería Bentonite</td>
<td>K$_2$, Na$_x$, Ca(OH)$_2$</td>
<td>10-13.5</td>
<td>90°C</td>
<td>12</td>
<td>batch</td>
<td>The bentonite is stable up to pH 12.6</td>
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<tr>
<td>Savage et al., 1982</td>
<td>different silicates</td>
<td>K$_2$, Na$_x$, Ca(OH)$_2$</td>
<td>13</td>
<td>70</td>
<td>3</td>
<td>batch</td>
<td>Silicates dissolve and secondary phases precipitate</td>
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</tbody>
</table>

**SYF** = simple young fluid, NACRA, 1995

**Clear:** smectites dissolve congruently at high pH > 13

Rather different elemental concentrations were obtained which indicates different dissolution/precipitation processes.

Excess Ca(OH)$_2$ led to carbonate precipitation, a saturated Ca(OH)$_2$ solution was effectively buffered by bentonite.

Smectite dissolution at large pH is supposed to be congruent, Si concentration affected by SiO$_2$ phases, solubility difficult to determine because of precipitation of .. (zeolites…)

For HLRW repositories low pH cements are recommended.
Aerobic corrosion is limited (even in lab)

Corrosion proceeds anaerobically

Corrosion products are 1:1 or 2:1:1 Fe-clay minerals

<table>
<thead>
<tr>
<th>experiment</th>
<th>T / t</th>
<th>observation</th>
<th>Model</th>
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</thead>
<tbody>
<tr>
<td>Guillaume et al., (2003)</td>
<td>Fe powder / plate in MX80 + water</td>
<td>300°C / 9 months</td>
<td>formation of new Fe/Mg-layer silicates (chlorite, saponite), zeolites, quartz</td>
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<tr>
<td>Lantenois et al., (2005)</td>
<td>Fe powder with suspensions of different smectites</td>
<td>80°C / 1.5 - 4 months</td>
<td>formation of new phases depends on di/trioctahedral smectite, exchangeable cations, pH</td>
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<tr>
<td>Wilson et al., (2006b)</td>
<td>Fe powder with Kunipia F suspension</td>
<td>80 - 250°C / 3 months</td>
<td>formation of magnetite and analcime, smectite alteration (amongst others)</td>
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<tr>
<td>Perronnet et al., (2007)</td>
<td>Fe powder with suspensions of different smectites</td>
<td>80°C / 3 months</td>
<td>different reaction products, CEC decrease and increase reduction of structural Fe but no secondary phases observed</td>
</tr>
<tr>
<td>Carlson et al., (2007)</td>
<td>carbon steel wires embedded in compacted MX80</td>
<td>50°C / appr. 2 years</td>
<td></td>
</tr>
</tbody>
</table>

Corrosion rate = f(bentonite) is currently investigated at BGR
Detachment of colloidal particles mainly depends on exchangeable Na$^+$

Detached colloids (which “survived” 46,000 g centrifugation) were mainly smectite

pH may also play a role but Na$^+$ and pH are systematically related
Sealing depends on swelling pressure,

Swelling pressure depends on dry density

What determines the variability? Ex. cation, microstructure?

Currently investigated at BGR
6 retention

Radionuclide retention depends on adsorption sites
Possible adsorption sites are interlayer or edge surface

Yet, retention capacity of different bentonites is supposed to be similar, despite possible slight differences of selectivities

However, bentonites can be modified with respect to the retention of certain radionuclides (e.g. $^{129}$I, Kaufhold et al., 2007)
T conductivity depends on
- Quartz+illite / smectite ratio
- Water content
- porosity (compaction)
- microstructure

Details still have to be investigated
Radiation may cause structural degradation but few studies were conducted:

- Rather large doses required for serious structural damage (e.g. Allard et al., 2012)
- Structural Fe particularly sensitive towards radiation
9 salt stability - NaCl

Two different batch tests 3 and 5 months

Fig. 5. Comparison of the CEC of all bentonites before and after 5 months reaction with NaCl solution.

9 salt stability - KCl

again cation exchange + carbonate exchange buffer observed

BUT !!

1) More silica was dissolved
2) The CEC slightly decreased
3) The amount of soluble silica (Na$_2$CO$_3$ extractable) increased
4) Water uptake capacity significantly decreased

\[ y = 0.3x \]
\[ R^2 = 0.9 \]

\[ y = 0.9x \]
\[ R^2 = 0.9 \]

\[ y = 1.2x \]
\[ R^2 = 0.9 \]

9 salt stability - KCl

Products were characterized:

Real Illitization (appr. 5 %)
- soda soluble silica increase

Non-swelling smectite (45 %)
- loss of water/EG-swelling capacity (may be reversible)
  - 50% of which with fixed K (no exchange in CEC tests)

Swellable K smectite (50 %)
- normal smectites with exchangeable K
In the stability tests some bentonites lost more of their swelling capacity and some less (in % of cause, to eliminate the effect of different CECs)

!! Interestingly, in all stability tests the bentonites showed the same trend: Some lost more % of their CEC (in all tests) and some less (were more stable in all tests)

The reason could not be found in the basic parameter set (Fe-content, LCD, BET, %Na,..)
The reason may be the different solubilities..

However, determination of the smectite solubility is not trivial, this will be investigated in an upcoming project together with GRS and TUM
Overall conclusions

Process is limited, bentonites different

All bentonites dissolve at high pH => low pH cement

Cation exchange fast, K induces illitization, some bentonites are more reactive than others – maybe solubility?

Fe rich are less stable

Quartz + illite content increases T-cond.

Normal bentonites are similar, bentonites can be upgrades, e.g. for I^{129} retention.

Under construction

Na bentonites less suitable

Under construction

+ stability: cement water

+ stability: drying

+ stability: salt solutions

- corrosion

- erosion

+ sealing (swelling capacity)

+ retention (radionuclide adsorption)

+ T conductivity (radionuclide adsorption)
Overall conclusions

Results obtained, yet, already help to identify suitable or less suitable HLRW bentonites

However, for a final recommendation all parameters have to be considered
Batch tests at 60°C, 3 – 5 months
4 g bentonite with 40 mL solution -> centrifuge -> dialysis

Analysis of solid products by: XRD (AD, EG, oriented), XRF, IR, DTA, CEC, soluble silica, water uptake capacity

!! Important to use different methods before interpretation !!
(particularly XRD alone is insufficient – because of effect of texture, layer per stack – which can change upon dispersion)
Experimental conditions

NaCl
(4 g, 40 mL 6 M NaCl, 60°C shaking, 3, 5 months)

KCl
(4 g, 40 mL 1 M KCl, 60°C shaking, 5 months)
Carbonates buffered the cation exchange. Some Wyoming bentonites even took up Ca\(^{2+}\) from the NaCl solution because of Ca-carbonate and gypsum dissolution.

No specific irreversible reactions of bentonite with NaCl solutions were found.

However, Na\(^{+}\) exchange facilitates colloid detachment which indirectly affects bentonite stability.
Long-Term Performance of Engineered Barrier Systems:

The EC Project PEBS

2nd Chinese-German Workshop on Radioactive Waste Disposal
Karlsruhe, October 15-16, 2012
Objective: Evaluate the sealing and barrier performance of the EBS with time, through development of a comprehensive approach, involving experiments, model development, and consideration of the potential impact on safety functions.

- Experiments cover the full range of conditions
  - from initial emplacement of wastes (high heat generation and EBS re-saturation)
  - to later stage establishment of near steady-state conditions, i.e. full re-saturation and thermal equilibrium with the host rock
- Results will be integrated in a way to connect the initial transient state of the EBS and its long-term state in a more convincing way
- Models are developed and improved to provide a more complete description of the THM and THMC behaviour of the EBS system
- The projects aims at providing a more quantitative basis for relating the evolutionary behaviour to the safety functions of the system and at further clarifying the significance of residual uncertainties for long-term performance assessment
PEBS is an EC co-funded project of

- **BGR, GRS** (Germany)
- **NAGRA, Solexerts, TK Consult** (Switzerland)
- **ENRESA, AITEMIN, CIMNE, UDC, CIEMAT, Golder, UAM** (Spain)
- **SKB, Clay Technology** (Sweden)
- **ANDRA** (France)
- **BRIUG** (China)
- **JAEA** (Japan)

PEBS started on March 1, 2010 and runs for 48 months.
Work Programme

- **WP1**: Analysis of system evolution during early post closure period: Impact on long-term safety functions (WP lead: SKB)
- **WP2**: Experimentation on key EBS processes and parameters (WP lead: ENRESA)
- **WP3**: Modeling of short-term effects and extrapolation to long-term evolution (WP lead: GRS)
- **WP4**: Analysis of impact on long-term safety and guidance for repository design and construction (WP lead: NAGRA)
- **WP B**: Chinese mock-up experiment on compacted bentonite buffer (WP lead: BRIUG)
- **WP5+6**: Dissemination and project management (WP lead and project coordinator: BGR)
Experiments Covering Different Stages in Repository Evolution

Early resaturation time
10 years

Resaturation period
50 years

Pressure recovery period
200 years

Long-term evolution

Thermal evolution

High T°

Buffer resaturation and swelling

Low S

Time after repository closure

Ongoing chemical effects (corrosion)

Task 3.1

Modeling in Task 3.2

Task 3.3

Task 3.4

HE-E expt

Febex mock-up

EB expt

Karlsruhe, October 15-16, 2012

PEBS Overview
Immediate Connections Between Tasks

Analysis of system evolution (WP1)

- HM experiments (Task 2.1)
- THM experiments (Task 2.2)
- THMC experiments (Task 2.3)

HM modeling (Task 3.1)
- THM modeling of HE-E (Task 3.2)
- THM modeling of bentonite buffer (Task 3.3)
- THMC modeling (Task 3.4)

Long-term extrapolation (Task 3.5)

Analysis of impact on long-term safety (WP4)

WP2

WP3

Chinese mock-up experimentation and modeling

WPB

Karlsruhe, October 15-16, 2012
WP1: Analysis of system evolution during early post closure period

WP1 objectives:

- **Identify important processes** during the early evolution of the EBS
- Discuss how the **short-term transients** will/may affect the long-term performance and the safety functions of the repository
- Describe the current treatment of the early evolution of the EBS in long-term safety assessments for spent nuclear fuel/HLW
- Identify the merits and shortcomings of the current treatment
- Discuss the needs for additional studies of these issues and how they can support future assessments – give directions to other WPs
- **Define** “scenarios” (simulation cases) related to events in the early evolution of the EBS
Tasks 2.1/3.1 Dismantling of the Mont Terri EB and related HM modeling

- A controlled **dismantling of the EB bentonite buffer**, for which the artificial hydration process started back in May 2002, after in depth evaluation of the monitoring data to further complete the already gained knowledge on the resaturation and swelling processes is performed. New **lab infiltration tests** provide further data.

- The HM modeling aims at providing a satisfactory scientific representation and a sound basis for **interpretation of the EB hydration phase** and of the dismantling data. New or improved constitutive laws (double structure approach, water density change) are developed and adjusted with the experimental data.
Experimental tasks comprise the **FEBEX mock-up and long-term THM infiltration tests** in cells at CIEMAT with bentonite and sand/bentonite buffer.

Modeling work includes:

- **Evaluation of existing models** for bentonite buffer evolution
- Incorporation of **new processes** into simulation of long-term lab experiments and development of **enhanced constitutive models**
- Simulation of long-term lab experiments and **extrapolation to large-scale** in-situ tests

Measured and calculated relative humidity in the FEBEX mock-up taking into account thermo-osmosis.
HE-E objective: Elucidate the early non-isothermal resaturation period and its impact on the THM behaviour

- provide the experimental data base required for the calibration and validation of existing thermo-hydraulic models of the early resaturation phase
- upscale thermal conductivity of the partially saturated buffer from laboratory to field scale for pure bentonite and sand-bentonite mixture

Characteristics:

- 1:2 scale (microtunnel 1.3 m)
- Natural resaturation from clay host rock
- Heater surface temperature: 140 °C
- Duration: June 2011 -> 2014
- Two symmetrical sections - different granular materials
Tasks 2.2.2/3.2: Mont Terri Heater Experiment HE-E (2)

Fig. 11

Karlsruhe, October 15-16, 2012

PEBS Overview
Scoping calculations for the design of the HE-E to assure that the experiment lay-out meets the requirements regarding temperature evolution and that instrumentation is adequate

Interpretative modeling of the HE-E by prediction/evaluation cycles with uncertainty assessment, concentrating on the thermal and thermomechanical behaviour in the early post-closure phase

Tasks 2.2.2/3.2: Mont Terri Heater Experiment HE-E (3)
Objectives of THMC experiments

- Investigate corrosion processes, alkaline plumes and interaction of pore water with concrete, bentonite, and C-steel (GAME tests: Geochemical Advanced Mock-up Experiments)

- Study processes at the interfaces canister/bentonite and concrete/bentonite in dedicated tests

THmC Simulation

- Improve current THC models to account for different types of pores (dual continua models), porosity changes (m) caused by swelling phenomena, and reactive gases: $O_2(g)$, $CO_2(g)$, $H_2(g)$

- Test THmC model with previous and ongoing lab and in situ tests
Objectives

- To study the property of GMZ Na-bentonite and the bentonite-canister reaction under coupled T-H-M-C conditions
- To simulate vertical placement of a container with radioactive waste
- To monitor the behavior of GMZ Na-bentonite barrier at high temperature and special water
- To provide data for future design for engineered barrier system
Assessment of the results of Task 3.1 - 3.4 regarding their implications for different time and space scales

**Identification of the significant processes** in the resaturation phase & afterwards

Development or modification of the available **formulations to incorporate phenomena and processes deemed to be relevant** for long-term predictions

**Performance of coupled numerical analysis** for long-term evolution of the engineered barrier system in the repository

**Evaluation of the model uncertainty** and its implications for long-term prediction

Compilation and evaluation of the usefulness of natural analogues for providing support, testing and validation of long-term predictions of current THMC models

Meaning of “long-term”:

- To the end of the resaturation phase ($10^2 – 10^3$ years)
- To the end of PA-considered time ($10^5 – 10^6$ years)
Modeling Cases for Long-Term Extrapolation

- Water uptake in the buffer (T < 100°C)
- Thermal evolution of the buffer (T > 100°C)
- Hydro-mechanical evolution of the buffer
- Geochemical evolution, especially at interfaces (canister – bentonite and bentonite – concrete)

The models for the relevant processes are in principle existing and will be used for long-term simulation. Such models include, e.g.
- Non-Darcy flow (threshold pressure and critical gradient)
- Thermo-osmosis
- Double structure model to account for microfabric evolution
- Different types of water in macro- and micropores
Objectives:

- **Develop a synthesis** showing how the EBS and near-field rock will behave both during and after the transient period

- **Obtain a fully balanced view of all findings** and relate them to the specific relevant time and spatial domains

- **Give feedback to design** in terms of guidance for performance limits or modifications to design
Tasks 4.1 & 4.2:

- Develop evaluation structure for models and status of process understanding as well as a report structure
- Review the findings in WP2 and WP3 including other relevant experiments, identify information gaps
- Develop qualitative process related description of the early evolution of the EBS
- Quantitative assessment of WP2 and WP3 outcomes and uncertainties involved, identification of disagreements
- Discuss the importance with respect to the performance criteria
- Assess the impact on the safety functions (based on completed SA studies)
- Evaluate the importance of the identified aspects of the early evolution of the EBS based on scenarios for clay and granite host rock at relevant conditions
Tasks 4.3:

- Propose improved approach for integrating the thermal and resaturation phase with the long term steady state phase for SA
- Identify remaining uncertainties and future R&D needs
- Link the impact on the long term safety requirements to the design requirements in the light of this
The research leading to these results has received funding from the European Atomic Energy Community's Seventh Framework Programme (FP7/2007-2011) under grant agreement n° 249681

The GRS contribution is co-funded by the German Ministry of Economy and Technology (BMWi), FKZ 02 E 10689
Klaus Wieczorek

klaus.wieczorek@grs.de

Gesellschaft für Anlagen- und Reaktorsicherheit (GRS)
Theodor-Heuss-Strasse 4
38122 Braunschweig
Germany
Numerical Simulations of THM Processes in Rock-Buffer-System surrounding High-Level Radioactive Waste

X.-S. Li\textsuperscript{1}; C.-L. Zhang\textsuperscript{2}; K.-J Röhlig\textsuperscript{1}

1. Institute of Disposal Research, Clausthal University of Technology
2. Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH

2nd Chinese - German Workshop on Radioactive Waste Disposal
Karlsruhe, October 15-16, 2012
Direct SNF Disposal in Drift

- Usable part (~ 23m)
  - Spacers
- SF packages
- Cell Head
  - Metallic plug
- Access Drift
  - Bentonite rings
  - Concrete rings

Dossier 2005  www.andra.fr 2005
Axisymmetric model for the rock-buffer-system
Coupled THM Modelling (CODE-BRIGHT)

- **Balance of energy:**
  \[
  \frac{\partial}{\partial t} \left[ E_s \rho_s (1 - \phi) + E_i \rho_i S_i \phi + E_g \rho_g S_g \phi \right] + \nabla \cdot \left( i_c + j_{Es} + j_{Ei} + j_{Eg} \right) = f^E
  \]

- **Balance of water mass:**
  \[
  \frac{\partial}{\partial t} \left( \theta^w \rho_i S_i \phi + \theta^w \rho_g S_g \phi \right) + \nabla \cdot \left( j^w_i + j^w_g \right) = f^w
  \]

- **Balance of air mass:**
  \[
  \frac{\partial}{\partial t} \left( \theta^a \rho_i S_i \phi + \theta^a \rho_g S_g \phi \right) + \nabla \cdot \left( j^a_i + j^a_g \right) = f^a
  \]

- **Balance of solid mass:**
  \[
  \frac{\partial}{\partial t} \theta^s \rho_s (1 - \phi) + \nabla \cdot \left( j^s_i \right) = 0
  \]

- **Stress equilibrium:**
  \[
  \nabla \cdot \sigma + b = 0
  \]

**Heat transport:** conduction, advection with water/vapour flow

**Water flow:** advection and vapour diffusion

**Gas pressure:** atmospheric

**Mechanical behaviour:**
- argillite-damage model for clay rock
- thermo-elasto-plastic model (BBM model) for bentonite
Thermal Constitutive Equations

- Fourier’s law
  \[ \mathbf{i}_c = -\lambda \nabla T \]
  \[ \lambda = \lambda_s^{(1-\phi)} \lambda_l^{(\phi S_l)} \lambda_g^{(1-S_l)} = \lambda_{sat}^{(1-S_l)} \]

- Internal energy of liquid
  \[ E_l = E_l^w \omega_l^w + E_l^a \omega_l^a \]

- Internal energy of gas
  \[ E_g = E_g^w \omega_g^w + E_g^a \omega_g^a \]

- Internal energy of solid
  \[ E_s = 4180.0 \, T \, (J/kg), \quad E_s^a = 1006.0 \, T \, (J/kg) \]
  \[ E_g^w = 2.5 \cdot 10^6 + 1900 \, T \, (J/kg) \quad E_g^a = 1006 \, T \, (J/kg) \]
  \[ E_s = 930 \, T \, (J/kg) \text{ for the Opalinus clay} \]

- Clay rock
  \[ \lambda = 1.5^{S_l} \cdot 0.7^{(1-S_l)} \]

- Bentonite
  \[ \lambda = 1.507^{S_l} \cdot 0.42^{(1-S_l)} \]
Hydraulic Constitutive Equations

- **Water/gas two phase Darcy flow**
  \[ q_\alpha = -K_\alpha (\nabla P_\alpha - \rho_\alpha g) \]
  \[ K_\alpha = k_{r\alpha} / \mu_\alpha \]

- **Relative water/gas permeability**
  \[ k_{rl} = S_l^{1/2} \cdot [1 - (1 - S_l^{1/\beta})^\beta]^2 \]
  \[ k_{rg} = 1 - k_{rl} \]

- **Water saturation – suction relationship**
  \[ S_l = \left[ 1 + \left( \frac{s}{P_0} \right)^{1/(1 - \beta)} \right]^{-\beta} \]

- **Intrinsic permeability related to porosity**
  \[ k = k_0 \frac{\phi^3 (1 - \phi_0)^2}{(1 - \phi)^2 \phi_0^3} \]

- **Diffusion of water vapour**
  \[ \mathbf{i}_g^w = -D_g^w \nabla \omega_g^w = - (\phi \rho_g S_g \mathbf{D}_m^w I + \rho_g D'_g) \nabla \omega_g^w \]
Mechanical Constitutive Equations

Elastoplastic-damage model for clay rock

\[
d\varepsilon^M_{ij} = d\varepsilon_{ij} + d\varepsilon^b_{ij}
\]

\[
\sigma_{ij} = (1 + \chi)\sigma^M_{ij} + \chi\sigma^b_{ij}
\]

\[
\chi = \frac{\varepsilon^b_v}{\varepsilon^b_q} = \frac{\varepsilon^b_q}{\varepsilon^b_q} = \chi_0 \cdot \exp\left(-\frac{L}{2}\right)
\]
Mechanical Constitutive Equations

Thermo-Elastoplastic model for compacted bentonite

Consolidation

Swelling

- suction = 0
- confining pressure = 1 MPa
Axisymmetric model for the rock-buffer-system

- **Initial state** before the construction (0-0.1 day)
- **Excavation and ventilation phase** (0.1-100 days):
  - The borehole has been drilled and ventilated for 100 days.
- **Backfilled phase** (100 days- 6 years):
  - The SNF canisters have been emplaced, the drilled borehole has been backfilled with bentonite buffer and heated by SNF canisters.
Heat output from HLW

\[ j_e = j_{eo} \cdot \exp[-abs(\lambda_e) \cdot t] \]
Excavation damaged zone (EDZ)

(a) Stress evolution
(b) Damaged zone
Temperature evolution
Pore-water pressure changes

![Graph showing pore-water pressure changes](image-url)
Porosity change in bentonite buffer

- Initial state $t = 0$
- $t = 250$ days
- $t = 1$ year
- $t = 2$ years
- $t = 3$ years

Distance to the canister (m)

Porosity (-)

Carbon steel canister with spent fuel

Bentonite Buffer

EDZ/Host rock
Water saturation in bentonite buffer

- Buffer/clay interface
- Buffer centre $r=0.4$ m
- Canister/buffer interface

<table>
<thead>
<tr>
<th>Degree of water saturation (%)</th>
<th>Time (day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1700</td>
</tr>
<tr>
<td>40</td>
<td>1700</td>
</tr>
<tr>
<td>30</td>
<td>1700</td>
</tr>
<tr>
<td>20</td>
<td>1700</td>
</tr>
<tr>
<td>10</td>
<td>1700</td>
</tr>
</tbody>
</table>

Bentonite Buffer

Carbon steel canister with spent fuel

EZ/Het rock
Thermal deformation

- Drift wall
- Rock r=0.2 m
- Rock r=1.3 m
- Rock r=4.3 m
- Rock r=25 m

Time (day)

Displacement (mm)

Backfilling heating

Step 1122
Display Vectors of Displacements factor 550.
Deformation (x50): Displacements of isochrones, step 100.
Conclusions

- Temperature:
  - $T_{\text{max}} = 157 \, ^\circ \text{C}$ at the surface of SNF containers at ~3 years
  - $T_{\text{max}} = 90 \, ^\circ \text{C}$ in the host rock

- Water saturation:
  - desaturation in the buffer near the containers due to the thermal evaporation of the pore water
  - resaturation in the buffer near the rock by taking up water from the saturated far-field

- Thermally-induced pore-water pressure is limited below 9 MPa, no fracturing is possible.

- Thermal expansion is revealed in the heated rock mass, while thermal compaction in the buffer occurs.

- Generally, no or little negative thermal effects are given by the modelling
Thank you for your attention!
Tuesday, October 16, 2012

TOPIC: RN-BEHAVIOR
R&D on HLW Treatment and Disposal in CIAE

by ZHANG Zhengtao, WANG Bo

R&D Laboratory on Radioactive Waste Conditioning and Disposal of
China Institute of Atomic Energy (CIAE)

2nd German-Chinese Workshop on Radioactive Waste Disposal
Karlsruhe, Germany
Oct. 15, 2012
China Institute of Atomic Energy

CIAE Major Fields of R&D on Radioactive Waste treatment and Disposal

- Reprocessing
- HLLW Vetrification
- Immobilization of Legacy Waste
- Chlorine Salt and Graphite Sleeves Of legacy
- Long-term Behavior of HLW Glass in Geological Repository
- Chemistry and Migration behavior of Actinide in Geological conditions
R&D Projects, 2010-2015

(1) Cold Crucible Melter for vitrification of HLLW

(2) Long-term Behavior of Simulated HLW-Glass in Geological Repository

(3) Chemistry and Migration behavior of Radionuclides under geological disposal conditions

(4) Immobilization of Legacy Wastes: Chlorine Salt in Glass-Ceramic

Self-Sustainable Propagating High Temperature Synthesis for Graphite Sleeves
(1) **Cold Crucible Melter for HLLW**

CCM is a versatile technology for vitrification of HLLW. The technology is now being used to vitrify the HLLW in some countries.

**Molten glass inside the CIAE cold crucible melter in operation**

**Molten glass tapping**
(1) Cold Crucible Melter for HLLW

Design and optimize a high and middle-frequency converter, 2011

- High-frequency: 592 kHz; Power: 48.6 KW
- Middle-frequency: 18 KW, frequency adjusts automatically.
Vitrification of simulated HLLW in 2015:

- Producing Capacity: 10 kg/h
- Higher Temperature: 1500°C;
(2) Long-term Behavior of HLW Glass in Geological Repository

Simulated HLW Glass Leaching experiment has been performed in CIAE, 2010

Temperature is a key parameter for the Long-term Behavior of HLW Glass

Figure 1: The leaching of the glass modifying elements.
The secondary products formation of simulated HLW glass at 150 °C

Figure 2: The secondary products (a), their SEM images (b), and their EDS (c).
Table 1: Mineral distribution of secondary products.

<table>
<thead>
<tr>
<th>Time (d)</th>
<th>Zeolite P</th>
<th>Mordenite</th>
<th>Nontronite</th>
<th>Dickite</th>
<th>Okonite</th>
<th>Quartz</th>
<th>Saponite</th>
<th>Tincalconite</th>
</tr>
</thead>
<tbody>
<tr>
<td>394</td>
<td>12%</td>
<td>28%</td>
<td>25%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>35%</td>
</tr>
<tr>
<td>546</td>
<td>2%</td>
<td></td>
<td></td>
<td>6%</td>
<td>1%</td>
<td></td>
<td></td>
<td>55%</td>
</tr>
<tr>
<td>730</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>35%</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

Glass was degraded into other minerals at 150°C
(2) Long-term Behavior of HLW Glass in Geological Repository

- Small-scale Interaction equipment of Glass-Container-Back fill materials-Host Rock
- U / Th glass
- Operation Temperature: 20-150°C
- Experimental Period: 4 years
1. Aqueous Solutions

- Corrosion rate of HLW glass with SEM
- Distribution of key elements in corrosion layer with EPMA (Electron probe X-ray microanalyser)

2. Canister Metal

- Corrosion rate of canister metal with SEM
- Distribution of Hydrogen in corrosion section of canister metal

3. Simulated HLW Glass

- Sampling period: 3, 6, 9, 12, 18, 24, 30, 36, 42, 48 months
- Analysis of U, Th, Nd, Re, Cs, Sr, Si, Na, B with ICP-MS/AES

- Corrosion rate of HLW glass with SEM
- Distribution of key elements in corrosion layer with EPMA (Electron probe X-ray microanalyser)
Table 2  Composition of simulated HLW glass

<table>
<thead>
<tr>
<th>Oxide</th>
<th>wt%</th>
<th>Oxide</th>
<th>wt%</th>
<th>Oxide</th>
<th>wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>50.232</td>
<td>La₂O₃</td>
<td>0.1326</td>
<td>Fe₂O₃</td>
<td>3.144</td>
</tr>
<tr>
<td>B₂O₃</td>
<td>18.48</td>
<td>SrO</td>
<td>0.0368</td>
<td>NiO</td>
<td>0.5728</td>
</tr>
<tr>
<td>Na₂O</td>
<td>11.190</td>
<td>Y₂O₃</td>
<td>0.016</td>
<td>K₂O</td>
<td>0.0912</td>
</tr>
<tr>
<td>Li₂O</td>
<td>2.94</td>
<td>MoO₃</td>
<td>0.1941</td>
<td>P₂O₅</td>
<td>0.0688</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>3.3816</td>
<td>MnO₂</td>
<td>0.016</td>
<td>SO₃</td>
<td>0.6448</td>
</tr>
<tr>
<td>CaO</td>
<td>4.536</td>
<td>Cs₂O</td>
<td>0.1152</td>
<td>Cr₂O₃</td>
<td>0.296</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.9897</td>
<td>BaO</td>
<td>0.0208</td>
<td>Nd₂O₃</td>
<td>0.01</td>
</tr>
<tr>
<td>MgO</td>
<td>0.84</td>
<td>U₃O₈</td>
<td>1.9728</td>
<td>ThO₂</td>
<td>0.035</td>
</tr>
<tr>
<td>Re₂O₇</td>
<td>0.052</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
(3). Chemistry and Migration Behavior of Radionuclides

(1) Migration of radionuclide at Room temperature
   - Solubility of Np, Pu, Tc, Am in Beishan underground water
   - Solubility of actinides and Tc at high temperature

(2) Migration of radionuclide in mock-up conditions
   - Migration of radionuclide in Backfilling materials
   - Migration of radionuclide in fracture fill material of host rock (BeiShan Granite)

(3) Modeling of the migration of radionuclide
(4) Immobilization Chlorine Salts in ceramics

Table 3 Composition of simulated chlorine salts

<table>
<thead>
<tr>
<th>Chlorine Salts</th>
<th>wt%</th>
<th>Chlorine Salts</th>
<th>wt%</th>
<th>Chlorine Salts</th>
<th>wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaCl₂</td>
<td>1.20</td>
<td>KI</td>
<td>0.15</td>
<td>NdCl₃</td>
<td>7.71</td>
</tr>
<tr>
<td>CeCl₃</td>
<td>2.33</td>
<td>LiCl-KCl</td>
<td>69.82</td>
<td>SrCl₂</td>
<td>1.00</td>
</tr>
<tr>
<td>CsCl</td>
<td>2.84</td>
<td>NaCl</td>
<td>14.95</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Nd and Ce been used to replace the actinides
(4) Immobilization legacy wastes in ceramics

- A bench scale of glass-ceramic fabrication facility to be established
- Demonstration of immobilization of chlorine salt to be performed
(4) Immobilization legacy wastes in ceramics

Table 4  Composition of simulated chlorine salts Ceramics（wt%）:

<table>
<thead>
<tr>
<th>Simulated Waste</th>
<th>4A-Zeolite</th>
<th>Glass Firt</th>
<th>Zr、Ti、P</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>40-60</td>
<td>15-30</td>
<td>2-6</td>
</tr>
</tbody>
</table>

- HLW Chlorine Salts loading up to 24 wt%,
- HLW Slurry loading up to 50 wt%;
- Ceramic Characterization: Leaching rate of Cs/Sr/Re/U < $1 \times 10^{-3}$ g/cm²·d, Th and Nd < $1 \times 10^{-4}$ g/cm²·d.
Self-Sustainable Propagating
High Temperature Synthesis for Graphite Sleeves

Contaminated Graphite

Decontamination → Incineration

99%

carbonwaste → 1% SHS → Ceramic
Thank You for Your Attention
Source Terms for Highly Radioactive Waste Forms

2nd Chinese-German Workshop on Radioactive Waste Disposal
Karlsruhe, October 15-16, 2012

Bernhard Kienzler
Nuclear Situation in Germany

- Ban on construction of nuclear power plants (2001)
- Ban on reprocessing (since 2005)
- De facto ban on spent fuel element transports (on-site interim storage)
- Complete phase-out until 2022 (2012)

Total Electricity Generation (2011): $612 \times 10^9$ kWh
## Radioactive Wastes in Germany

### Heat producing wastes: ca. 29,030 m³
- **Spent Fuel (disposed directly)**
  - from power reactors: 21,800 m³
  - pilot / test reactors: 5,530 m³
  (THTR/AVR, PKA/IKA, res. reactors)
- **Reprocessing**
  - HLW Glass: 670 m³
  - CSD-B, CSD-C (hulls / end pieces): 850 m³
  - Others: 180 m³

### Non heat producing wastes: ca. 280,000 m³
- **NPP operation:** 300 m³/yr
- **Others**
  - Decommissioning
  - Research
  - Industry
  - Medical applications
  - Scales

### Disposal Strategy:
- **Interim Storage** min. 30 yrs.
- **Deep underground disposal**
  - since 1977 Gorleben salt dome
  - 2012 "Site Selection Law"

* from La Hague and Sellafield

Quelle: BfS 2011
Project: Preliminary safety analysis analysis for Gorleben (vSG)

Analysis of the suitability of the Gorleben site on the basis of a preliminary Safety Case basing on:

1. Preliminary safety analysis with emphasis on **long-term safety**, showing in a comprehensible, documented and traceable way if and under which conditions a safe disposal is possible at the site.

2. Development of an optimized **disposal concept** under consideration of operational safety.

3. Determination of additional required (future) **research** and **exploration** needs

Present state of **science and technology** and all timely available **results of exploration**.
Structure of vSG

Basics
- WP2: Geo-scientific site description
- WP3: Specification and quantity of wastes
- WP4: Safety and verification concept

Planning the disposal
- WP5: Disposal concept
- WP4: Design and optimization

System analysis
- WP11: Human Intrusions
- WP12: Operat. Safety
- WP10: Release scenarios radiolog. consequences
- WP7: FEP catalogue
- WP8: Scenarios
  - probable
  - less prob.
- WP9: Integrity
  - yes
  - no
  - complete isolation
    - yes
    - no
  - no aquatic transport path
  - gas path
  - aqueous path

Synthesis
- WP13: Evaluation of Results
- WP14: Recommendations
  - Peer Review
Source term for heat producing wastes

- HLW glass
  - Temperature dependence of HLW glass dissolution
  - Kinetics of HLW glass dissolution
- Spent nuclear fuel from LWRs
  - Instant release fraction
  - Matrix dissolution
- Temperature effects
  - Radiolytic reactions
  - Spent nuclear fuel corrosion
- Compacted hulls, end pieces and spacers (CSD-C waste)
- Boundary Conditions
- Radionuclide source term
  - Kinetically controlled radionuclide mobilization
  - Thermodynamically Controlled Radionuclide Mobilization
- Radionuclide solubility
- Sorption
Boundary conditions

- Inventories
- Types of wastes / canisters / backfill
  - Thick-walled canisters, corrosion allowance by carbon steel
- Disposal concept: Ratio of waste mass / volume to open pore space
- Probable evaluation:
  - Penetration of saturated salt solutions (6m NaCl or 4 m MgCl$_2$ solution)
  - NaCl solution unbuffered
    - $6 \leq \text{pH} \leq 9$
  - Reducing conditions / consumption of oxygen by steel corrosion
- Hydrocarbon degradation below critical value
- Carbonate-free system
HLW Glass
WAK and Vitrification Plant Karlsruhe (VEK)

**WAK (1971-1991)**
- Reprocessing of 200 t of spent fuel
- 60 m³ HAWC
- $7.7 \times 10^{17}$ Bq

**VEK**
- 1996 – 1998 constr. mock-up;
- 1999 – 2005 construction VEK
- 2009 – 2010 hot operation;

Foto: WAK
Vitrification of High Level Liquid Waste

WAK

60 m³ HLLW ➔ 50 t HLW Glass in 130 Canisters
5 CASTOR Casks
Operational Data of VEK

- Active operation start: 16.09.2009
- End of vitrification: September 2010
- 130 Canisters filled
- 5 CASTOR containers loaded
- Transport to Interim Storage Facility February 2011
- Decontamination and dismanteling
Glass quality: Test procedures

- **MCC-1** static leaching of monolithic sample at constant temperature (40°C, 90°C), sampling at 3, 7, 14, 28 d
- **MCC-2** static test (elevated temperature)
- MCC-nn ...
- **Soxhlet test** (1879 extraction method) evaporation of solvent (leaching in distilled water)

- **Immersion Tests**
  powder, fragments, relevant groundwater
Glass Corrosion

Real HLW glass structure

Network formers: Si, B

Network modifiers: Na, K, Ca, Cs, ...

Gel Layer: SiO₂, Al, Mg, OH

solution

SiO₂

Na⁺, Cs⁺

H⁺, H₂O

Mg²⁺
Present investigations on HLW glass

Examination of the VEK-glass samples by Raman spectroscopy

Objectives:
- Investigation of homogeneity of VEK glass with respect to RN / glass constituents
- Precipitates of noble metal
- Crystalline oxides enriched in radionuclides

Materials:

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mass / g</th>
<th>Dose rate / mSv/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>#23 (3 fragm.)</td>
<td>0.4365</td>
<td>450</td>
</tr>
<tr>
<td>#57 (1 big, 2 small fragm., + particles)</td>
<td>1.033</td>
<td>500</td>
</tr>
<tr>
<td>#71 (1 fragm.)</td>
<td>0.750</td>
<td>500</td>
</tr>
</tbody>
</table>

Fragments of #23 mass (0.089 ± 0.001) g
Raman spectroscopy of the VEK-glass

**Results:**
- high fluorescence intensities @ 785 nm.
- different glass fragments did not reveal significant differences
- and did not allow any conclusion about
  - phase separations or
  - presence of precipitates in the glass.

Raman spectra of inactive sample
- laser of 785 nm at 10 mW (red spectra),
- laser of 532 nm at 5 mW (green spectra)

Comparison of Raman spectra @ 785 nm
- VEK 57-2 (blue line)
- VEK 23-1 (green line)
- inactive glass (red line)
Spent Nuclear Fuel
Experiments - Disposal
Complex structure of spent fuel

- Cladding: C
- Gap region: C, I, Cs, Se, Tc
- Enriched rim: Pu

- Fuel grains: U, Pu, Ln, Sr
- Fission gas bubbles: Kr, Xe, I
- Grain boundaries: C, I, Cs, Se, Tc
- Rim enriched with Pu
- Epsilon-particles
- Metallic precipitates: Mo, Ru, Pd, Tc, Rh, Ag, Cd, In, Sb, Sb
- Oxide precipitates: Rb, Cs, Ba, Zr, Nb, Mo, Tc

α-radiography

20 µm
**Definition of instant / fast release**

*Project related definition or PA related definition*

RN release by matrix corrosion controlled by radiolysis, hydrogen, Cl-....

 ↔

 initial (fast) release of RN controlled by chemistry of fuel, spatial distribution, burn-up, lin. power (reactor operation)

- gap
- large cracks
- grain boundaries
  - close to surface
  - rim
  - grain boundaries along cracks
1. Partners / Beneficiaries

2. Associated Groups (AG)

Groups participating at their own costs with specific RTD contributions or particular information exchange functions, or mobility measures (for European AGs only)
Used (spent) nuclear fuel interactions

**Radiolysis of water**
Generation of oxidants ($H_2O_2$, $OH^-$, $HO_2^-$, $O_2$) and reductants ($H$, $H_2$, $e^-_{aq}$)

**Matrix dissolution**
$UO_2$ and other RNs and FPs into solution

Deep Reducing Underground Conditions:
- Formation of $H_2$ by steel corrosion
- Supressing $UO_2$ corrosion by hydrogen effect
- Inhibiting the $UO_2$ oxidation

Secondary phase precipitation
$U(VI)$ phases may incorporate other FPs and RNs
Br⁻ free systems: Rate decreasing with increasing p(H₂)

Details

http://digbib.ubka.uni-karlsruhe.de/volltexte/1000029420
Summary

- Source terms for heat producing wastes under potential rocksalt conditions ✓
- Source terms for non-heat producing wastes under potential rocksalt conditions ✓
- Variation of boundary conditions ✓
- Identification of open questions
- Filling the gaps by
  - in-house R&D
  - third party funded R&D projects
  - international projects (EU) and networks
Radio-nuclides Migration Research to Support Geological Disposal of HLW in CIAE

ZHOU Duo, ZHANG Zhen-tao, WANG Bo, LONG Hao-qi, BAO Liang-jin, CHEN Xi, SONG Zhi-xin, JIANG Tao
1. Introduction
2. Beishan Granite and Groundwater Composition and Properties
3. Disposal Behavior of Simulated Glass
4. Chemical Behavior of Key Nuclides in Groundwater
5. Interaction of Radio-nuclides with Medium
6. Problems of Disposal Chemical Research
7. Consideration and Prospect
1. Introduction

- The deep geological disposal is internationally recognized feasible as a safe disposal of HLW.

- The core task for deep geological disposal of HLW is to contain radio-nuclides as much as possible and to retard the radio-nuclides migration with the help of multiple barrier means.

- Current research in CIAE is more focused on geochemical behavior of key radio-nuclides such as neptunium-237 ($^{237}$Np), plutonium-239 ($^{239}$Pu), americium-241 ($^{241}$Am) and technetium-99 ($^{99}$Tc) in groundwater intrusion scenario.
2. Beishan Granite and Groundwater Composition and Properties

Table 1. Beishan Granite Component

<table>
<thead>
<tr>
<th>Species</th>
<th>percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na₂O</td>
<td>4.51%</td>
</tr>
<tr>
<td>MgO</td>
<td>3.76%</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>16.46%</td>
</tr>
<tr>
<td>SiO₂</td>
<td>55.22%</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.89%</td>
</tr>
<tr>
<td>K₂O</td>
<td>3.43%</td>
</tr>
<tr>
<td>CaO</td>
<td>6.00%</td>
</tr>
<tr>
<td>TiO₂</td>
<td>1.37%</td>
</tr>
<tr>
<td>MnO</td>
<td>0.09%</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>1.50%</td>
</tr>
<tr>
<td>FeO</td>
<td>4.35%</td>
</tr>
<tr>
<td>CO₂</td>
<td>0.68%</td>
</tr>
<tr>
<td>H₂O⁺</td>
<td>1.24%</td>
</tr>
</tbody>
</table>

The granite is mainly composed of silicon oxide (SiO₂) and aluminum oxide (Al₂O₃); Ferrous oxide (FeO) and ferric oxide (Fe₂O₃) are minor components.
Properties: Low hydraulic conductivity, low diffusion constant and high sorption
## 2. Beishan Granite and Groundwater Composition and Properties

### Table 2. Beishan Groundwater Composition

<table>
<thead>
<tr>
<th>Species</th>
<th>Concentration, mM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na⁺</td>
<td>47.89</td>
</tr>
<tr>
<td>K⁺</td>
<td>0.37</td>
</tr>
<tr>
<td>Ca²⁺</td>
<td>6.02</td>
</tr>
<tr>
<td>Mg²⁺</td>
<td>2.12</td>
</tr>
<tr>
<td>HCO₃⁻</td>
<td>2.18</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>50.44</td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>14.8</td>
</tr>
<tr>
<td>F⁻</td>
<td>0.17</td>
</tr>
<tr>
<td>NO₃⁻</td>
<td>0.48</td>
</tr>
<tr>
<td>Total Alkalinity</td>
<td>109 mg/L</td>
</tr>
<tr>
<td>Total Carbonate</td>
<td>2.32</td>
</tr>
<tr>
<td>pH</td>
<td>7.58</td>
</tr>
<tr>
<td>Eh(mV)</td>
<td>-200</td>
</tr>
<tr>
<td>Ionic Strength (mM)</td>
<td>~130</td>
</tr>
</tbody>
</table>

There are several main components of groundwater which is from geological voids,

- **Cation**: Na⁺, Ca²⁺, Mg²⁺, K⁺, Fe²⁺, Fe³⁺;
- **Anion**: Cl⁻, SO₄²⁻, HCO₃⁻, CO₃²⁻, F⁻, NO₃⁻.

Properties: Slightly alkaline and strongly reducing
Leaching behavior of key frame elements was investigated at 150°C and 90°C in our lab.

- At 150°C, sudden alteration phenomenon happened for simulated glass with action of groundwater, which results in **substantial leaching** for key frame elements (Na, Li, Si, Al);
- While at 90°C corrosion just only happened on the surface of simulated glass, which leads to **gentle leaching**.

---

**3. Disposal Behavior of Simulated Glass**
3. Disposal Behavior of Simulated Glass

Leaching behavior of radioactive substitute elements was investigated at 150°C and 90°C in our lab.

- At 150°C, 60 percent of molybdenum (Mo) as Tc substitute is leaching out from simulated glass;
- While at 90°C, little Mo only on the glass surface is leaching out.
3. Disposal Behavior of Simulated Glass

Corrosion behavior: Large amounts of secondary product formed at high temperature (150°C)

- With simulated glass soaked in groundwater for 394 days, in the soaking liquid emerged some acicular crystal, in which silicon (Si) and oxygen (O) are main elements, a preliminary judge for quartz;
- With simulated glass soaked in groundwater at for 546 days, in the soaking liquid emerged some white powder, in which silicon (Si), sodium (Na) and oxygen (O) are main elements, a preliminary judge for zeolite;
- With the simulated glass soaked in groundwater for 730 days, the bulk glass had altered, abundant of white powder formed, the crystal shape is cubic, the main elements of the bulk are sodium (Na) and boron (B), a preliminary judge for borate.

Frame elements spectrogram of secondary product with EDS
3. Disposal Behavior of Simulated Glass

**Corrosion behavior:** continuous alteration reaction occurred at high temperature (150°C)

- With glass soaked in groundwater at 150°C, a large number of Si is leaching out from glass. When concentration of Si in the soaking liquid reached saturation, **quartz** would form.

- As the reaction progresses, lots of silicate mineral phase such as **zeolite** (which is more stable than glass) would form and the glass would be destroyed.

- At the same time, large amounts of boron (B) and sodium (Na) elements are released, which results in super-saturation for B and Na, so **borate** would form.

Crystal phase spectrogram of corrosion product with XRD
4. Chemical Behavior of Key Nuclides in Groundwater

Solubility and Species

Table 3. Solubility data of radio-nuclides in underground water

<table>
<thead>
<tr>
<th>nuclides</th>
<th>pH</th>
<th>Solubility (mol/L)</th>
<th>valence</th>
<th>control phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Np(V)</td>
<td>8.4</td>
<td>$5 \times 10^{-5}$</td>
<td>98.5% Np(V)</td>
<td>NpO$_2$OH</td>
</tr>
<tr>
<td>Np(IV)</td>
<td>8.0</td>
<td>$1 \times 10^{-8}$</td>
<td>100% Np(IV)</td>
<td>Np(OH)$_4$</td>
</tr>
<tr>
<td>Pu(IV)</td>
<td>8.4</td>
<td>$1 \times 10^{-8}$</td>
<td>100% Pu(IV)</td>
<td>Pu(OH)$_4$</td>
</tr>
<tr>
<td>Tc(IV)</td>
<td>8.0</td>
<td>$3 \times 10^{-9}$</td>
<td>100% Tc(IV)</td>
<td>TcO(OH)$_2$</td>
</tr>
<tr>
<td>Am</td>
<td>8.1</td>
<td>$5 \times 10^{-10}$</td>
<td>100% Am(III)</td>
<td>Am(OH)$_3$</td>
</tr>
</tbody>
</table>

- Neptunium, plutonium and technetium exist as tetra-valent species in reducing environment, which results in low solubility. Control phase in Table 3 is speculated by authors.
- The pH and carbonate concentration become the main factors affecting solubility through hydrolysis and complex reaction.
- In the range of pH 7-10, pH variation has little effect on solubility of tetra-valent species such as Np(IV), Pu(IV), Tc(IV).
- Complex reaction of Pu(IV) and Am(III) with CO$_3^{2-}$ ion results in increased solubility; There is no obvious increase for solubility of Np(IV) and Tc(IV) with the concentration of CO$_3^{2-}$ increasing.
- Solubility of Pu(IV) and Am(III) decreases remarkably with temperature increasing.
- Solubility of Np(IV) both in pure water system and in the Beishan groundwater increases with temperature increasing.
4. Chemical Behavior of Key Nuclides in Groundwater

Colloidal Behavior-Ultracentrifugation Method

<table>
<thead>
<tr>
<th></th>
<th>storage time</th>
<th>ionic strength</th>
<th>pH</th>
<th>humic acid</th>
<th>centrifugal speed/rpm</th>
<th>stacking density /kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Np colloidal quantity</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>60000-100000</td>
<td>2150</td>
</tr>
<tr>
<td>Pu colloidal quantity</td>
<td>↑</td>
<td>no significant effect</td>
<td>↑</td>
<td>no effect</td>
<td>80000-100000</td>
<td>8896</td>
</tr>
<tr>
<td>Tc colloidal quantity</td>
<td>↓</td>
<td>↓</td>
<td>no significant effect</td>
<td>↑</td>
<td>40000-100000</td>
<td>5485</td>
</tr>
</tbody>
</table>

Colloidal stacking density of Np is far less than that of Pu and Tc, which shows Np colloid is mainly pseudo colloid. Humic acid concentration has almost no effect on the formation of colloidal Pu, which illuminates that real colloid come into being.
4. Chemical Behavior of Key Nuclides in Groundwater

Colloidal Behavior-Ultrafiltration Method for Pu, Am Colloidal Research

- Tetra-valent Pu(IV) mainly exists as ionic form in pure water, while in groundwater colloid is main existent form of Pu(IV).
- Existence of Pu (IV) colloid makes concentration 2 orders of magnitude higher than solubility of Pu(IV) in groundwater.
- Colloidal granularity of Pu(IV) is mainly distributed between 100 nm and 450 nm, the proportion of Pu(IV) colloidal quantity in groundwater is about 85%.

- Am mainly exists as large colloidal form in groundwater, while in pure water, Am exists as small colloidal form.

- Colloidal research with membrane filter method for Am and Pu in groundwater, shows that Am mainly exists as pseudo colloidal form, Pu mainly exists in the form of real colloid.


4. Chemical Behavior of Key Nuclides in Groundwater

Redox Behavior

Pu

- Hydrogen peroxide ($H_2O_2$) can reduce penta-valent Pu($V$) into tetra-valent Pu($IV$) which further hydrolyzes to form colloid;
- The increase of pH, temperature and concentration of $H_2O_2$ leads to increase of reductive rate;
- The existence of cations such as $K^+$, $Ca^{2+}$, $Mg^{2+}$ has no significant effect on reductive rate of Pu($V$), while existence of anions leads to increase of reductive rate of Pu($V$). (sequence of ability: $F^-$ $SO_4^{2-}$ $HCO_3^-$ $Cl^-$)
- Granite powder can reduce penta-valent Pu($V$) into tetra-valent Pu($IV$) most of which is adsorbed on surface of granite, reductive rate increases with pH and temperature increasing.

Tc

- In alkaline water, iron powder can reduce pertechnetate ($TcO_4^-$) into technetium dioxide dihydrate ($TcO_2\cdot2H_2O$) which is easily oxidized to $TcO_4^-$ by solution of hydrogen peroxide ($H_2O_2$).
- $TcO_4^-$ in distilled water can be reduced to tetravalent Tc($IV$) by bivalent tin (Sn($II$)), the redox reaction equation can be expressed as: $3Sn(II) + 2Tc(IV)\rightarrow3Sn(IV) + 2Tc(IV)$.
- In alkaline water, activation energy $Ea$ for reduction of $TcO_4^-$ by Sn($II$) is 29.08 kJ/mol, the reaction rate equation is: $-dc_{(TcO_4^-)}/dt = k\cdot c_{(TcO_4^-)}\cdot c_{(OH^-)} - 0.478\cdot c_{(Sn(II))} \cdot 0.629$. 

5. Interaction of Radio-nuclides with Medium

Adsorption Kd of Np, Pu, Am and Tc in various medium was determined with batch experimental under anoxia atmosphere at normal temperature, which results are listed in table 4.

Table 4. Adsorption Kd (ml/g) value of Np, Pu, Am, Tc in various medium

<table>
<thead>
<tr>
<th></th>
<th>Iron powder</th>
<th>Ferrous oxide (FeO)</th>
<th>Ferric oxide (Fe$_2$O$_3$)</th>
<th>Ferroferric oxide (Fe$_3$O$_4$)</th>
<th>bentonite</th>
<th>granodiorite</th>
<th>crack infilling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Np</td>
<td>~3×10$^3$</td>
<td>-</td>
<td>-</td>
<td>~1×10$^3$</td>
<td>30~90</td>
<td>~1×10$^3$</td>
<td>~8×10$^2$</td>
</tr>
<tr>
<td>Pu</td>
<td>~2×10$^4$</td>
<td>~1×10$^4$</td>
<td>~2×10$^4$</td>
<td>~1×10$^4$</td>
<td>~3×10$^3$</td>
<td>~2×10$^3$</td>
<td>-</td>
</tr>
<tr>
<td>Am</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>~1×10$^4$</td>
<td>~3×10$^3$</td>
<td>-</td>
</tr>
<tr>
<td>Tc</td>
<td>~2×10$^3$</td>
<td>~500</td>
<td>~3</td>
<td>~7</td>
<td>10~80</td>
<td>~3×10$^3$</td>
<td>-</td>
</tr>
</tbody>
</table>

Adsorption Kd of Pu and Am on bentonite and granite is vary large, so that Pu and Am in repository can be strongly blocked and contained in the near field and far field of repository;

Adsorption Kd of Np and Tc on granite is vary large, while that on bentonite is smaller, which indicates the near field has weak blockade and tolerance for Np and Tc.

With strong adsorption properties, Fe can strong block migration of Np, Pu and Tc.
5. Interaction of Radio-nuclides with Medium

Effect of Temperature on Sorption of Np

- Kd values of Np adsorbed on granite samples increase with temperature increasing.
- Temperature has little effect on the desorption percentage (1.6%~3.8%) in potassium chloride (KCl) solution which can desorb Np(IV) adsorbed electro-statically on granite samples.
- Desorption percentage (17%~26.5%) in potassium oxalate(K₂C₂O₄) solution increases with temperature increasing, K₂C₂O₄ solution can desorb Np(IV) in amorphous phase minerals.

<table>
<thead>
<tr>
<th>Temperature (℃)</th>
<th>30℃</th>
<th>45℃</th>
<th>60℃</th>
<th>80℃</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kd (ml/g)</td>
<td>1593</td>
<td>1711</td>
<td>2152</td>
<td>2183</td>
</tr>
<tr>
<td>ΔH° (KJ·mol⁻¹)</td>
<td>36.7</td>
<td>36.7</td>
<td>36.7</td>
<td>36.7</td>
</tr>
<tr>
<td>ΔS° (J·mol⁻¹·K⁻¹)</td>
<td>184.0</td>
<td>184.0</td>
<td>184.0</td>
<td>184.0</td>
</tr>
<tr>
<td>ΔG° (KJ·mol⁻¹)</td>
<td>-19.0</td>
<td>-21.7</td>
<td>-24.5</td>
<td>-28.2</td>
</tr>
</tbody>
</table>

\[ \ln K_d = -4419 \left( \frac{1}{T} \right) + 22.13 \]
5. Interaction of Radio-nuclides with Medium

Effect of Temperature on Adsorption of Am

Kd values of Am adsorbed on granite samples increase with temperature increasing.

High temperature is favorable for the adsorption of Am on granite.

Adsorption Kd of Am on granite samples at different temperatures are less than desorption Kd' value, which indicates the adsorption is irreversible.
5. Interaction of Radio-nuclides with Medium

Effect of Temperature on Adsorption of Tc

Kd of hepta-valent Tc(Ⅶ) in granite samples increases with temperature increasing.

On the large area of mineral surface, hepta-valent Tc(Ⅶ) is reduced into tetra-valent Tc(Ⅳ) which has low solubility.

The free energy is negative, which indicates that the adsorption reaction is a spontaneous reaction.

Table 8. Adsorption Kd and ΔG of $^{99}$Tc on granite

<table>
<thead>
<tr>
<th>temperature</th>
<th>30℃</th>
<th>45℃</th>
<th>60℃</th>
<th>80℃</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kd(ml/g)</td>
<td>1439.82</td>
<td>2306.17</td>
<td>2849.50</td>
<td>3079.50</td>
</tr>
<tr>
<td>ΔG(kJ/mol)</td>
<td>-25.68</td>
<td>-26.96</td>
<td>-28.23</td>
<td>-29.92</td>
</tr>
</tbody>
</table>
5. Interaction of Radio-nuclides with Medium

Free-aqueous Diffusion Coefficient of Np, Pu, Tc

Table 9. Effect diffusion coefficient of Np, Pu, Tc and its influence factors

<table>
<thead>
<tr>
<th></th>
<th>pH=8.46</th>
<th>D(m²/s)</th>
<th>Activation energy (kJ/mol)</th>
<th>Temperature</th>
<th>Viscosity</th>
<th>pH</th>
<th>Concentration of Fe²⁺ or Sn²⁺</th>
</tr>
</thead>
<tbody>
<tr>
<td>Np(35°C)</td>
<td>1.32×10⁻¹⁰</td>
<td>49.80</td>
<td>T↑D↑</td>
<td>η↑D↓</td>
<td>pH↑D↓</td>
<td>Fe²⁺↑D↓</td>
<td></td>
</tr>
<tr>
<td>Pu(35°C)</td>
<td>1.32×10⁻¹⁰</td>
<td>150.6</td>
<td>T↑D↑</td>
<td>η↑D↓</td>
<td>pH↑D↑</td>
<td>Fe²⁺↑D↑</td>
<td></td>
</tr>
<tr>
<td>Tc(30°C)</td>
<td>2.92×10⁻⁹</td>
<td>15.42</td>
<td>T↑D↑</td>
<td>η↑D↓</td>
<td>pH↑D↓</td>
<td>Sn²⁺↑D↓</td>
<td></td>
</tr>
</tbody>
</table>

Free-aqueous diffusion coefficients of Np, Pu, Tc increase with temperature increasing.
Free-aqueous diffusion coefficients of Np, Pu, Tc decrease with viscosity increasing.
5. Interaction of Radio-nuclides with Medium

Diffusion Coefficient within Matrix

Table 10. Diffusion coefficients of Np, Pu, Tc in bentonite and granite

<table>
<thead>
<tr>
<th></th>
<th>atmosphere</th>
<th>groundwater</th>
<th>bentonite</th>
<th>granite</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>capillary</td>
<td>static</td>
<td>dynamic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>back-to-back</td>
<td>constant</td>
<td>constant</td>
</tr>
<tr>
<td>$D_{\text{Tc}}$ (m$^2$/s)</td>
<td>air</td>
<td>$2.9 \times 10^{-9}$</td>
<td>$1.1 \times 10^{-10}$</td>
<td>$1.6 \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td>anoxic</td>
<td>-</td>
<td>$9.7 \times 10^{-11}$</td>
<td>$7.1 \times 10^{-11}$</td>
</tr>
<tr>
<td>$D_{\text{Np}}$ (m$^2$/s)</td>
<td>air</td>
<td>$1.3 \times 10^{-10}$</td>
<td>$(4-8) \times 10^{-13}$</td>
<td>$8.2 \times 10^{-12}$</td>
</tr>
<tr>
<td></td>
<td>anoxic</td>
<td>-</td>
<td>$(3-5) \times 10^{-13}$</td>
<td>-</td>
</tr>
<tr>
<td>$D_{\text{Pu}}$ (m$^2$/s)</td>
<td>air</td>
<td>$1.3 \times 10^{-10}$</td>
<td>$2.5 \times 10^{-14}$</td>
<td>-</td>
</tr>
<tr>
<td>$D_{\text{Am}}$ (m$^2$/s)</td>
<td>air</td>
<td>-</td>
<td>$2.5 \times 10^{-14}$</td>
<td>-</td>
</tr>
<tr>
<td>$D_{\text{Sr}}$ (m$^2$/s)</td>
<td>air</td>
<td>-</td>
<td>$2.4 \times 10^{-11}$</td>
<td>$1.6 \times 10^{-12}$</td>
</tr>
<tr>
<td>$D_{\text{Cs}}$ (m$^2$/s)</td>
<td>air</td>
<td>-</td>
<td>$1.5 \times 10^{-12}$</td>
<td>$1.4 \times 10^{-11}$</td>
</tr>
</tbody>
</table>

The diffusion coefficients of Am and Pu in bentonite and granite are very low due to strong adsorption properties of bentonite and granite;

The diffusion coefficients of Tc and Np are relatively bigger, depending on chemical speciation in medium.

Technetium is dominated by pertechnetate (TcO$_4^-$) in aqueous phase, Neptunium is dominated by penta-valent neptunyl (NpO$_2^+$).

The negatively charged TcO$_4^-$ diffuses more fast than the positively charged NpO$_2^+$, due to electrostatic repulsion of negatively charged surface of geological medium.
6. Problems of Disposal Chemical Research

Long-Term Disposal Properties of Glass

(1) Leaching source parameters for glass are seriously lack, which needs for us to strengthen the research in this field.

(2) Materials of HLW packaging body and disposal container are not identified, the comprehensive research about interaction between glass with buffer backfill materials and groundwater is still very weak;

(3) Certain progress about buffer backfill has been made, but research about material which weakens corrosion of HLW glass and packaging body is vary lack and need to be strengthen.
6. Problems of Disposal Chemical Research

Chemistry of Nuclides in Groundwater

(1) The lack of direct and rapid detection means for nuclide species;
(2) The lack of means for analysis of precipitation or solid phase;
(3) Lack of research for colloid system;
(4) Lack of dissolution and precipitation kinetics.
6. Problems of Disposal Chemical Research

Radionuclide - Medium Interaction

(1) Lack of research on microcosmic interfacial chemistry;
(2) Basic data are scarce;
(3) The adsorption mechanism is not studied enough;
(4) The coupling effect of multiple factors is less studied;
(5) Coexistence system of radio-nuclides is less studied.
7. Consideration and Prospect

(1) Establish sophisticated equipment and optimize analysis means to improve chemical behavior research of actinides and fission product elements in groundwater;

(2) To carry out research on the chemical behavior of key nuclides in solid-liquid interface;

(3) Under thermo-hydro-mechanical-chemical-radical coupling condition, strengthen research on migration behavior of key nuclides in backfill material and undisturbing surrounding rock;

(4) Research on mechanism of gas release, impact of microorganism and organic matter on radionuclide migration, radiolysis effect in geological disposal environment;

(5) Develop long-term chemical stability study and corrosion behavior study for HLW package, HLW glass and spent fuel under disposal;

(6) Research and develop corrosion inhibitor for glass and packaging materials;

(7) Establishment geological chemical databases for disposal of HLW and develop migration model for HLW repository.
Thank you for your attention!
Chemical Behavior of Plutonium in Groundwater

J. Y. Xu

Chengdu University of Technology, Chengdu, China

October, 2012
Outline

introduction

Prior research in China

Our current & future work
The Plutonium is a word from the Latin “pluto”

Pluto, Greek god of wealth, ruled the dark underworld of myth.

This shows that Pu is one of the toxic elements in nature.

So, The Plutonium was under the spotlight attract much attention in HLW.
What is the fate of plutonium?

Plutonium Cycling in the Environment

- Biological Uptake and Biotransformations
- Thermal and Photochemical Reactions
- "Hot particle" and Fission Product Contamination
- Gaseous and Aerosol Release
- Radiocolloid Formation
- Precipitation, Polymerization and Dissolution
- Aqueous Transport
- Complexation And Hydrolysis
- Oxidation Reduction and Disproportionation
- Coprecipitation And Release Upon Dissolution
- Sorption/Ion Exchange and Desorption on Inorganic, Organic and Colloidal Materials

Hydrosphere
Prior Work on Pu chemical behavior in groundwater, in China

(1) Pu speciation

<table>
<thead>
<tr>
<th>Added Pu</th>
<th>Pu(Ⅲ) %</th>
<th>Pu(Ⅳ) %</th>
<th>Pu(V) %</th>
<th>Pu(VI) %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pu(Ⅲ) 100%</td>
<td>2.76</td>
<td>82.52</td>
<td>10.43</td>
<td>0.65</td>
</tr>
<tr>
<td>Pu(Ⅳ) 100%</td>
<td>2.89</td>
<td>82.27</td>
<td>13.17</td>
<td>0.81</td>
</tr>
<tr>
<td>Pu(Ⅴ) 100%</td>
<td>2.01</td>
<td>82.49</td>
<td>10.53</td>
<td>0.87</td>
</tr>
<tr>
<td>Pu(Ⅵ) 100%</td>
<td>2.23</td>
<td>81.05</td>
<td>12.12</td>
<td>1.08</td>
</tr>
</tbody>
</table>

1. Initially, we put the *tervalent* / tetravalent / pentavalent / hexavalent Pu into the groundwater, respectively.
2. After 60 days balance, the *tetravalent* plutonium is dominant specation in the groundwater.
3. As the table shows: the equilibrium concentration of *tetravalent* plutonium is from eighty-one point zero five to eighty-two point five two percent.
1. The figure shows that the experimental solubility of amorphous plutonium tetra hydroxide compare with results by computational simulation.
2. The square shape (■) denotes “in absence of sodium nitrite”. The diamond shape (◆) denotes “in presence of sodium nitrite”. The line (—) denotes results by computational simulation.
3. The experimental results shows that the solubility of plutonium is basically consistent with the results simulated by software in absence of sodium nitrite.
4. At the same time, amorphous plutonium tetra hydroxide is controlling phase of plutonium solubility in groundwater.
1. Hydrogen peroxide ($H_2O_2$) is a stable radiolysis product in groundwater.
2. Pentavalent plutonium can be reduced to tetravalent plutonium by hydrogen peroxide.
3. Tetravalent plutonium dominates the solubility of plutonium in groundwater.
4. So, the effect of hydrogen peroxide ($H_2O_2$) on pentavalent plutonium reduction is very important.
5. As shown in the figure, the rate of pentavalent plutonium is gradually increasing with the increased concentration of hydrogen peroxide.
(4) The effect of pH on Pu(V) reduction

1. The pH of groundwater have a significant impact on the stability of *pentavalent* plutonium.
2. The rate of *pentavalent* plutonium reduction is significantly increasing with the increase of pH value.
(5) The effect of temperature on Pu (V) reduction

The reaction temperature of pentavalent plutonium and hydrogen peroxide was studied. The activation energy of the reduction reaction is eighty-four kilo-joule per mole.
(6) The reaction mechanism of $\text{H}_2\text{O}_2$ and Pu(V)

**Possible mechanism:**

\[ \text{H}_2\text{O}_2 \rightleftharpoons \text{H}^+ + \text{HO}_2^- \]  \hspace{1cm} (1)

\[ \text{PuO}_2^+ + \text{HO}_2^- \rightleftharpoons \text{PuO}_2\text{O}_2\text{H} \]  \hspace{1cm} (2)

\[ \text{PuO}_2\text{O}_2\text{H} \rightleftharpoons \text{PuO}_2\text{O}_2\text{H}^\neq \]  \hspace{1cm} (3) \text{ Rate-controlling reaction }

\[ \text{PuO}_2\text{O}_2\text{H}^\neq \rightleftharpoons \text{Pu}^{4+} + \text{reductant} \]  \hspace{1cm} (4)

**Rate equation:**

\[ \text{rate} = (3.93 \pm 1.93) \times 10^{-9} \times c(\text{Pu}) \times c(\text{H}_2\text{O}_2) \times c(\text{H}^+)^{-1} \]
1. Potassium, sodium, calcium, magnesium, and ferrous cations commonly exist in groundwater.
2. The reaction rate of pentavalent plutonium and hydrogen peroxide have no significant changes in presence of potassium, sodium, calcium, magnesium.
3. However, iron ion significantly accelerates the reaction rate of pentavalent plutonium and hydrogen peroxide.
1. Bicarbonate, nitrate, fluoride, chloride and sulphate ions also commonly exist in groundwater.
2. The reaction rate of pentavalent plutonium and hydrogen peroxide is accelerated in the presence of these inorganic anion.
3. It is fact that different anions will have different influence on the reaction rate.
1. The groundwater show some reduction capability to pentavalent plutonium, itself.
2. Ferrous, sulfide and nitrous ions, goethite, iron sulfide and humic acid may coexist in the groundwater.
3. Hydrogen peroxide is more conducive to the reduction of pentavalent plutonium.
1. Amorphous plutonium can form complex with bicarbonate.

2. So, the solubility of amorphous plutonium in the groundwater is increasing with bicarbonate levels increased

3. Carbonate has also a similar effect to amorphous plutonium.

4. The solubility of amorphous plutonium in groundwater is increasing linearly with bicarbonate or carbonate ion concentration.
(11) Possible complex reaction of HCO$_3^-$, CO$_3^{2-}$ and Pu(OH)$_4$(am)

$$\text{Pu(OH)}_4(\text{am}) + 2\text{HCO}_3^- = \text{Pu(OH)}_4(\text{HCO}_3)_2^{2-} \quad (1)$$
$$\text{Pu(OH)}_4(\text{am}) + 2\text{HCO}_3^- = \text{Pu(OH)}_2(\text{HCO}_3)_2^{2-} + 2\text{H}_2\text{O} \quad (2)$$
$$\text{Pu(OH)}_4(\text{am}) + 2\text{CO}_3^{2-} = \text{Pu(OH)}_4(\text{CO}_3)_2^{4-} \quad (3)$$

1. Possible complex reaction of bicarbonate (HCO$_3^-$), carbonate (CO$_3^{2-}$) and amorphous plutonium is as follow: reaction one (1), two(2) and reaction three (3).
2. So, these complex reaction increase solubility of amorphous plutonium tetra hydroxide in the groundwater.
1. The plutonium adsorption behavior on the surface of the rock influences the migration in the groundwater.
2. The plutonium adsorption behavior has been researched on the surface of the granite in the groundwater.
3. The results show that plutonium adsorption reach balance on the surface of granite in the groundwater after about six hundred minutes.
1. The pH of groundwater is the **key factor** of plutonium **adsorption** on surface of the granite.
2. The **lower** the pH of groundwater, the **more detrimental** to the adsorption of plutonium.
1. The **pyrrhotite** is the **key mineral** influencing plutonium adsorption on granite.
2. The pyrrhotite was separated from the granite.
3. There are **seventy-five** percent pyrrhotite and **kaolinite, feldspar, quartz** **fifteen** percent in selected mineral.
4. Plutonium adsorption capacity on the pyrrhotite surface is increasing with the **pH** of groundwater.
1. The **clay mineral** is also the key mineral influencing plutonium adsorption on granite.
2. The clay mineral was separated from the granite.
3. Plutonium adsorption capacity on the surface of clay is increasing with the pH of groundwater.
Focus of our further research—*isolate plutonium from biosphere*

Migration behavior of plutonium in the groundwater around clay rock region

- **Colloid transport**
- **humic acid**

Establish optimal migration model for migration of Pu in clay rock region
Thanks for your attention
Feasibility of CS Canister Used for HLW Geological Disposal

Junhua Dong, Wei Ke
Institute of Metal Research, Chinese Academy of Sciences
Shenyang, China
Background

- Geological disposal of HLW include multi-barriers, which is known as the natural barrier and the engineering barrier.
- the engineering barrier includes glass solidification, canister, overpack and buffer material.

Overpack is the first barrier to isolate the radionuclide from human being. Its corrosion mode determines its serving life.
In the oxygen free underground water for HLW geological disposal, carbon steel was thought to satisfy the most technical criterions for isolating the HLW besides some low corrosion resistance.

Corrosion of CS canister was thought to obey the anodic dissolution galvanized by the hydrogen evolving reaction mode, which occurred as general corrosion.

Passivation mode was thought to be ease of pitting corrosion caused by chloride ion, which induce the stress corrosion cracking of CS canister.

Anodic active dissolution / Passivation / Local corrosion? What will happen for the CS canister in the underground water during more than thousand years disposal? It needs a correct answer for HLW geological disposal engineering design.
Background

Thermodynamics of CS Canister Corrosion

\[
3\text{Fe} + 4\text{H}_2\text{O} = \text{Fe}_3\text{O}_4 + 8\text{H}^+ + 8\text{e} \tag{1}
\]

\[
E=-0.08664-0.05916\text{pH} \tag{2}
\]

\[
3\alpha\text{-FeOOH} + \text{H}^+ + \text{e} = \text{Fe}_3\text{O}_4 + 2\text{H}_2\text{O} \tag{3}
\]

\[
E=0.2845-0.05916\text{pH} \tag{4}
\]

\[
\text{Fe} + 2\text{H}_2\text{O} = \alpha\text{-FeOOH} + 3\text{H}^+ + 3\text{e} \tag{5}
\]

\[
E=-0.04540-0.05916\text{pH} \tag{6}
\]

\[
\text{Fe}^{2+} + 8\alpha\text{-FeOOH} + 2\text{e} = 3\text{Fe}_3\text{O}_4 + 4\text{H}_2\text{O} \tag{7}
\]

\[
E=0.08609+0.02958\log[\text{Fe}^{2+}] \tag{8}
\]

\[
\text{Fe}^{3+} + 8\alpha\text{-FeOOH} + 3\text{e} = 3\text{Fe}_3\text{O}_4 + 4\text{H}_2\text{O} \tag{9}
\]

\[
E=0.3137+0.01972\log[\text{Fe}^{3+}] \tag{10}
\]
Background

Kinetics of CS Canister Corrosion

- The open circuit potential determines the corrosion mode of anodic dissolution or passivation.
- The chemical compositions of the ground water and the corrosion products make effects on localized corrosion potential and dissolving mode of the passive film during the long term disposal.
### Background

**Chemicals contained in the underground water**

Beishan, China

<table>
<thead>
<tr>
<th>ion</th>
<th>mol/L</th>
<th>ion</th>
<th>mol/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>F^-</td>
<td>1.31×10^{-4}</td>
<td>Na^+</td>
<td>5.42×10^{-2}</td>
</tr>
<tr>
<td>Cl^-</td>
<td>3.39×10^{-2}</td>
<td>K^+</td>
<td>6.36×10^{-4}</td>
</tr>
<tr>
<td>NO_3^-</td>
<td>3.08×10^{-4}</td>
<td>Ca^{2+}</td>
<td>1.54×10^{-3}</td>
</tr>
<tr>
<td>SO_4^{2-}</td>
<td>1.39×10^{-2}</td>
<td>Mg^{2+}</td>
<td>1.01×10^{-2}</td>
</tr>
<tr>
<td>CO_3^{2-}</td>
<td>0.84×10^{-4}</td>
<td>pH</td>
<td></td>
</tr>
<tr>
<td>HCO_3^-</td>
<td>1.90×10^{-3}</td>
<td>TDS</td>
<td></td>
</tr>
</tbody>
</table>

Calculated by Japanese

<table>
<thead>
<tr>
<th>chemicals</th>
<th>mol/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCO_3^-/CO_3^{2-}/H_2CO_3</td>
<td>&lt;7.3×10^{-2}</td>
</tr>
<tr>
<td>SO_4^{2-}</td>
<td>&lt;6.1×10^{-2}</td>
</tr>
<tr>
<td>HS^-/H_2S</td>
<td>&lt;9.2×10^{-1}</td>
</tr>
<tr>
<td>Cl^-</td>
<td>&lt;5.9×10^{-1}</td>
</tr>
<tr>
<td>P (Title)</td>
<td>&lt;2.9×10^{-6}</td>
</tr>
<tr>
<td>NO_3^-</td>
<td>0.0</td>
</tr>
<tr>
<td>NH_3</td>
<td>&lt;1.6×10^{-4}</td>
</tr>
<tr>
<td>NH_4^+</td>
<td>&lt;5.1×10^{-3}</td>
</tr>
<tr>
<td>B(Totle)</td>
<td>&lt;1.7×10^{-3}</td>
</tr>
<tr>
<td>pH</td>
<td>5.9~8.4</td>
</tr>
</tbody>
</table>
Target of the present study

• What is the corrosion mode of CS canister? Anodic active dissolution or passivation?

• What is the effect of the chemicals in the underground water?
  \( \text{HCO}_3^-/\text{Cl}^-/\text{SO}_4^{2-}/\text{pH} \)

• Does the CS canister satisfy the technical request for HLW geological disposal?
Experiment

- Polarization curves
- Potentiostatic current decay
- Corrosion potential monitoring
- EIS measurement
- XRD detection and SEM observation

<table>
<thead>
<tr>
<th>Electrolyte</th>
<th>C/mol/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCO$_3^-$</td>
<td>0.01 ~ 0.1</td>
</tr>
<tr>
<td>HCO$_3^-$+Cl$^-$</td>
<td>0.01 ~ 0.5</td>
</tr>
<tr>
<td>HCO$_3^-$+SO$_4^{2-}$</td>
<td>0.01 ~ 0.5</td>
</tr>
<tr>
<td>HCO$_3^-$+ Cl$^-$ +SO$_4^{2-}$</td>
<td>$\Sigma=0.1$</td>
</tr>
</tbody>
</table>
Results and discussions

Polarization behaviors and corrosion potentials of CS immersed in HCO₃⁻ solutions

1. CS keeps same anodic dissolution at low potential in all HCO₃⁻ solution, but changes from limited diffusion to passivation and transpassivation at high potential with increasing HCO₃⁻ concentration.

2. The corrosion potential of CS increases from active to passive during the immersion
Results and discussions

XRD patterns of the corrosion products of CS immersed in HCO$_3^-$ solutions and the corrosion potential of CS drawn in Pourbaix diagram

Anode: $\text{Fe} + 2\text{H}_2\text{O} = \alpha$-FeOOH + 3H$^+$ + 3e, $E_e$=-0.742V, pH=8.33

Cathode: $\text{Fe}^{3+} + 8\alpha$-FeOOH + 3e = 3Fe$_3$O$_4$ + 4H$_2$O, $E_e$ = -0.0287V
Results and discussions

Polarization behaviors and corrosion potentials of CS in 0.01M HCO₃⁻ solutions containing Cl⁻.

CS keeps anodic active dissolution in 0.01M HCO₃⁻ solutions containing Cl⁻, morphologies after long term immersion show a general corrosion.
Results and discussions

Polarization behaviors and corrosion potentials of CS in 0.01M HCO₃⁻ solutions containing Cl⁻

Increase of Cl⁻ concentration decreases the corrosion potential; morphologies after long term immersion show a general corrosion.
Results and discussions

XRD patterns of the corrosion products of CS immersed in 0.01M HCO$_3^-$ solutions containing Cl$^-$ and the corrosion potential of CS drawn in Pourbaix diagram

Anode:  $\text{Fe} + 2\text{H}_2\text{O} = \alpha\text{-FeOOH} + 3\text{H}^+ + 3\text{e}$, pH=8.33, $E_e$=-0.742V

Cathode: $\text{Fe}^{2+} + 8\alpha\text{-FeOOH} + 2\text{e} = 3\text{Fe}_3\text{O}_4 + 4\text{H}_2\text{O}$, $E_e$ = -0.306V

$3 \alpha\text{-FeOOH} + \text{H}^+ + \text{e} = \text{Fe}_3\text{O}_4 + 2\text{H}_2\text{O}$
Results and discussions

Polarization behaviors and corrosion potentials of CS in 0.01M HCO$_3$- solutions containing SO$_4^{2-}$

CS keeps anodic active dissolution in 0.01M HCO$_3$- solutions containing SO$_4^{2-}$. Increase of SO$_4^{2-}$ concentration decreases the corrosion potential; morphologies after long term immersion show a general corrosion.
Results and discussions

XRD patterns of the corrosion products of CS immersed in 0.01M HCO₃⁻ solutions containing SO₄²⁻ and the corrosion potential of CS drawn in Pourbaix diagram

Anode:  \[ \text{Fe} + 2\text{H}_2\text{O} = \alpha\text{-FeOOH} + 3\text{H}^+ + 3\text{e}, \text{pH}=8.33, \text{E}_e=-0.742\text{V} \]

Cathode: \[ \text{Fe}^{2+} + 8\alpha\text{-FeOOH} + 2\text{e} = 3\text{Fe}_3\text{O}_4 + 4\text{H}_2\text{O}, \text{E}_e = -0.306\text{V} \]

\[ 3\alpha\text{-FeOOH} + \text{H}^+ + \text{e} = \text{Fe}_3\text{O}_4 + 2\text{H}_2\text{O}, \text{E}_e = -0.4521\text{V} \]

\[ 2\text{H}^+ + 2\text{e} = \text{H}_2, \quad \text{E}_e = -0.7366\text{V} \]
Results and discussions

Polarization behaviors and corrosion potentials of CS in 0.01M HCO₃⁻ solutions containing both SO₄²⁻ and Cl⁻

CS keeps anodic active dissolution in 0.01M HCO₃⁻ solutions containing both SO₄²⁻ and Cl⁻, morphologies after long term immersion show a general corrosion.
Results and discussions

XRD patterns of the corrosion products of CS immersed in 0.01M HCO$_3^-$ solutions containing both SO$_4^{2-}$ and Cl$^-$ and the corrosion potential of CS in Pourbaix diagram.

Anode: \( \text{Fe} + 2\text{H}_2\text{O} = \alpha\text{-FeOOH} + 3\text{H}^+ + 3e, \text{pH}=8.33, E_e=-0.742V \)

Cathode: \( \text{Fe}^{2+} + 8\alpha\text{-FeOOH} + 2e = 3\text{Fe}_3\text{O}_4 + 4\text{H}_2\text{O}, E_e= -0.306V \)

\( 3 \alpha\text{-FeOOH} + \text{H}^+ + e = \text{Fe}_3\text{O}_4 + 2\text{H}_2\text{O}, \text{Ee}= -0.4521V \)

\( 2\text{H}^+ + 2e = \text{H}_2, \quad \text{E}_e= -0.7366V \)
Results and discussions

Polarization behaviors and corrosion potentials of CS in 0.05M HCO$_3^-$ solutions containing Cl$^-$

CS conducts anodic transpassivation in 0.05M HCO$_3^-$ solutions containing Cl$^-$, morphologies after long term immersion show a localized corrosion.
Results and discussions

Polarization behaviors and corrosion potentials of CS in 0.05M HCO$_3^-$ solutions containing Cl$^-$

CS conducts anodic transpassivation in 0.05M HCO$_3^-$ solutions containing Cl$^-$, morphologies after long term immersion show a localized corrosion.
Results and discussions

XRD patterns of the corrosion products of CS immersed in 0.05M HCO$_3^-$ solutions containing Cl$^-$ and the corrosion potential of CS drawn in Pourbaix diagram

\[
\text{Anode: } \text{Fe} + 2\text{H}_2\text{O} = \alpha\text{-FeOOH} + 3\text{H}^+ + 3\text{e}, \text{pH}=8.33, E_e=-0.742\text{V}
\]

\[
\text{Cathode:Fe}^{2+} + 8\alpha\text{-FeOOH} + 2\text{e} = 3\text{Fe}_3\text{O}_4 + 4\text{H}_2\text{O}, E_e = -0.306\text{V}
\]
Results and discussions

Polarization behaviors and corrosion potentials of CS in 0.05M HCO$_3^-$ solutions containing SO$_4^{2-}$

CS conducts anodic transpassivation in 0.05M HCO$_3^-$ solutions containing high SO$_4^{2-}$ concentration.
Results and discussions

Polarization behaviors and corrosion potentials of CS in 0.05M HCO$_3^-$ solutions containing SO$_4^{2-}$.

CS conducts anodic active dissolution in 0.05M HCO$_3^-$ solutions containing low SO$_4^{2-}$ concentration. Increase of SO$_4^{2-}$ concentration decreases the corrosion potential; morphologies after long term immersion show a general corrosion.
Results and discussions

XRD patterns of the corrosion products of CS immersed in 0.05M HCO₃⁻ solutions containing SO₄²⁻ and the corrosion potential of CS drawn in Pourbaix diagram

Anode:  Fe + 2H₂O = α-FeOOH + 3H⁺ + 3e, pH=8.33, Eₑ=-0.742V

Cathode:Fe²⁺ + 8α -FeOOH + 2e = 3Fe₃O₄ + 4H₂O, Eₑ= -0.306V

3 α -FeOOH + H⁺ + e = Fe₃O₄ + 2H₂O, Eₑ = -0.4521V
Results and discussions

Polarization behaviors and corrosion potentials of CS in 0.05M HCO₃⁻ solutions containing both SO₄²⁻ and Cl⁻.

CS conducts localized anodic dissolution in 0.05M HCO₃⁻ solutions containing both SO₄²⁻ and Cl⁻, morphologies after long term immersion show a pitting corrosion.
Results and discussions

XRD patterns of the corrosion products of CS immersed in 0.05M HCO$_3^-$ solutions containing both SO$_4^{2-}$ and Cl$^-$ and the corrosion potential of CS in Pourbaix diagram

Anode:  \[
\text{Fe} + 2\text{H}_2\text{O} = \alpha-\text{FeOOH} + 3\text{H}^+ + 3\text{e}, \quad \text{pH}=8.33, \quad E_e=-0.742\text{V}
\]

Cathode: \[
\text{Fe}^{2+} + 8\alpha-\text{FeOOH} + 2\text{e} = 3\text{Fe}_3\text{O}_4 + 4\text{H}_2\text{O}, \quad E_e = -0.306\text{V}
\]

\[
3 \alpha-\text{FeOOH} + \text{H}^+ + \text{e} = \text{Fe}_3\text{O}_4 + 2\text{H}_2\text{O}, \quad E_e = -0.4521\text{V}
\]
Results and discussions

Polarization behaviors and corrosion potentials of CS in 0.1M HCO₃⁻ solutions containing Cl⁻

CS conducts transpassivation corrosion at low Cl⁻ concentration, morphologies show general corrosion; but converts to localized corrosion at higher than 0.05M
Results and discussions

Polarization behaviors and corrosion potentials of CS in 0.1M HCO₃⁻ solutions containing Cl⁻

The corrosion potential of CS decreases with increasing Cl⁻ concentration, corrosion mode converts from transpassivation to passivation.
Results and discussions

XRD patterns of the corrosion products after the immersion

Anode:  \[ \text{Fe} + 2\text{H}_2\text{O} = \alpha\text{-FeOOH} + 3\text{H}^+ + 3\text{e}, \text{pH}=8.33, E_e= -0.742\text{V} \]

Cathode: \[ \text{Fe}^{3+} + 8\alpha\text{-FeOOH} + 3\text{e} = 3\text{Fe}_3\text{O}_4 + 4\text{H}_2\text{O}, E_e = -0.0287\text{V} \]

\[ \text{Fe}^{2+} + 8\alpha\text{-FeOOH} + 2\text{e} = 3\text{Fe}_3\text{O}_4 + 4\text{H}_2\text{O}, E_e = -0.306\text{V} \]

\[ 3 \alpha\text{-FeOOH} + \text{H}^+ + \text{e} = \text{Fe}_3\text{O}_4 + 2\text{H}_2\text{O}, E_e = -0.4521\text{V} \]
Results and discussions

Polarization behaviors and corrosion potentials of CS in 0.1M HCO$_3^-$ solutions containing SO$_4^{2-}$

CS conducts anodic transpassivation in 0.1 HCO$_3^-$ solutions containing high SO$_4^{2-}$ concentration. morphologies after long term immersion show a general corrosion.
Results and discussions

Polarization behaviors and corrosion potentials of CS in 0.1M HCO$_3^-$ solutions containing SO$_4^{2-}$

<table>
<thead>
<tr>
<th>Solution</th>
<th>Time (days)</th>
<th>Potential vs SCE (V)</th>
<th>Current Density (A/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 mol/L NaHCO$_3$+0.1 mol/L Na$_2$SO$_4$</td>
<td>0 6 12 18 24 30 36</td>
<td>0.5 0.5 0.5 0.5 0.5 0.5 0.5</td>
<td>0.5 0.5 0.5 0.5 0.5 0.5 0.5</td>
</tr>
<tr>
<td>0.1 mol/L NaHCO$_3$+0.2 mol/L Na$_2$SO$_4$</td>
<td>0 6 12 18 24 30 36</td>
<td>0.5 0.5 0.5 0.5 0.5 0.5 0.5</td>
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<td>0.5 0.5 0.5 0.5 0.5 0.5 0.5</td>
</tr>
</tbody>
</table>

CS conducts anodic transpassivation in 0.1M HCO$_3^-$ solutions containing low SO$_4^{2-}$ concentration. Morphologies after long term immersion show a general corrosion.
Results and discussions

XRD patterns of the corrosion products after the immersion

Anode: \[ \text{Fe} + 2\text{H}_2\text{O} = \alpha\text{-FeOOH} + 3\text{H}^+ + 3\text{e}, \quad \text{pH}=8.33, \quad E_e=-0.742\text{V} \]

Cathode: \[ \text{Fe}^{3+} + 8\alpha\text{-FeOOH} + 3\text{e} = 3\text{Fe}_3\text{O}_4 + 4\text{H}_2\text{O}, \quad E_e = -0.0287\text{V} \]

\[ \text{Fe}^{2+} + 8\alpha\text{-FeOOH} + 2\text{e} = 3\text{Fe}_3\text{O}_4 + 4\text{H}_2\text{O}, \quad E_e = -0.306\text{V} \]

\[ 3 \alpha\text{-FeOOH} + \text{H}^+ + \text{e} = \text{Fe}_3\text{O}_4 + 2\text{H}_2\text{O}, \quad E_e = -0.4521\text{V} \]
Results and discussions

Polarization behaviors and corrosion potentials of CS in 0.1M HCO$_3^-$ solutions containing both SO$_4^{2-}$ and Cl$^-$

CS conducts transpassivation corrosion in 0.1M HCO$_3^-$ solutions containing both SO$_4^{2-}$ and Cl$^-$, localized corrosion morphologies were shown in high Cl$^-$ and low SO$_4^{2-}$ concentrations but general corrosion morphologies in low Cl$^-$ and high SO$_4^{2-}$.
Results and discussions

Polarization behaviors and corrosion potentials of CS in 0.1M HCO$_3^-$ solutions containing both SO$_4^{2-}$ and Cl$^-$. 

![Graphs showing polarization behaviors and corrosion potentials](image-url)
Results and discussions

XRD patterns of the corrosion products after the immersion

Anode:  $\text{Fe} + 2\text{H}_2\text{O} = \alpha\text{-FeOOH} + 3\text{H}^+ + 3\text{e}, \text{pH}=8.33, E_e=-0.742\text{V}$

Cathode: $\text{Fe}^{2+} + 8\alpha\text{-FeOOH} + 2\text{e} = 3\text{Fe}_3\text{O}_4 + 4\text{H}_2\text{O}, E_e = -0.306\text{V}$

$3\alpha\text{-FeOOH} + \text{H}^+ + \text{e} = \text{Fe}_3\text{O}_4 + 2\text{H}_2\text{O}, E_e = -0.4521\text{V}$
Corrosion modes of CS in the underground water

- Anodic active dissolution
- Trans-passivation
- Localized dissolution
- Passivation

Concentrated HCO₃⁻ solutions with low content of SO₄²⁻ and/or Cl⁻

Anodic dissolution in limited diffusion

Dilute HCO₃⁻ solutions with high content of SO₄²⁻ and/or Cl⁻
Effect of the ground water on the corrosion behavior of CS canister

- In pure $\text{HCO}_3^-$ solution, the corrosion potential of the immersed CS locates in limited diffusion range at low concentration but trans-passivation range at high concentration.

- Ether increasing $\text{Cl}^-$ or $\text{SO}_4^{2-}$ concentration in $\text{HCO}_3^-$ solutions can decrease the corrosion potentials of the immersed CS, which can converts corrosion mode from trans-passivation to localized corrosion even general corrosion.

- $\text{Cl}^-$ can cause pitting corrosion under proper conditions; $\text{SO}_4^{2-}$ just causes general corrosion;

- The mixture of $\text{Cl}^-$ and $\text{SO}_4^{2-}$ in $\text{HCO}_3^-$ solutions can also decrease the corrosion potentials of the immersed CS, high ratio of [Cl$^-$] to [SO$_4^{2-}$] causes pitting corrosion, low ratio of [Cl$^-$] to [SO$_4^{2-}$] causes general corrosion.
Results and discussions

Evolution of the Nyquist plots of low carbon steel during immersion

- 0.01C
- 0.01C+0.1Cl
- 0.01C+0.1S
- 0.01C+0.05Cl+0.05S
Results and discussions

Evolution of the Nyquist plots of low carbon steel during immersion
Results and discussions

Evolution of the Nyquist plots of low carbon steel during immersion
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Evolution of the Nyquist plots of low carbon steel during the immersion
Results and discussions

Evolution of the Nyquist plots of low carbon steel during immersion
Evolution of the Nyquist plots of low carbon steel during immersion
Corrosion rate of CS

- In 0.01M HCO$_3^-$ solution with Cl$^-$ and SO$_4^{2-}$, the corrosion rate is about 100$\mu$m/a.
- When HCO$_3^-$ concentration is higher than 0.05M, whether it contains Cl$^-$ or SO$_4^{2-}$, the corrosion rate will increase to about 1000$\mu$m/a.
- Relationship between corrosion current density and thickness loss for steel:
  \[100\mu\text{A/cm}^2 = 1.13\text{mm/a}\]
- If 1000a are required for the life time of CS canister during the disposal, the thickness design will be more than 1000mm, which meets a big problem!
Feasibility of CS Canister Used for HLW Geological Disposal

• The corrosion mode of CS canister will be observably influenced by the chemicals and concentrations in the underground water.

• In dilute HCO$_3^-$ solutions with Cl$^-\text{ and SO}_4^{2-}$, CS conducts anodic active dissolution, and may satisfy the requests for HLW geological disposal

• In more concentrated HCO$_3^-$ solutions with Cl$^-\text{ and SO}_4^{2-}$, CS conducts anodic trans-passivation or localized corrosion, and the corrosion rate is close to 1000$\mu$m/a, which may cause big difficulties for design and manufacture of the CS canisters.
谢谢垂听，欢迎光临

中国科学院金属研究所
Institute of Metal Research, Chinese Academy of Sciences

Thank you for your attention
Direct Disposal of Casks for Transportation and Storage CASTOR®

Enrique Biurrun

DBE TECHNOLOGY GmbH, Peine
Hoisting Cage for 85t Payload

Waste Emplacement Machine

Backfilling Slinger Truck in a Disposal Drift
Feasibility of Cask Direct Disposal

- Repository Design (thermal, mechanical)

- Handling and Disposal Design
  - Cask and cart loading into the shaft cage
  - Shaft hoisting to the underground disposal level
  - Cask and cart unloading from the shaft cage
  - Cask transfer in the shaft station to the transport and disposal vehicle
  - Transport to the disposal borehole with a battery driven locomotive
  - Cask disposal
Database 1

Handling and Transport of 12 different casks

<table>
<thead>
<tr>
<th>Transport and Storage Cask – Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>CASTOR® V/19 (up to Series Nr. 005)</td>
</tr>
<tr>
<td>CASTOR® V/19* (from Series Nr. 006)</td>
</tr>
<tr>
<td>CASTOR® V/52</td>
</tr>
<tr>
<td>CASTOR® Iia</td>
</tr>
<tr>
<td>CASTOR® Ic (Series Nr. 02)</td>
</tr>
<tr>
<td>CASTOR® 440/84</td>
</tr>
<tr>
<td>CASTOR® HAW 20 / 28 CG (up to Series Nr. 015)</td>
</tr>
<tr>
<td>CASTOR® HAW 20 / 28 CG (from Series Nr. 016)</td>
</tr>
<tr>
<td>CASTOR® HAW 28 M</td>
</tr>
<tr>
<td>CASTOR® TS 28 V</td>
</tr>
<tr>
<td>TN 24 E / TN 85</td>
</tr>
</tbody>
</table>

Cask Masses up to 160 t
Cask Variants

CASTOR® V/19

Source: GNS
Cask Variants

CASTOR® HAW 28 M

Quelle: GNS
Cask Example

CASTOR® HAW 28 M

Source: GNS
Features to consider in the design

- 7 different distances between trunnions
  
  (4.720 mm – 5.200 mm)

- Different trunnion geometries at the cask head (lid) end

- Different trunnion geometries at the cask bottom end

- Different diametrical distances between trunnions,
  
  (2.395 mm - 2.720 mm) at the head end

- Different diametrical distances between trunnions,
  
  (2.395 mm - 2.720 mm) at the bottom end

- Different position of the cask’s centers of gravity
## Hoisting System Design Data

### Schacht Hoist with 175 t payload

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shaft diameter</td>
<td>7.5 m</td>
</tr>
<tr>
<td>Disposal horizon</td>
<td>870 m</td>
</tr>
<tr>
<td>Shaft depth</td>
<td>950 m</td>
</tr>
<tr>
<td>Cask weight (max.)</td>
<td>160 t</td>
</tr>
<tr>
<td>Transport cart weight</td>
<td>15 t</td>
</tr>
<tr>
<td>Cage weight including floating floor</td>
<td>48 t</td>
</tr>
<tr>
<td>Counterweight</td>
<td>133 t</td>
</tr>
<tr>
<td>Ropes (6) diameter</td>
<td>66 mm</td>
</tr>
<tr>
<td>Maximum unbalance</td>
<td>90 t</td>
</tr>
<tr>
<td>Hoisting speed</td>
<td>1 m/s</td>
</tr>
</tbody>
</table>
Shaft Cage

Shaft Cage for 175 t Payload

- Cage ropes
- Cage bail
- Head frame
- Cage guide block
- Vertical beams
- Floating floor
- Cage bottom frame
- Tail ropes
Shaft Cage for 175 t Payload
Shaft Hoisting System

25t Crane

Machine floor
Hoisting machine and
Auxiliary hoist

Gripping and lifting
device

Bumper for hoisting cage
and counter weight
Gripper
Selda-system

Hoisting Cage
Shaft station at 0 m

Shaft cellar

Fire doors

Shaft diameter enlargement to 12m

Shaft station at disposal level - 870m

Rope deflector at Level - 895m
Handling Steps Underground

- Unloading from the shaft cage
- Transfer in the shaft station to transport and disposal vehicle
- Transport to the disposal borehole with a battery driven locomotive
- Disposal
Shaft Hoisting Cart

- Behältergewicht max. 160t
- Tragzapfen
- Eigengewicht ca. 15t
- 6 x 30t Achsen
- 2530
- 2280
- 1435
- Balken – zur Anpassung an Behälter
- Verriegelung

DEILMANN-HANIEL
SHAFT SINKING
Shaft Station at the 870 m-Level
Requirements on the Gantry Crane

- Operational
  - Cask lifting from the shaft hoisting cart
  - Cask loading onto disposal device (optionally in slightly inclined position as the borehole)
  - Handling of different cask types without backfitting

- Regulatory
  - KTA 3902 4.3 Lastaufnahmeverrichtung mit erhöhten Anforderungen – Status 06/1999 (lifting equipment for higher requirements)
  - According to 7.4.1.1 und 7.4.2.1 lifting capacity design with 1.25-times factored load
  - DIN 15018 Krane (11/1984)
Gantry Crane

Hydraulik - Agregat

Schwenkarm

Schwenkbalken

Hubportal

ca. 2800

7500

7000
Hoist and Swing Gear

- Displacement gear
- Hanger assembly
- Lift and swing beam
- Guide skid
- Lifting skid
- Lifting fishplate
### Gantry Crane Technical Data

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>ca. 130 t</td>
</tr>
<tr>
<td>Payload</td>
<td>max. 160 t</td>
</tr>
<tr>
<td>Length</td>
<td>ca. 8 m</td>
</tr>
<tr>
<td>Width</td>
<td>ca. 7.5 m</td>
</tr>
<tr>
<td></td>
<td>With electric engine for turning beam</td>
</tr>
<tr>
<td>Width</td>
<td>ca. 7 m</td>
</tr>
<tr>
<td></td>
<td>With electro-hydraulic engine for turning beam</td>
</tr>
<tr>
<td>Height</td>
<td>ca. 7 m</td>
</tr>
<tr>
<td>Height max.</td>
<td>ca. 8 m</td>
</tr>
</tbody>
</table>
CASTOR® Cask Disposal Field

Disposal field for 70 casks
Disposal Machine

Ansicht A

Schubvorrichtung
Hub 4x1630

500

2500

4500

6 Luftkissen ã 400 kN

Ansicht B

CASTOR® Behälter

Gleitsteine

2:1

1040

2090

2700

9300

14000

5000

Stützstempel
Cask on Lost Skid

![Diagram of Cask on Lost Skid with dimensions: height 390, length 6120]
DBE TECHNOLOGY GmbH

Thank you for your attention!
AGENDA

2nd Chinese-German Workshop on Radioactive Waste Disposal
Karlsruhe
October 15-16, 2012

Venue
Karlsruhe Institute of Technology (KIT)
Campus North, Building 419

Monday, October 15

11:30 - 13:00  Arrival & Registration & refreshment & Kantine

13:00  Welcome address KIT and PTKA/BGR/BMWi
13:15  Welcome address Mr. Lin, CNNC

13:30  Geological Disposal of high-level radioactive waste in China: update 2012 (Wang, BRIUG)
14:00  A new approach for siting a repository for HLW in Germany (Bräuer, BGR)

<table>
<thead>
<tr>
<th>Topic: Host rock characterization (rock mechanics / hydrogeology)</th>
</tr>
</thead>
</table>

14:30  Rock mass characterization for the preselected Beishan area, Gansu province of China’s HLW radioactive waste repository (Wang, CAS, Institute of Soil & Rock Mechanics)
15:00  Multi-scale applications of electrical resistivity tomography in the site characterization for HLW disposal (Zhou, Nanjing University)
15:30  Characterization of fracture networks on different scales (Li, Nanjing University)

16:00  Break

16:30  German experience & investigations regarding host rock characterization (Shao, Sönke, BGR)
17:00  Radionuclide transport in crystalline formations: laboratory and field experiments (Schäfer, KIT-INE)
17:30  A fractional derivative approach to creep of rock salt (Zhou, CU of Mining & Technology)
18:00  Basics of waste disposal in rock salt mass (Lux, TUC)

19:00  Dinner

21:30  Bus transport to hotels
Tuesday, October 16

**Topic: Technical / geotechnical barriers**

08:30  THMC-testing of expandable clays for potential use in HLW disposal repository (Liu, East China Institute of Technology)
09:00  Experimental investigation on thermo-hydraulic behavior of compacted GMZ02 bentonite (Ye, Tongji University)
09:30  Initial results on stability of natural GMZ Ca-Bentonite & modified Na-Bentonite under Thermal/radiation Aging (Yang, China Institute for Radiation Protection)
10:00  THM-Behavior of clay (Zhang, GRS)

**Break 10:30**

11:00  Bentonite characterization / behavior (Kaufhold/Dohrmann, BGR)
11:30  Project “PEBS” (Wiezcorek, GRS)
      Modeling of Bentonite behavior (Li, TU Clausthal)

12:00 – 13:00 Lunch

**Topic: RN-Behavior**

13:00  Study on the long-term behavior of HLW glass in geological conditions (Wang, CAEA)
13:30  Source Terms for highly radioactive wastes (HLW glass and spent fuel)
      (Geckeis, Kienzler, KIT/INE)
14:00  RN migration research to support geological disposal of HLW in China (Zhou, CAEA)
14:30  Critical issues for Pu239 in geological disposal (Tuo, Chendu University)
      Chemical behavior of 239Pu in the groundwater solution (Huang, Chendu University)

**Topic: Technical/Engineering**

15:00  Feasibility of CS canister used for HLW geological disposal (Dong, CAS, Inst. of Metal Research)
15:30  German concepts for containers/casks for HLW-disposal (Filbert, Bollingerfahr, Biurrun, DBE Tec)
16:00  Summary

**Adjourn 17:00**

**Transport to Karlsruhe Main Station / Hotels**

Optional: Technical visit Schachtanlage Konrad, October 18, 2012

**Wednesday, October 17**

Transport by bus from Karlsruhe to Wolfenbüttel (Parkhotel)

**Thursday, October 18**

Technical Visit “Schachtanlage Konrad”, bus to Frankfurt
<table>
<thead>
<tr>
<th>Name</th>
<th>Organization</th>
<th>Address</th>
<th>Email</th>
</tr>
</thead>
<tbody>
<tr>
<td>Junhua DONG</td>
<td>Institute of Metal Research, CAS</td>
<td>62, Wencui Road, Shenyang, 110016, China</td>
<td><a href="mailto:jhdong@imr.ac.cn">jhdong@imr.ac.cn</a></td>
</tr>
<tr>
<td>Bo WANG</td>
<td>China Institute of Atomic Energy (CIAE)</td>
<td>P.O. Box 275-93, Xin Zhen, Fang Shan District, Beijing 102413</td>
<td><a href="mailto:yxywb4672@163.com">yxywb4672@163.com</a></td>
</tr>
<tr>
<td>Duo ZHOU</td>
<td>China Institute of Atomic Energy (CIAE)</td>
<td>P.O. Box 275-93, Xin Zhen, Fang Shan District, Beijing 102413</td>
<td><a href="mailto:zd-ciae@163.com">zd-ciae@163.com</a></td>
</tr>
<tr>
<td>Hongwei ZHOU</td>
<td>China University of Mining and Technology (Beijing)</td>
<td>Xueyuan Road D11, Beijing 100083</td>
<td><a href="mailto:zhw@cumtb.edu.cn">zhw@cumtb.edu.cn</a></td>
</tr>
<tr>
<td>Xiaozhao LI</td>
<td>Nanjing University</td>
<td>Han Kou Road #22, Nanjing 210093</td>
<td><a href="mailto:lixz@nju.edu.cn">lixz@nju.edu.cn</a></td>
</tr>
<tr>
<td>Weimin YE</td>
<td>Tongji University</td>
<td>1239 Siping Road, Shanghai</td>
<td><a href="mailto:Ye_tju@tongji.edu.cn">Ye_tju@tongji.edu.cn</a></td>
</tr>
<tr>
<td>Tao LIU</td>
<td>Southwest university of science and technology</td>
<td>59, Mid-section of Quinglong Road, Fucheng district, Mianyang, Sichuan, China, 621010</td>
<td><a href="mailto:swust_lt@sina.com">swust_lt@sina.com</a></td>
</tr>
<tr>
<td>Jinyong XU</td>
<td>Chengdu University of Technology</td>
<td>No. 1, Dongsan Road, Erxianqiao, Chenghua District, Chengdu</td>
<td><a href="mailto:xujinyong@cdut.cn">xujinyong@cdut.cn</a></td>
</tr>
<tr>
<td>Lin Sen</td>
<td>CNNC, Department of International Business</td>
<td>No.1, Nansanxiang, Sanlihe, Xicheng</td>
<td><a href="mailto:Lins8080@163.com">Lins8080@163.com</a></td>
</tr>
<tr>
<td>Ning LI</td>
<td>China Nuclear Power Engineering Co., Ltd.</td>
<td>No. 117, Xisanhuanbeilu, Haidian District, Beijing, 100840</td>
<td><a href="mailto:lininga@cnpe.cc">lininga@cnpe.cc</a></td>
</tr>
<tr>
<td>Xuhong WANG</td>
<td>China Nuclear Power Engineering Co. Ltd.</td>
<td>No. 117, Xisanhuanbeilu, Haidian District, Beijing, 100840</td>
<td><a href="mailto:wangxh@cnpe.cc">wangxh@cnpe.cc</a></td>
</tr>
<tr>
<td>Qiuyu YANG</td>
<td>China Nuclear Power Engineering Co. Ltd.</td>
<td>No. 117, Xisanhuanbeilu, Haidian District, Beijing, 100840</td>
<td><a href="mailto:yangqy@cnpe.cc">yangqy@cnpe.cc</a></td>
</tr>
<tr>
<td>Liang XIE</td>
<td>China Nuclear Power Engineering Co. Ltd.</td>
<td>No. 117, Xisanhuanbeilu, Haidian District, Beijing, 100840</td>
<td><a href="mailto:xieliang@cnpe.cc">xieliang@cnpe.cc</a></td>
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<tr>
<td>Hongbin MA</td>
<td>China Nuclear Power Engineering Co. Ltd.</td>
<td>No. 117, Xisanhuanbeilu, Haidian District, Beijing, 100840</td>
<td><a href="mailto:anhuima@yahoo.cn">anhuima@yahoo.cn</a></td>
</tr>
<tr>
<td>Zhongtian YANG</td>
<td>China Institute for Radiation Protection</td>
<td>Xuefu street, P.O. Box 120, 030006, Taiyuan, Shanxi Province</td>
<td><a href="mailto:ztyang@263.net">ztyang@263.net</a></td>
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<td>Qiyou ZHOU</td>
<td>Nanjing University</td>
<td>Han Kou Road #22, Nanjing 210093</td>
<td><a href="mailto:zhouqy@nju.edu.cn">zhouqy@nju.edu.cn</a></td>
</tr>
<tr>
<td>Pinghui LIU</td>
<td>East China Institute of Technology</td>
<td>No. 56 Xuefu Road, Fuzhou City, Jiangxi Province, 344000</td>
<td><a href="mailto:pinghui_liu@126.com">pinghui_liu@126.com</a></td>
</tr>
<tr>
<td>Guibin WANG</td>
<td>Institute of Rock and Soil Mechanics, Chinese Academy of Science</td>
<td>Xiao Hong Shan, Wuchang District, Wuhan, Hubei, China, 40071</td>
<td><a href="mailto:gbwang@whrs.ac.cn">gbwang@whrs.ac.cn</a></td>
</tr>
<tr>
<td>Taian LUO</td>
<td>East China Institute of Technology</td>
<td>No. 56 Xuefu Road, Fuzhou City, Jiangxi</td>
<td><a href="mailto:taluo@ecit.cn">taluo@ecit.cn</a></td>
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<tr>
<td>Ju WANG</td>
<td>Beijing Research Institute of Uranium Geology</td>
<td>10 Xiaoguandongli, Anwai, Beijing 100029</td>
<td><a href="mailto:Wangju@briug.cn">Wangju@briug.cn</a></td>
</tr>
<tr>
<td>Nana LI</td>
<td>Beijing Research Institute of Uranium Geology</td>
<td>10 Xiaoguandongli, Anwai, Beijing 100029</td>
<td><a href="mailto:linana@briug.cn">linana@briug.cn</a></td>
</tr>
<tr>
<td>Yuanxin JIN</td>
<td>Beijing Research Institute of Uranium Geology</td>
<td>10 Xiaoguandongli, Anwai, Beijing 100029</td>
<td><a href="mailto:jinyuanxin@briug.cn">jinyuanxin@briug.cn</a></td>
</tr>
<tr>
<td>Xiyong WANG</td>
<td>Beijing Research Institute of Uranium Geology</td>
<td>10 Xiaoguandongli, Anwai, Beijing 100029</td>
<td><a href="mailto:wangxiyong@briug.cn">wangxiyong@briug.cn</a></td>
</tr>
<tr>
<td>Yu TAO</td>
<td>CNNC, Department of International Cooperation</td>
<td>No.1, Nansanxiang, Sanlihe, Xicheng</td>
<td><a href="mailto:549502986@qq.com">549502986@qq.com</a></td>
</tr>
<tr>
<td>STEININGER Walter</td>
<td>KIT/PTKA-WTE</td>
<td>Karlsruhe Institut für Technologie, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen</td>
<td><a href="mailto:Walter.steninger@kit.edu">Walter.steninger@kit.edu</a></td>
</tr>
<tr>
<td>BRÄUER Volkmar</td>
<td>BGR</td>
<td>Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Geozentrum Hannover Stilleweg 2, 30655 Hannover</td>
<td><a href="mailto:Volkm.braeuer@bgr.de">Volkm.braeuer@bgr.de</a></td>
</tr>
<tr>
<td>SHAO Hua</td>
<td>BGR</td>
<td>Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Geozentrum Hannover Stilleweg 2, 30655 Hannover</td>
<td><a href="mailto:shao@bgr.de">shao@bgr.de</a></td>
</tr>
<tr>
<td>SÖNNKE Jürgen</td>
<td>BGR</td>
<td>Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Geozentrum Hannover Stilleweg 2, 30655 Hannover</td>
<td><a href="mailto:Juergen.soennke@bgr.de">Juergen.soennke@bgr.de</a></td>
</tr>
<tr>
<td>DOHRMANN Reiner</td>
<td>BGR</td>
<td>Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Geozentrum Hannover Stilleweg 2, 30655 Hannover</td>
<td><a href="mailto:Reiner.dohrmann@bgr.de">Reiner.dohrmann@bgr.de</a></td>
</tr>
<tr>
<td>KAUFHOLD Stephan</td>
<td>BGR</td>
<td>Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Geozentrum Hannover Stilleweg 2, 30655 Hannover</td>
<td><a href="mailto:Stephan.kaufhold@bgr.de">Stephan.kaufhold@bgr.de</a></td>
</tr>
<tr>
<td>MENTE Michael</td>
<td>BGR</td>
<td>Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Geozentrum Hannover Stilleweg 2, 30655 Hannover</td>
<td><a href="mailto:Michael.mente@bgr.de">Michael.mente@bgr.de</a></td>
</tr>
<tr>
<td>LUX Karl-Heinz</td>
<td>TU Clausthal</td>
<td>Institut für Aufbereitung, Deponietechnik und Geomechanik, Lehrstuhl für Deponietechnik und Geomechanik, Erzstraße 20, 38678 Clausthal-Zellerfeld</td>
<td><a href="mailto:lux@tu-clausthal.de">lux@tu-clausthal.de</a></td>
</tr>
<tr>
<td>HERCHEN Kai</td>
<td>TU Clausthal</td>
<td>Institut für Aufbereitung, Deponietechnik und Geomechanik, Erzstraße 20, 38678 Clausthal-Zellerfeld</td>
<td><a href="mailto:Kai.Herchen@tu-clausthal.de">Kai.Herchen@tu-clausthal.de</a></td>
</tr>
<tr>
<td>HOU Michael</td>
<td>TU Clausthal</td>
<td>Technische Universität Clausthal, Institut für Erdöl- und Erdgastechnik, Agricolastraße 10 38678 Clausthal-Zellerfeld</td>
<td><a href="mailto:hou@tu-clausthal.de">hou@tu-clausthal.de</a></td>
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<td>Name</td>
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<tr>
<td>LI Xiaoshuo</td>
<td>TU Clausthal</td>
<td>Technische Universität Clausthal, Institut für Endlagerforschung, Adolph-Roemer-Straße 2A, 38678 Clausthal-Zellerfeld</td>
<td><a href="mailto:xiaoshuo.li@tu-clausthal.de">xiaoshuo.li@tu-clausthal.de</a></td>
</tr>
<tr>
<td>ROTHFUCHS Tilman</td>
<td>GRS</td>
<td>Gesellschaft für Anlagen- und Reaktorsicherheit mbH, FB Endlagersicherheitsforschung, Theodor-Heuss-Str. 4, 38122 Braunschweig</td>
<td><a href="mailto:Tilman.rothfuchs@grs.de">Tilman.rothfuchs@grs.de</a></td>
</tr>
<tr>
<td>MÖNIG Jörg</td>
<td>GRS</td>
<td>Gesellschaft für Anlagen- und Reaktorsicherheit mbH, FB Endlagersicherheitsforschung, Theodor-Heuss-Str. 4, 38122 Braunschweig</td>
<td><a href="mailto:Joerg.moenig@grs.de">Joerg.moenig@grs.de</a></td>
</tr>
<tr>
<td>ZHANG Chun-Liang</td>
<td>GRS</td>
<td>Gesellschaft für Anlagen- und Reaktorsicherheit mbH, FB Endlagersicherheitsforschung, Theodor-Heuss-Str. 4, 38122 Braunschweig</td>
<td><a href="mailto:Chun-Liang.zhang@grs.de">Chun-Liang.zhang@grs.de</a></td>
</tr>
<tr>
<td>WIECZOREK Klaus</td>
<td>GRS</td>
<td>Gesellschaft für Anlagen- und Reaktorsicherheit mbH, FB Endlagersicherheitsforschung, Theodor-Heuss-Str. 4, 38122 Braunschweig</td>
<td><a href="mailto:Klaus.wieczorek@grs.de">Klaus.wieczorek@grs.de</a></td>
</tr>
<tr>
<td>BREUSTEDT Michael</td>
<td>DBE TECHNOLOGY</td>
<td>Eschenstraße 55, D-31224 Peine</td>
<td><a href="mailto:breustedt@dbe.de">breustedt@dbe.de</a></td>
</tr>
<tr>
<td>BÜHLER Michael</td>
<td>KIT/PTKA-WTE</td>
<td>KIT, Hermann-von-Helmholtz-Platz 1,</td>
<td><a href="mailto:Michael.buehler@kit.edu">Michael.buehler@kit.edu</a></td>
</tr>
<tr>
<td>BITTDORF Holger</td>
<td>KIT/PTKA-WTE</td>
<td>KIT, Hermann-von-Helmholtz-Platz 1,</td>
<td><a href="mailto:holger.bittdorf@kit.edu">holger.bittdorf@kit.edu</a></td>
</tr>
<tr>
<td>STACHEDER Markus</td>
<td>KIT/PTKA-WTE</td>
<td>KIT, Hermann-von-Helmholtz-Platz 1,</td>
<td><a href="mailto:Markus.stacheder@kit.edu">Markus.stacheder@kit.edu</a></td>
</tr>
<tr>
<td>KIENZLER Bernhard</td>
<td>KIT/INE</td>
<td>KIT, Hermann-von-Helmholtz-Platz 1,</td>
<td><a href="mailto:Bernhard.kienzler@kit.edu">Bernhard.kienzler@kit.edu</a></td>
</tr>
<tr>
<td>GECKEIS Horst</td>
<td>KIT/INE</td>
<td>KIT, Hermann-von-Helmholtz-Platz 1,</td>
<td><a href="mailto:Horst.geckeis@kit.edu">Horst.geckeis@kit.edu</a></td>
</tr>
<tr>
<td>SCHÄFER Thorsten</td>
<td>KIT/INE</td>
<td>KIT, Hermann-von-Helmholtz-Platz 1,</td>
<td><a href="mailto:Thorsten.schafer@kit.edu">Thorsten.schafer@kit.edu</a></td>
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