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3rd Chinese-German Workshop on Radioactive Waste Disposal

Plaza Holiday Inn
Jiayuguan, Gansu Province, China
May 15-19, 2017

A joint workshop organized by
Beijing Research Institute of Uranium Geology, (BRIUG), China
China National Nuclear Corporation (CNNC), China
Federal Institute for Geosciences and Natural Resources (BGR), Germany
Project Management Agency Karlsruhe (PTKA) - Karlsruhe Institute of Technology, Germany

Ed. W. Steininger

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www.ptka.kit.edu/wte/171.php
des PTKA zu finden.
Foreword

Most countries using nuclear power have to deal with the problem of safe disposal of radioactive, esp. highly radioactive, wastes (spent fuel, high-level waste, and some types of long-lived radioactive waste). Though worldwide a repository is still pending, the progress in some national programs is very promising, so that in the next five to ten years the realization of an operating repository might be possible.

Internationally there is consensus that the preferred solution to dispose of these waste types is disposal in deep geological repositories. Preferable and favored host-rock media are 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. Moreover, it is undisputable 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. It is also accepted that international cooperation is an essential part in any national program worldwide.

Against this general background, the 1st Chinese-German Workshop on Radioactive Waste Disposal was successfully held in Beijing, May 2007. The main purpose of this workshop was to present ideas, exchange information, and to foster discussion among the experts. Considering the bilateral common interests and the changes in the national programs, PTKA, BGR, and BRIUG decided to organize jointly the 2nd Chinese-German Workshop on Radioactive Waste Disposal held in Karlsruhe in 2012.

It was recognized that the purpose of the first workshop still was very important and it deemed necessary to inform mutually on new developments and advancements in the national HLW-disposal programs. Especially the exchange on current R&D outcomes and the progress made on results regarding crystalline and argillaceous host rock, should be emphasized. The Chinese and German attendants represented academia, industry, research, state-owned organizations and other important institutions involved in radioactive waste management activities.

Since then in both countries progress was made and important changes occurred in waste management.

Because of the impressive progress in the Chinese program, esp. with respect to siting and towards the implementation of an Underground Research Laboratory, it was agreed upon to organize the 3rd Workshop in China. This should provide the opportunity to share with one another the progress that has been made within our national programmes emphasizing crystalline rock and clay rock, to discuss current scientific activities, and to look at how we might broaden our cooperation. The highlight of the workshop was the visit of the siting region in Beishan and the underground exploration tunnel.
About 100 participants attended the workshop. There were a lot of interesting and informative presentations on current R&D activities on aspects of site selection, repository concepts, modelling, experiments, and safety case. These presentations served as basis for exchange and discussion.

It was agreed to collect the excellent presentations and to make them 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 and very much appreciate the support and interest of CNNC and BMWi.

Ju Wang, BRIUG  Hua Shao, BGR  Walter Steininger, PTKA
Table of Contents

Keynote: Geological disposal of high-level radioactive waste in China: Update 2017 Wang, J., Beijing Research Institute of Uranium Geology, (BRIUG) 1

**Topic 1: Site Selection**

<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany’s new approach for siting a nuclear waste repository</td>
<td>71</td>
</tr>
<tr>
<td>Bräuer, V., Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)</td>
<td></td>
</tr>
<tr>
<td>Research progress on the design of high-level radioactive waste disposal URL in china</td>
<td>95</td>
</tr>
<tr>
<td>Rong, F., The Fourth Research and Design Engineering Corporation of CNNC</td>
<td></td>
</tr>
<tr>
<td>Underground exploration for mechanical and hydraulic characterization of host rocks</td>
<td>96</td>
</tr>
<tr>
<td>Hesser, J., Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)</td>
<td></td>
</tr>
<tr>
<td>A new rock classification system $Q_{HLW}$ for geological disposal and its application in China’s URL site Selection</td>
<td>114</td>
</tr>
<tr>
<td>Chen, L., Beijing Research Institute of Uranium Geology (BRIUG)</td>
<td></td>
</tr>
<tr>
<td>Underground application of non-destructive geophysical methods (seismic, temperature, EMR, ERT) for site investigation</td>
<td>145</td>
</tr>
<tr>
<td>Musmann, P., Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), et al.</td>
<td></td>
</tr>
<tr>
<td>Siting of clay formation as the potential host rock for HLW disposal repository in northwest China</td>
<td>180</td>
</tr>
<tr>
<td>Liu, X., Jiujiang University, et al.</td>
<td></td>
</tr>
</tbody>
</table>

**Topic 2: Repository Concepts and Technology**

<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concepts and emplacement technologies for an HLW repository in Germany</td>
<td>225</td>
</tr>
<tr>
<td>Bertrams, N., DBE Technology GmbH</td>
<td></td>
</tr>
<tr>
<td>Test of VPC glass in Beishan granite-GMZ bentonite barrier</td>
<td>242</td>
</tr>
<tr>
<td>Zhang, Z., China Institute of Atomic Energy (CIAE)</td>
<td></td>
</tr>
<tr>
<td>Disposal without monitoring? Yin without Yang?</td>
<td>243</td>
</tr>
<tr>
<td>Lux, K.-H., Clausthal University of Technology</td>
<td></td>
</tr>
<tr>
<td>Long-term performance of GMZ bentonite as buffer material for HLW repository in China</td>
<td>292</td>
</tr>
<tr>
<td>Liu, Y., Beijing Research Institute of Uranium Geology (BRIUG)</td>
<td></td>
</tr>
<tr>
<td>Laboratory investigations of HLRW bentonites</td>
<td>330</td>
</tr>
<tr>
<td>Kaufhold, St., Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)</td>
<td></td>
</tr>
<tr>
<td>Investigation into chemical effects on mechanical properties of GMZ bentonite</td>
<td>353</td>
</tr>
<tr>
<td>Ye, W., Tongji University, et al.</td>
<td></td>
</tr>
<tr>
<td>Sealing performance of clay-based materials</td>
<td>354</td>
</tr>
<tr>
<td>Zhang, C-L., Gesellschaft für Anlagen- und Reaktorsicherheit (GRS)</td>
<td></td>
</tr>
<tr>
<td>Corrosion behavior of low carbon steel for HLW geological disposal</td>
<td>372</td>
</tr>
<tr>
<td>Dong, J., Institute of Metal Research, Chinese Academy of Sciences</td>
<td></td>
</tr>
</tbody>
</table>
**Topic 3: Modelling**

Benchmark project for flow and transport in fractured rock and coupled THM processes in bentonite  
*Shao, H., Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)*  

Analysis of discontinuities based on the integration of measurements, experiments and modeling  
*Li, X., Nanjing University*

**d³f++ - Modelling tool for density-driven flow and transport**  
*Zhao, H., Gesellschaft für Anlagen- und Reaktorsicherheit (GRS)*  

**3D geological model of URL in Xinchang preselected site**  
*Luo, H., Beijing Research Institute of Uranium Geology (BRIUG)*

Simulation of density-driven flow in heterogeneous and fractured porous media  
*Wittum, G., Goethe University Frankfurt/Mai, et al.*

Discrete fracture network modelling of surrounding rock for HLW disposal  
*Liu, J., Beijing Research Institute of Uranium Geology (BRIUG), et al.*

Continuous workflows for process analysis in radioactive waste disposals  
*Kolditz, O., Helmholtz-Zentrum für Umweltforschung (UFZ), et al.*

Hydrogeological characterization of fractured granite in Xinchang Area  
*Ji, R., Beijing Research Institute of Uranium Geology (BRIUG)*

ReSUS: A new probabilistic and sensitivity analysis software tool and its test problems  
*Li, X., Clausthal University of Technology, et al.*

**Topic 4: Experiments**

Coupled processes controlling radionuclide behavior in nuclear waste repository compartments  
*Schäfer, T., Karlsruhe Institute of Technology, Institute for Nuclear Waste Disposal (KIT-INE), et al.*

Research on EDZ characterization system for URL: Field EDZ monitoring experiment at Beishan Exploration Tunnel  
*Yang, Ch., Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, et al.*

Mineralogical investigations of large-scale deposition tests  
*Kaufhold, St., Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)*

The redox behavior of uranium on Beishan granite  
*Kang, M., Sun Yat-sen University, et al.*

GRS’ on-site demonstration work on buffer and backfill materials  
*Czaikowski, O., Gesellschaft für Anlagen- und Reaktorsicherheit (GRS), et al.*

Adsorption of radionuclides on Beishan granite  
*Guo, Z., Lanzhou Universit, et al.*

Application of seismic and electro-magnetic reflection methods for underground investigation in a salt mine  
*Musmann, P., Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), et al.*
The latest progress of radionuclide migration in CIAE  
Zhou, D., China Institute of Atomic Energy (CIAE), et al.  

Preliminary research on technical feasibility of applying TBM in URL engineering  
Ma, H., Beijing Research Institute of Uranium Geology (BRIUG), et al.  

**Topic 5: Safety Case Aspects**

Advance in safety assessment of geological disposal of HLW in China at siting stage  
Li, H., China Institute for Radiation Protection  

Safety case approaches in Germany  
Wolf, J., Gesellschaft für Anlagen- und Reaktorsicherheit (GRS)  

**Special Sessions**

**Session 1 Repository Concept and Engineered barriers**

A preliminary study on in situ tests of disposal process of high-level waste in underground research laboratory in China  
Hou, W., China Nuclear Power Engineering Co., Ltd  

Performance of buffer material under coupled THM conditions  
Chao, S., Beijing Research Institute of Uranium Geology (BRIUG)  

Detecting the redox condition of groundwater environment in Beishan granite using fracture mineral distribution and geochemistry  
Xiao Tian, X., Beijing Research Institute of Uranium Geology (BRIUG)  

Effect of GMZ bentonite on the corrosion evolution of NiCu low alloy steel  
Wei, X., Institute of Metal Research, Chinese Academy of Sciences, et al.  

Discussion on retrievability strategy of radioactive waste disposal in China  
Wang, X., China Nuclear Power Engineering Co., Ltd  

Calculation on nuclide transport for rock cavern disposal by compartment model  
Liu, X., China Nuclear Power Engineering Co., Ltd  

Preparation of large-scale compacted block of bentonite-sand mixture as HLW buffer  
Sheng, X., Lanzhou University  

Laboratory investigations of joint on self-sealing behaviour of compacted bentonite block  
Wang, Y., Lanzhou University  

**Session 2 Construction Technologies and Hydrogeology**

Research of granite mechanical properties  
Wang, Y., China Institute of Water Resources and Hydropower Research  

Detection technologies of geological safety for disposal laboratory construction  
Yang, F., China University of Mining & Technology, Beijing  

Study on the relationship between mineral composition and engineering intensity of the upper mudstone at the Bayinggebi group in the Tamusu preselected site of clay rock as the host rock for HLW repository  
Liu, P., East China University of Technology
Field experiment on deformation monitoring of surrounding rock in BET 1034
Li, E., PLA University of science and technology

The study of BET fracture grouting 1035
Xu, Q., The Forth Research and Design Engineering Corporation of CNNC

Study on the security monitor method of URL 1036
Duan, X., The Fourth Research and Design Engineering Corporation of CNNC

Experimental analysis study on direct tensile test of rocks in URL for high-level radioactive waste disposal 1037
Liu, C., Shandong University

Introduction of the Beishan Exploration Tunnel (BET) 1063
Chen, L., Wang, J., Beijing Research Institute of Uranium Geology (BRIUG)

Annex
Agenda 1074
List of Participants 1081
Pictures 1088
Geological disposal of high level radioactive waste in China: Update 2017

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Abstract: In October 2012 the State Council of China approved an updated “Medium- to- Long Term Plan for the Development of Nuclear Power Plants in China (2011–2020),” which reaffirmed its support for nuclear power development in China. The updated plan is that the installed capacity of NPP should reach 58 GW by the year 2020, while other 30 GW under construction. The spent fuel generated from those NPPs will reach 83,000 tons by 2050. The Chinese policy is that the spent fuel from light water reactors should be reprocessed first, followed by vitrification, and then finally disposed in a centralized geological repository. The preliminary repository concept is a shaft-tunnel model, located in saturated zones in granite, and the final form for disposal is vitrified HLW and some amount of spent fuel which are not suitable for reprocessing. The geological disposal program is divided into three stages: (1) Laboratory Studies and Site Selection for HLW Repository (2006–2020); (2) Underground in-situ tests (2021–2040); (3) Repository construction (2041–2050).

One of the major milestones set in 2006 was to complete the construction of an underground research laboratory (URL) by 2020. However, in the latest “Nuclear Energy Development in the 13th Five-Year Plan” in 2017, the goal to build the URL has been changed to “start the construction of an URL in the 13th Five Year Plan”.

The deep geological disposal program for HLW in China entered into a new steady development stage in the 21st Century. Significant progresses have been made in the areas of law and regulation, technical standards, site selection and site characterization, engineered barrier study, conceptual design for repository and underground research laboratory.

The highlights of the geological disposal program are summarized below. The Law on Prevention of Radioactive Pollution was issued in 2003, demanding that the high level radioactive waste should be disposed of in deep geological repositories. The R&D Plan and Guidelines for Geological Disposal of High Level Radioactive Waste was published in 2006. The Nuclear Safety Guideline “Site Selection for Geological Disposal Facilities of High-Level Radioactive Waste” was published in 2013.

The Beishan area in Western China’s Gansu province was selected as the first priority area for the HLW repository, the site characterization methodologies have been established, and more than 70 boreholes have been drilled in order to characterize the sites.

The Gaomiaozi bentonite has been selected as the first-priority buffer material for China’s repository, and a large scale mock-up (China-Mock-Up) has been established in order to study the behavior of bentonite under coupled thermal-hydraulic-mechanical-chemical conditions. Migration behavior data on some key radionuclides have been obtained, while preliminary safety assessment conducted.

During 2015-2017, significant progresses have been achieved for the construction of the URL. In 2016, the site for the URL has been determined: the Xinchang site in Beishan region has been selected as the final site for URL, and comprehensive site investigation has been conducting in the
site since then. The preliminary design for the URL also completed, which includes 3 shafts and one ramp to be excavated by TBM. The major characterization level of the URL will be -240 m and -560 m. Right now, the preparation for the URL is underway.

In order to obtain technology for the construction and monitoring of underground facilities in the Beishan granite, the Beishan Exploration Tunnel (BET) was built in 2015, several in situ experiments have been completed in BET.

The progress and achievements in the past years have provided sound bases for China to build an underground research laboratory and to develop technologies for final disposal of high level radioactive waste.
CHINESE-GERMAN WORKSHOP ON RADIOACTIVE WASTE DISPOSAL
May 28-31, 2007, Beijing, China
2nd Chinese-German workshop on Radioactive Waste Disposal
October, 2012, Karlsruhe, Germany

中国高放废物地质处置及地下实验室规划进展

Ju WANG 王 駒，核工业北京地质研究院
Beijing Research Institute of Uranium Geology, China National Nuclear Corporation (CNNC)
Nuclear power plants in the Chinese Mainland in 2016: 36 reactors in operation, 20 under construction

中国大陆核电站：36个投入运行，24个在建
Nuclear power plants in China

- 30 reactors in operation in 2016
- 24 reactors under construction in 2016
- Plan for 2020:
  - 58 GW in operation
  - 30 GW under construction

Total amount of spent fuel from the 58 reactors: 14,000 tons
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
Nuclear fuel cycle: from spent fuel to repository
A 3-step strategy for HLW disposal

Here we are

Site → URL → Repository

中国高放废物地质处置 3 部曲式的技术路线
Site selection--History

1986: Site selection started
1989: 6 regions selected for high level radioactive waste repository
1990: sub-area selection in Beishan site, NW China’s Gansu province
2000: systematical site characterization in NW China’s Gansu, Xinjiang, Inner Mongolia
2007: 1st Chinese-German workshop held in Beijing
2012: 2nd Chinese-German workshop held in Karslur
2016: an URL site selected
6 candidate regions for repository

- NW China: Beishan
- Xinjiang
- Inner Mongolia
- SW China
- E China
- S China
Beishan: a flat hilly area
1-Q, 2-Metamorphic rock, 3-Bantan unit, 4-Jiujing unit
Beishan site: considered as the first priority site for China’s high level radioactive waste repository （北山：中国高放废物处置库首选场址）

- 39 boreholes have been drilled in the site.
- 已经完成 39 个钻孔

- 6 boreholes are drilling today (May 16, 2017)
Opening Ceremony for borehole BS16 (May 13, 2017)
Core samples from BS 16
Surface geophysical survey: to investigate the faults
钻孔双栓塞水文地质试验系统是国内首套适合干旱地区低渗透介质渗透性评价的先进设备。具有性能优良、自动化数据采集、分段适时监测压力温度等特点。最大安装深度600米工作；最大降深190米；抽水流量范围4.8-50l/min。

Double Packer Hydraulic Test System is an advanced equipment suitable for hydraulic characterization of low-permeable medium in arid area. It is characterized by advanced performance and automatic data acquisition and timely monitoring of pressure/ temperature in different intervals. Maximum Installed Depth: 600m; Maximum Drawdown: 190m; Discharge: 4.8-50l/min.
Groundwater chemistry

- TDS 3-4 g/L
- pH 7-8
- Eh -250 mV
- Cl\(^-\), SO\(_4^{2-}\)
Preliminary concept model for hydrogeology

"Active zone"

Stagnant water

REPOSITORY
Rock mechanical studies

- Uniaxial/triaxial compressive test
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
The 4 candidate areas in Xinjiang
2. Engineering design

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 disposal concept

Host rock

Vitrifided waste

Container and canister

Buffer material

高放废物处置库概念设计
Preliminary repository concept

- Container
- Canister
- Buffer
- Glass
3. Engineered barrier system development

The GMZ bentonite deposit, located in Inner Mongolia, has been selected as the most potential supplier for buffer material.

The tonnage of the GMZ bentonite is about 160 million ton.

A large-scale mock-up has been 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)
台架运行数据
5. Safety assessment

• Preliminary safety assessment has been conducted for China’s repository concept, by using Beishan site as a reference site.
Disposal System
Variant Case 2: short-cut the NF host rock

- Peak annual dose from a single waste package is $1.45\times10^{-4}\mu Sv/yr$
- Simple scaling to the whole repository, the peak annual dose is 0.02 mSv/yr.
Plan for China’s Underground Research Laboratory
Start to build an Underground Research Laboratory for geological disposal of high level radioactive waste
Basic consideration for China’s URL

“Area-specific URL”
- Located at 500m-700m in depth;
- Large-sized, and with complete functions
- Expandable,
- International level,
- Open for International cooperation
- One URL in granite, one in clay
Main functions/roles of URL

- **Basic functions:**
  - Characterization of deep geological environment
  - Implementation of full-scale tests
  - Technology development
  - Demonstration of the disposal technologies
  - International cooperation and Staff training
  - Public acceptance

- **and probably:**
  - Provide parameters for the repository design, safety assessment,
  - Become a part of the final repository……
R&D Plan before 2020

Project I: Basic theoretic and technologic studies
- Design and construction technologies
- Measurement techniques of key parameters
- Long-term stability analysis

Project II: Pre-studies of URL
- Site selection
- R&D planning in URL
- URL design
- Data acquisition and management system

Project III: URL construction
- Surface facilities
- Shaft and access galleries
- Experimental galleries
- Other subsidiary systems

Timeline: 2014 - 2020
The 9 candidate sites for URL

Xinjiang
Beishan
Inner Mongolia

地下实验室场址筛选
Xinchang, the site for China’s URL has been selected in March 2016.
Geological Map of Xinchang site
Xinchang has been selected as the URL site in 2016

甘肃北山新场：地下实验室场址
Design for China’s URL, and site characterization in Xinchang are underway.
Core sample from BS32: good integrity
URL design
地下实验室方案设计
The Beishan URL
岩体完整性好，强度高，极高摩擦性  
小转弯半径  
转弯排渣方式  
反坡排水  
长距离物料运输

TBM will be used for excavation

敞开式TBM，19英寸滚刀，小刀间距
刀盘、主机、主轴承优化设计
胶带输送机内侧机架加高设计
大功率排水泵，分级排水
胶轮运输车
The main structure of the URL specifications:

- **depth**: 560m
- **inclination**: 1:10
- **D**: 7m
- **Radius**: 400m
- **-240m level**
- **-560m level**
试验水平平巷及实验硐室布置方案

- 560m level：TBM和钻爆各施工一条，中间设联络通道。
- 公用硐室：避险硐室、电气、通信，等。
- 240 level：EDZ评价、注浆试验、和素迁移试验，等。
礼仪广场 | 能量广场
普通游客流线：先到达能量广场，然后沿轴线逐步展开游览活动
平沙落日大荒西
陇上明星高复低
Beishan Exploration Tunnel (BET, -50m), more experiment conducted in 2016
现场试验布局

十月井断裂
Shiyuejing Fault

支护试验硐室
Support Test Tunnel

超前探测试验硐室
Advanced Detection Tunnel

注浆试验硐室
Grouting Tunnel

泵房
Pump Chamber

水仓
Sump

避险硐室
Rescue Chamber

小型断裂
Fracture Zone of Small Scale

EDZ和地下水监测试验硐室
EDZ and Groundwater Monitoring Tunnel
Next 5 year

- URL: Site characterization, design and construction
- Site selection for the HLW repository
- Engineering design and engineered barrier study
- Behaviour of key radionuclides
- Safety case and safety assessment
北山营地, Camp in Beishan
中秋月圆
北山星空, Galaxy in Beishan
Welcome to Beishan!
Mission: safe disposal of the waste!
我们坚信，中核地质人将以
彻底埋葬高放废物！
Abstract: In consequence of a decision of the German government the use of nuclear energy for the industrial generation of electricity will end in 2022 at the latest. Against this background Germany resolved to take a new approach to look for a disposal facility for heat-generating radioactive waste in particular. On the basis of a transparent and scientifically-based procedure, a location is to be sought which guarantees optimal levels of safety for a period of one million years. The legislator stipulated that a “Commission for the Storage of High-level Radioactive Waste” with a pluralistic membership was to define the basic stipulations before the implementation of the actual site selection procedure. The recommendations together with the evaluated Site Selection Act (StandAG) have been presented to the German Bundestag (national parliament) in 2016, and have been enacted by parliament in 2017. Defining sites for underground exploration is to follow on from the end of surface exploration in 2023. The decision on a site is expected in 2031 after completion of the underground exploration and a comparison of the sites. The subsequent approval process is then expected to take several more years. The commission was of the opinion that the emplacement of high-level radioactive waste at the chosen site with the "best possible safety" will not begin until 2050, insofar as there are no unforeseen delays. The Repository Commission elaborated detailed recommendations on how the selection process should proceed. They are documented in a final report. The site regions to be explored will be identified based on the pre-defined criteria across the whole of the country – based on a white map of Germany. This means that those regions in Germany considered to be worthy of investigation after taking into consideration all of these criteria will only be revealed during the course of this site selection process. The potential host rocks which have been identified are salt, claystone and crystalline rocks.

Phase 1 of the site selection process begins with the exclusion of regions based on the exclusion criteria and minimum requirements. A comparative analysis is then undertaken on the basis of the existing data by applying the assessment criteria and the representative preliminary safety investigations. Surface exploration then takes place in phase 2 (involving drilling and seismic surveys) of those site regions identified in phase 1. This is then followed by underground exploration (constructing a mine and carrying out underground investigations) at those sites selected at the end of phase 2.

An additional need for more research will be required in Germany in future as a result of changes to legal frameworks, and the associated complete restart of the search for a disposal facility. The following thematic changes have arisen compared to the previous research programmes:

- More intense research activity in covering a range of potential host rocks (rock salt, claystone, crystalline rocks).
- The analysis of longer interim storage of radioactive waste.
- Scientific investigations on alternative disposal methods instead of direct disposal.
- More intense incorporation of socio-technical issues.
In addition to research work focused at a national level, international co-operation activities of German research institutes are also indispensable for disposal facility research. The most important component at the scientific-technical level is the collaboration in international rock laboratories, which is undertaken by Germany in particular because of a shortage of in-situ investigation possibilities within its own borders. Apart from geoscientific-technical research activities, it is also indispensable to implement socio-technical issues, which make it possible to transparently present and explain the current scientific understanding of technical and social issues to interested and critical members of the general public and all stakeholders.
Germany`s new approach for siting a nuclear waste repository

Volkmar Bräuer

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30655 Hannover
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April 9, 2013 was a historic day:
The German Federal Government and the Federal States agreed for the first time on a new site selection for a nuclear waste repository in Germany!
The total disposal roadmap

- **Stage 1:** Site selection procedure
  3 phases pursuant to Site Selection Act by 2031

- **Stage 2:** Mining development of the site

- **Stage 3:** Emplacement of radioactive waste in the repository mine
  from ca. 2050 for 20-30 years

- **Stage 4:** Monitoring before sealing of repository mine

- **Stage 5:** Sealed repository mine
  feasible in this century
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New Site Selection Act (StandAG)
Time schedule (Stage 1)

Repository Commission (ended in 2016)

Phase 1: Exclusion of regions and comparative analysis
- Definition of sites for surface exploration

Phase 2: Surface exploration by end 2023
- Definition of sites for underground exploration

Phase 3: Underground exploration and Environmental Impact Assessment by 2031
- Site comparison and final site selection
New Site Selection Act (StandAG)
Time schedule (Stage 1)

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Phase 1: Exclusion of regions and comparative analysis
Definition of sites for surface exploration

Phase 2: Surface exploration by end 2023
Definition of sites for underground exploration

Phase 3: Underground exploration and Environmental Impact Assessment by 2031
Site comparison and final site selection
Repository Commission (1)

Repository Commission
“Storage of high-level radioactive waste”

34 members:
8 (representatives of Bundesländer (German states), 8 (members of the Bundestag)
8 (scientists), 8 (representatives of civil society), 1+1 (Chairperson)
(groundwork done by: scientific institutions such as BGR)

General Objectives:
Analyse and assess fundamental issues, elaborate criteria and recommendations, evaluate alternatives for final disposal, reporting on a consensus basis, min. 2/3 majority
Working basis:

➢ GEOLOGY = safety for long periods of time

- with the best possible safety for the storage of high-level radioactive waste in particular
- ensuring the best possible safety for a period of one million years
- assessing the host rocks – rock salt, claystone and crystalline rocks in a scientifically based, neutral selection procedure based on a “blank map” of Germany
Working basis:

GEOLOGY = safety for long periods of time
- with the best possible safety for the storage of high-level radioactive waste in particular
- ensuring the best possible safety for a period of one million years
- assessing the host rocks – rock salt, claystone and crystalline rocks in a scientifically based, neutral selection procedure based on a “blank map” of Germany
1. The commission submitted recommendations to the Bundestag, Bundesrat and the German government on July 5th 2016

2. German Bundestag evaluated and redetermined the Site Selection Act on the basis of the report

3. The Site Selection Act passed the Bundestag on March 23rd 2017 and has been enacted
Commission findings (1)

General Objective

*Define site region and then a site which demonstrates the best possible safety to isolate the waste for a time period of one million years*

**GEOLOGY = Safety for long periods of time**

- Storage in deep geological formations
- “Best possible site” in a neutral procedure
- Criteria are the key guides for the procedure
- Additional research necessary, e.g. for containers
- Repository mine with retrievability/recovery is a new concept
- Self-critical system (reversibility of decisions, e.g. to correct errors)
Commission findings (2)
Geoscientific Criteria

Criteria:

1. Exclusion criteria
e.g. volcanic activity

2. Minimum requirements
e.g. depth of effective isolating rock zone

3. Weighing criteria
e.g. no or only slow transport by groundwater at the level of the repository
Stage 1

Phase 1: Step 1

1. Exclusion criteria
geoscientific

Target:
Identification of
geological search areas

Geological search areas

Large-scale vertical movements
Active fault zones
Mining activity
Seismic activity
Volcanic activity
Groundwater age
Stage 1

Phase 1: Step 1

2. Minimum requirements geoscientific

- Rock permeability: $< 10^{-10}$ m/s
- Minimum thickness: 100 m (crystalline rock can be less)
- Minimum depth: 300 m and as deep as possible Erosion or decompaction in case of claystone, in case of salt + 300 m salt layer above CRZ
- Minimum area for realisation:
  - Salt: 200 °C: 1.3 km²; 100 °C: 2.3 km²
  - Claystone: 100 °C: 6.6 km²
  - Granite: 100 °C: 3.6 km²
- Integrity of CRZ maintained for 1 million years

Aquifer

<table>
<thead>
<tr>
<th>300 m</th>
<th>Host rock</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Containment providing rock zone (CRZ)</td>
</tr>
<tr>
<td>100 m²</td>
<td>Repository area</td>
</tr>
</tbody>
</table>

- Host rock = Barrier rock

- Salt: $\geq 2.3$ km² (100 °C)
- Claystone: $\geq 6.6$ km²
- Granite: $\geq 3.6$ km²
Criteria in practise: Permeability as an example

Data on this criterion are available for various host rocks. Attention is given here to where and how the permeability was determined.

<table>
<thead>
<tr>
<th>Permeability (k)</th>
<th>Rock salt</th>
<th>Opalinus Clay</th>
<th>Granite (unfractured)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laboratory:</td>
<td>k &lt; 10^{-21} m²</td>
<td>k &lt; 10^{-19} m²</td>
<td>ca. 10^{-20} m²</td>
</tr>
<tr>
<td>&quot;undisturbed&quot; rock</td>
<td>k &lt; 10^{-20} m²</td>
<td>k &lt; 10^{-19} m²</td>
<td>k &lt; 10^{-18} m²</td>
</tr>
<tr>
<td>In-situ:</td>
<td>k &lt; 10^{-14} m²</td>
<td>k &lt; 10^{-16} m² to 10^{-13} m²</td>
<td>k &lt; 10^{-15} m²</td>
</tr>
</tbody>
</table>

Data source: BGR
Stage 1

Phase 1: Step 2

Selection of partial areas with particularly favourable geological conditions

3. Weighing criteria geoscientific

Data from BGR and Services of Federal States (Länder)

Geoscientific weighing

Groups of criteria:

1: Quality of ability to isolate and reliability of evidence
2: Verifying isolation capacity
3: Other safety relevant properties
Identification and selection of site regions for exploration from the surface

Regional data from BGR and Federal States (Länder)

Geoscientific weighing criteria

Representative preliminary safety investigations

Planning scientific weighing criteria
Stage 1

Phase 2:
Surface exploration

Determining sites for underground exploration

Proceedings, criteria, assessments

Geoscientific criteria

Further-developed preliminary safety investigations

Socio-economic potential analyses
Stage 1

Phase 3
Underground exploration

Determine site

Repository site

Proceedings, criteria, assessments

Geoscientific criteria

Site-specific test criteria (= exclusion criteria) still to be defined and exploration programmes

Comprehensive preliminary safety investigations, comparative safety investigations
Requirements for research and technological development

The commission is of the opinion that research on repositories in Germany has a good foundation, and provides a good basis for redefining the focus of research activities in the years to come. Gaps in knowledge that could hinder the new selection process should be closed, for instance:

➢ Three host rock types with appropriate repository concepts,
➢ Container development,
➢ Safety and verification concepts,
➢ Setting up arrangements to correct errors, including retrieval of the casks during the operating phase and recovery of the casks after closure,
➢ Safety-related verification for containers and inventories for a longer period of interim storage,
➢ Accompanying research on participation and acceptance in a democratic constitutional state,
➢ Interdisciplinary and transdisciplinary approaches for cooperation of technical and non-technical disciplines with societal players.
Conclusions

➢ There is no ideal host rock!
Claystones, rock salt and crystalline rocks are being investigated internationally as potential host rocks. The crucial aspect is a favourable overall geological setting.

➢ The geological conditions in Germany are well studied, the host rocks rock salt, claystone and crystalline rocks are regionally present.

➢ Good exploration methods are available.

➢ Research results on the characterisation of host rocks in international cooperation projects are necessary

➢ The search for a site in Germany can begin!
Thank you!

祝你们在北山坑探设施取得重大成就
The research progress on the design of Chinese URL

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Abstract: This paper introduces the research progress on the design of Chinese URL. The determination of general structure of URL for HLW is a key point in the process of engineering design. Based on analyzing the influence factors such as functional requirements, categorization of URL and topographic conditions, several types of conceptual structure model have been given out, and also technical comparisons have been made between the different types of conceptual structure model, in order to provide a reference about the design of general plan of URL in China.
Underground exploration for mechanical and hydraulic characterization of host rocks

Jürgen Hesser

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**Determination of initial rock stress using the BGR-overcoring method**

The BGR overcoring method is a stress release method to determine the rock stresses. Methods of this kind measure rock mass deformations initiated by overcoring a pilot borehole. The stresses causing these rock mass deformations can be determined from back calculations of the measured deformations, applying specific material parameters and taking the borehole geometry into consideration. In the past, the BGR-overcoring method was successfully applied at various sites and continuously improved to meet specific requirements in different host rocks.

In the 1980s rock stress measurements were conducted in the Grimsel Rock Laboratory in the crystalline formation of the Aar Massif. A distinct anisotropic deformation behavior of the rock specimens was identified and it was found, that the horizontal stresses are higher than the theoretical overburden pressure. In the 1990s extensive investigations were done to determine the rock stresses in salt rock. The results provide a quite isotropic state of rock stresses and also an isotropic deformation behavior of the rock salt. Adjustments of the measurement method had to be done for experiments in claystone in the Mont Terri Rock Laboratory, because of the significant anisotropy concerning the rock mass behavior and the rock stresses. In 2015 and 2016 rock stress investigation has been done in oolitic limestone. Similar to the results in the crystalline formation, an anisotropic deformation behavior of the rock specimens were observed as well as an anisotropy of the rock stresses.

By reference of the mentioned investigations, the presentation will give an overview of the rock stress determination using the BGR-overcoring method with site specific results and experience.

**Hydraulic characterization of fractured rock**

In the fractured rock, two aspects are important to be addressed: natural fracture network flow path and near-field hydraulic properties around tunnels and caverns. Special methods and individual methodology concerning hydraulic characterization of such fractured rock should be considered.

To determine hydraulic connectivity between different fracture systems, hydraulic interference method using multi-packer systems in multiple boreholes is indispensable. Based on the fracture data analysis, hydraulic information (e.g. aperture, hydraulic conductivity) of a fracture system may be evaluated.

The hydraulic properties of the EDZ (excavation damaged zone) may significantly influence potential axial water flow and can impact the technical feasibility and ultimate quality of tunnel sealing.

Therefore a systematical measurement along a borehole using e.g. a short-interval packer may be useful to determine the fracture permeability and extension of excavation zone.
Underground exploration for mechanical and hydraulic characterization of host rocks

Jürgen Hesser & Hua Shao

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Outline

- Sites of hydraulic and mechanical investigations in crystalline rock
- Permeability in the near-field and the far-field of openings
- Hydraulic characterization of fractures
- Deformation behaviour of crystalline rock
- Determination of rock stresses
Grimsel Test Site (Switzerland)

Juchlistock
Central Aare-massiv
Tunnel: length 1200 m
depth 450 m
altitude 1730 mNN

Bird's-eye view

Fine-grained Aar Massif
Discrete fracture zones

German-Swiss cooperation
since 1984

Focus of Investigation Programs
Development of methodology
- Geology
- Rock mechanics
- Hydraulics
- Mass transport
- Engineered Barrier Systems

BGR Bundesanstalt für Geowissenschaften und Rohstoffe
GEOZENTRUM HAMBURG
Hard Rock Laboratory Äspö (Sweden)

Granitoid rock: highly fractured mylonite and fine-grained granite

German-Swedish cooperation since 1996

Focus of Investigation Programs
Application of methods and models
- Hydraulics
- Mass transport
- Engineered Barrier Systems

Äspö spiral tunnel
length 3600 m
depth 450 m
Distance-related hydraulic permeability

- Gas injection (pulse test)
- Mechanic double packer system with surface packer
- High permeability in the near-field of openings
- Low permeability for longer distance
  → Excavation with drilling and blasting
  → Excavation damaged zone (EDZ)
Scale dependency of solute transport in fractured rock

<table>
<thead>
<tr>
<th>Scale Type</th>
<th>Injection</th>
<th>Extraction</th>
<th>C_{max}/C_0(-)</th>
<th>t_{max} (d)</th>
<th>t_{5%}(d)</th>
<th>t_{50%}(d)</th>
<th>t_{95%}(d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small scale (&lt; 10 m) (VE520)</td>
<td>1800 µS/cm</td>
<td>80 µS/cm</td>
<td>0.25</td>
<td>3.5</td>
<td>1.4</td>
<td>5.1</td>
<td>18.4</td>
</tr>
<tr>
<td>Intermediate scale (&lt;70 m) (VE493)</td>
<td>80 µS/cm</td>
<td>300 µS/cm</td>
<td>0.018</td>
<td>11</td>
<td>5.8</td>
<td>19.4</td>
<td>49.6</td>
</tr>
<tr>
<td>Large scale (&gt; 100 m) (VE800)</td>
<td>80 µS/cm</td>
<td>300 µS/cm</td>
<td>0.015</td>
<td>26.7</td>
<td>19.9</td>
<td>38.6</td>
<td>63</td>
</tr>
</tbody>
</table>
Principle of flow and transport mechanism in fractured rock

Small scale (dimension < 10 m)
- Single fracture model
- Flow and advection in fracture

Intermediate scale (dimension < 50 m)
- Fracture network model
- Flow and advection in fracture system

Large scale (dimension > 100 m)
- Coupled fracture and matrix model
- Flow and Advection in Fracture System
- Diffusion and sorption in Matrix
Rock stress determination – BGR-overcoring method

In-situ measurements

Laboratory tests

[Images of in-situ measurement equipment and laboratory test setup]

[Graphs showing deformation in 1/1000 mm vs. overcoring depth]

[Graphs showing load in MPa vs. deformation in 1/1000 mm]
Calculating
- maximal principle stresses $S_1$
- minimal principle stresses $S_2$
- angle $\alpha$ between measuring direction 1 and direction $S_1$

using
- deformation modulus $E$
- Poisson’s ratio $\nu$ and
- deformation of pilot borehole $\Delta D$
Rock stress determination – BGR-overcoring method

**anisotropic** deformation behaviour of rock mass

Calculating

- maximal principle stresses **S1**
- minimal principle stresses **S2**
- angle \( \alpha \) between measuring direction 1 and direction S1

using

- deformation modulus \( E_1 \) and \( E_2 \)
- Poisson’s ratios \( \nu_1 \) and \( \nu_2 \)
- angle \( \theta \) between measuring direction 1 and direction E1
- deformation of pilot borehole \( \Delta D \)
Deformation behaviour – dilatometer measurements

- E = 35 GPa to 45 GPa
- Small variations of deformation modulus between different measuring directions
- Deformation modulus are independent from load level
  ➔ Elastic and isotropic deformation behaviour of the rock mass

Mean deformation modulus = 40 GPa
Poissons’s value = 0.2 (literature)
Rock stress determination isotropy

Calculation with isotropic deformation behaviour

- $S_1 = 25$ MPa to $40$ MPa
- $S_2 = 15$ MPa to $30$ MPa

Horizontal stresses are significantly higher than gravitational stress.

Maximal principle stresses $S_1$ are mostly oriented to the east.
Observed deformations were almost completely reversible

→ Elastic deformation behaviour

• Significant anisotropic deformation behaviour
  • $E_1 = 34 \text{ GPa} \text{ to } 42 \text{ GPa}$
  • $E_2 = 28 \text{ GPa} \text{ to } 35 \text{ GPa}$

Poisson’s values $= \nu_1 = \nu_2 = 0,25$
Rock stress determination anisotropy

- $S_1 = 13 \text{ MPa} \text{ to } 36 \text{ MPa}$
- $S_2 = 8 \text{ MPa} \text{ to } 24 \text{ MPa}$

Calculated stress values smaller in relation to isotropy
Stress orientation is similar to results of isotropy
Orientation changes in borehole depths between 70 m and 100 m

Calculation with **anisotropic** deformation behaviour
Rock stress determination – state of stress in 3D

Result of rock stress determination is not unmistakable to define the spatial state of stress. More than one ellipsoid can be constructed.

Three measurement planes are necessary to determine unambiguously the three-dimensional state of stress.
Conclusion

- Hydraulic and mechanical investigations were done at Hard Rock Laboratory Äspö (Sweden) and Grimsel Test Site (Switzerland).
- Permeability tests showed high permeability in the contour zone of openings and low permeability for longer distances.
- Hydraulic characterization of fractures strongly depends on scale of investigation area which has to be considered in the development of geotechnical models and in numerical calculations.
- An elastic and isotropic deformation behaviour of crystalline rock was observed with dilatometer measurements.
- Biaxial laboratory tests provided an elastic and anisotropic deformation behaviour.
- An anisotropic state of stress was determined for the Grimsel test site. Horizontal stresses were significantly higher than gravitational stress. Maximal stresses were oriented to the east.
Thank you very much for your attention
A new rock suitability classification system for geological disposal (Q_{HLW}) and its application in the selection of China's URL site

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Abstract: As the last barrier to the biosphere, the host rock is essential to the long-term stability and safety of the high-level radioactive waste (HLW) disposal repository. In particular, the near-field of the repository is subjected to a hazardous multi-field coupled condition, which will deteriorate the properties of host rock, thus affecting the safety and long-term stability of the repository. However, the conventional rock mass classification methods are mainly concerned with the constructability in order to provide reliable basis for selection of excavation methods and supporting systems. Taking into account the limitations of the existing classification systems, a new quantitative rock mass classification system named Q_{HLW} system is proposed to evaluate the suitability of the host rock for HLW disposal.

Q_{HLW} system is developed on the basis of Q-system, and considers both the long-term safety and constructability requirement of the host rock for disposal. Thus, some additional parameters, including the fracture zone, groundwater chemistry, thermal effect, hydraulic conductivity and strength/stress ratio are also taken into account in light of their significant influence on the long-term safety of HLW disposal. The avoidance strategy is highlighted in the proposed system by excluding the rock volume with unfavorable conditions, particularly adjacent to the large scale fracture zones. In the proposed system, the Q’ index (the product of the first four parameters in Q-method) is considered as the basic constructability index. By incorporating other parameters of groundwater chemistry index, thermal effect index, hydraulic conductivity index and strength/stress ratio index, the Q_{HLW} system is established in which the suitability of host rock is classified into three classes at the repository and tunnel scales, namely high suitability, moderate suitability and low suitability. At the repository scale, the classification procedure consists of two steps. The first step is to identify the potential site according to the geological characteristics and the avoidance strategy of fracture zones. On this basis, the suitability of rock mass is classified by using the evaluation equation of Q_{HLW} system.

Based on Q_{HLW} system, the suitability of nine potential sites of underground research laboratory in China is evaluated at the repository scale. It is found that the Q_{HLW} system is feasible and has good applicability in identifying suitable rock volume for HLW repository project. According to the analysis result, Xinchang, Shazaoyuan, Suanjingzi, Yamansu, Aqishan and Nuorigong can be considered as suitable sites of Underground Research Laboratory for HLW disposal. Furthermore, the existing data indicate that Xinchang site located in Beishan area has the highest suitability for its high rock mass integrity, low permeability and high strength/stress ratio.
A new rock suitability classification system for geological disposal ($Q_{\text{HLW}}$) and its applications

Liang CHEN, Ju WANG

Beijing Research Institute of Uranium Geology, CNNC
Outline

- Research Background
- Presentation of the $Q_{HLW}$-system
  - Parameter sets
  - Evaluation method
- Application in the China’s URL site selection
- Discussion and Perspectives
Design: multi-barriers system

Preliminary conceptual model for China’s HLW repository

Host rock: important to the long-term safety and stability of the repository
Basic requirement of host rock in disposal (IAEA, 1999)

- The geological setting, geometrical, physical and chemical characteristics that combine to inhibit the movement of radionuclides from the repository.
- Not to be affected by future geodynamic phenomena (climatic changes, seismicity…) that could unacceptably impair the isolation capability of the system.
- Hydrogeological characteristics and the geological environment should tend to restrict groundwater flow within the repository & support safe waste isolation…
- Physicochemical and geochemical characteristics should tend to limit the release of radionuclides from the disposal facility to the accessible environment…
- Underground engineering characteristics of the site should permit application of an optimised plan of underground workings and the construction of excavations in compliance with appropriate mining rules…

Geological setting, future natural changes, hydrogeology, geochemistry…

Long-term safety

Construction and engineering conditions

Constructability and stability
Conventional Rock classifications \((Q, \text{ RMR})\)

- Main concern is the constructability, with the purpose to choose a suitable supporting system
- Safety requirement of HLWD is not considered

- Inadequate in identifying a suitable rock volume for disposal purpose

(Aikas et al., 2000; Roshoff et al., 2002; Singh and Goel., 1999)
Presentation of the $Q_{\text{HLW}}$-system
Basic assumptions/preconditions

The essential idea: to adjust an existing constructability index, by the additional parameters influencing the long-term safety/stability of the repository.

Basic assumptions:

1. Potential site is sufficiently large and deep for disposal purpose;
2. Located in a stable geological environment, and with a sufficient distance from large potentially deformable faults;
3. Relatively low seismic and tectonic activity;
4. Lack of oxidizing groundwater (Eh<0).
### Parameter sets

#### The essential idea: to adjust an existing constructability index, by the additional parameters influencing the long-term safety/stability of the repository.

#### Parameters considered at different scales

<table>
<thead>
<tr>
<th>Scale</th>
<th>Influencing factor</th>
<th>Fracture zones</th>
<th>Geochemistry of groundwater</th>
<th>Thermal effect</th>
<th>Q’</th>
<th>Strength/stress ratio</th>
<th>Hydraulic conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repository scale</td>
<td></td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Tunnel scale</td>
<td></td>
<td>√</td>
<td></td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
</tbody>
</table>

**Basic constructability index**
\[ Q_{HLW}^R = C_{chm}^R \times C_T^R \times Q' \times \frac{J_w^R,HLW}{SRF_{HLW}^R} \]

- **Groundwater chemistry index**
- **Hydraulic conductivity index**
- **Strength/stress ratio**
- **Constructability**
- **Thermal effect index**

**Reduction factor (0,1)**

**Equivalent “Q-value”**
## Classification of the fracture zones

<table>
<thead>
<tr>
<th>Types</th>
<th>Length</th>
<th>Position requirements</th>
<th>Respect zone (m)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$\text{Length} \geq L_A$</td>
<td>Intersecting any part of the repository is prohibited</td>
<td>$l_{\text{ref.A}}$</td>
<td>$L_A$, $L_B$ and $L_C$ are the length limits and can be determined according to the region-special seismic activity, geological conditions and the design of the engineered barriers.</td>
</tr>
<tr>
<td>B</td>
<td>$L_B \leq \text{Length} &lt; L_A$</td>
<td>Intersecting the disposal tunnel and disposal hole is prohibited</td>
<td>$l_{\text{ref.B}}$</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>$L_C \leq \text{Length} &lt; L_B$</td>
<td>Intersecting the disposition hole is prohibited</td>
<td>$l_{\text{ref.C}}$</td>
<td></td>
</tr>
</tbody>
</table>
First step: Identification of the potential sites
Q_{HLW}-system: At repository scale

Groundwater chemistry index ($C_{chm}$)

<table>
<thead>
<tr>
<th>Description of groundwater chemistry</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$6&lt;$pH$&lt;10$, TDS$&lt;50$g/L, $Cl^-$ $&lt;20$ g/L</td>
<td>1.0</td>
</tr>
<tr>
<td>One of the conditions ($6&lt;$pH$&lt;10$, TDS$&lt;50$g/L, $Cl^-$ $&lt;20$ g/L) not satisfied</td>
<td>0.8</td>
</tr>
<tr>
<td>At least two of the conditions ($6&lt;$pH$&lt;10$, TDS$&lt;50$g/L, $Cl^-$ $&lt;20$ g/L) not satisfied</td>
<td>0.1</td>
</tr>
</tbody>
</table>

- Quite favorable, not reduce the rock “quality”
- Basically suitable
- Unfavorable, resulting in important degradation of rock suitability

\[
Q_{HLW}^R = C_{chm}^R \times C_T^R \times Q' \times \frac{J_{w,HLW}^R}{SRF_{HLW}^R}
\]
Hydraulic conductivity index – $J_{w, HLW}$

- $K \leq 10^{-8}\text{m/s}$, acceptable for radioactive disposal (SKB, 1999; Andersson et al., 2000)
- $K \leq 10^{-9}\text{m/s}$, resulting in a favorable performance of engineered barriers (SKB, 2004).

$$J_{w, HLW}^R = \begin{cases} 
1.0 & \text{Per}(K < 10^{-9}\text{m/s}) \geq 90\% \\
0.66 & 70\% \leq \text{Per}(K < 10^{-9}\text{m/s}) < 90\% \\
0.33 & 50\% \leq \text{Per}(K < 10^{-9}\text{m/s}) < 70\% \\
0.1 & \text{Per}(K < 10^{-9}\text{m/s}) < 50\% 
\end{cases}$$
Strength/stress index – $SRF^R_{HLW}$

- $\sigma_{ucs}/\sigma_1<5$, moderate spalling and rock burst is possible.
- $5<\sigma_{ucs}/\sigma_1<10$, Spalling of the rock can occur.
- $\sigma_{ucs}/\sigma_1>10$, Construct without any stress problem.

(Grimstad and Barton, 1993)
\textbf{Q}_{\text{HLW}}\text{-system: At repository scale}

\textbf{Strength/stress index} – \( SRF_{\text{HLW}}^R \)

- \( \sigma_{\text{ucr}}/\sigma_1 < 5 \), moderate spalling and rock burst is possible.
- \( 5 < \sigma_{\text{ucr}}/\sigma_1 < 10 \), Spalling of the rock can occur.
- \( \sigma_{\text{ucr}}/\sigma_1 > 10 \), Construct without any stress problem.

\begin{equation}
SRF_{\text{HLW}}^R = \begin{cases} 
0.5 & \text{Per}(\sigma_{\text{UCS}} / \sigma_1 \geq 5) \geq 90\% \\
1.0 & 70\% \leq \text{Per}(\sigma_{\text{UCS}} / \sigma_1 \geq 5) < 90\% \\
5 & 50\% \leq \text{Per}(\sigma_{\text{UCS}} / \sigma_1 \geq 5) < 70\% \\
20 & \text{Per}(\sigma_{\text{UCS}} / \sigma_1 \geq 5) < 50\% 
\end{cases}
\end{equation}

\textbf{Q}_{\text{HLW}}^R = C_{\text{chm}}^R \times C_T^R \times Q' \times \frac{J_{w,\text{HLW}}^R}{SRF_{\text{HLW}}^R}

(\text{Grimstad and Barton, 1993})
Suitability evaluation at repository scale

\[ Q_{HLW}^R = C_{chm}^R \times C_T^R \times Q' \times \frac{J_{w,HLW}^R}{SRF_{HLW}^R} \]

<table>
<thead>
<tr>
<th>( Q_{HLW}^R )</th>
<th>Class</th>
<th>Suitability</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>(100, 1000]</td>
<td>I</td>
<td>High suitability</td>
<td>The rock volume is very suitable for repository construction.</td>
</tr>
<tr>
<td>(40, 100]</td>
<td>II</td>
<td>Moderate suitability</td>
<td>Basically suitable for repository construction, but need some engineering measures to ensure the long-term safety of the repository.</td>
</tr>
<tr>
<td>(0.0, 40]</td>
<td>III</td>
<td>Low suitability</td>
<td>Should be avoided in the site selection of the repository.</td>
</tr>
</tbody>
</table>
A new rock mass classification system Q_{HMW} for high-level radioactive waste disposal

L Chen, J Wang, ZH Zong, J Liu, R Su, YH Guo, YX Jin, WM Chen, RL Ji, HG Zhao, XY Wang, XT Tian, H Luo, M Zhang

A new rock mass classification system named Q_{HMW} system is proposed with the purpose of evaluating the suitability of the host rock for high-level radioactive waste (HLW) disposal. In the system, the rock mass classification system is developed on the basis of Q system, and considers both the long-term safety and constructability requirement of the host rock for disposal. Thus, some additional parameters, including the fracture zone, groundwater chemistry and thermal effects, are taken into account in light of their significant influences on the long-term safety of HLW disposal. The assessment strategy is extended in the proposed system by including the rock volume with unfavorable conditions, particularly adjacent to the large scale fracture zones. In the proposed system, the G index (the product of the first four parameters in Q system) is considered as the basic constructability index. By incorporating the influence of other parameters, the Q_{HMW} system is established in which the suitability of the host rock is classified into four classes at the repository and tunnel scale. As a preliminary validation, the system is applied to the lecture area, a potential region for HLW disposal in China. Using the classification method, the repository scale and tunnel scale, the most suitable disposal site is Xincheng block of the Shandian area is identified. The rock classification at the tunnel scale is carried out along two deep boreholes. The proposed system is found to be a rational tool to identify suitable rock volume of different scales for HLW disposal.

1. Introduction

In the last decades, considerable spent nuclear fuel and high-level radioactive waste (HLW) have been produced in nuclear industrialized countries. The safe disposal of these radioactive wastes has become a critical issue to the sustainable development of the nuclear industry and environment protection. At present, the leading concept of managing the HLW is deep geological disposal (ULAE, 2003). The most challenging task of geological disposal is to isolate the long-lived radioactive waste over hundreds of thousands of years (Nuclear Energy Agency, 2013). As the last barrier to the biosphere, the host rock is essential to the stability and long-term safety of the repository. The selection of rock volume with favorable geological, geochemical, geotectonic and geomechanical conditions is thereby of high importance during the development process of the repository.

Rock mass classification is widely considered as a practical and usable method in evaluating the “quality” of rock mass in underground engineering. However, the conventional methods are mainly concentrated on the properties of rock masses relevant to constructability, with the purpose of choosing the suitable supporting systems or excavation methods (Burton et al., 1974; Grienshab and Burton, 1993; Bieniawski, 1989). In light of the avoidance strategy in geological disposal (i.e., avoidance of adverse rock conditions or geological structures), the main objective of rock mass classification is to select a suitable rock volume for HLW disposal. In this regard, beside the aspect of constructability, the long-term safety requirement is also the core concern of rock classification. In particular, the near field of the repository is subjected to a complex coupled physical and chemical condition due to the groundwater flow, nuclear transport and engineered barrier degradation. The characteristics of the host rock under such a hazardous environment are critical to the long-term stability and safety of the repository, which are mainly considered in the existing rock classification methods. Therefore, the conventional methods are inadequate in identifying a suitable rock volume for disposal purpose (Alici et al., 2000; Rosshoff et al., 2002; Singh and Goel, 1999; Makurat and Loset, 2001).

In spite of the known limitations of the existing methods (Rosshoff et al., 2002; Anderson et al., 2000), only few research achievements have been documented in developing a new rock classification system for HLW disposal. In this work, the most remarkable work could be the HRC-system (Melloun et al., 2013) which was developed from the first rock classification system (HRC system) for nuclear waste disposal in crystalline bedrock (Hagino, 2006). With the purpose to avoid such
Application in the URL site selection
9 candidate URL sites
Fracture distribution of the candidate sites:

- Aqishan
- Yamansu
- Tianhu
- Jiujing
- suanjingzi
- Xinchang
- Shazaoyuan
- Tamusu
- Nuorigong
Double-Packer system

Beishan region
Permeability

Xinjiang

Inner Mongolia
$J_{w,HLW}^R$ of different sites

- **Jiujing**
  - $J_{w,HLW}^R = 0.10$

- **Xinchang**
  - $J_{w,HLW}^R = 1.0$

- **Shazaoyuan**
  - $J_{w,HLW}^R = 0.66$

- **Suanjingzi**
  - $J_{w,HLW}^R = 1.0$

- **Yamansu**
  - $J_{w,HLW}^R = 1.0$

- **Tianhu**
  - $J_{w,HLW}^R = 0.33$

- **Aqishan**
  - $J_{w,HLW}^R = 0.66$

- **Tamusu**
  - $J_{w,HLW}^R = 0.10$

- **Nuorigong**
  - $J_{w,HLW}^R = 0.66$
Rock classification system - $Q_{HLW}$
Conclusions

1. Compared to the conventional system, the $Q_{HLW}$-system is capable to give a more comprehensive evaluation on the suitability of host rock, by taking into account the additional parameters related to the long-term safety of the repository.

2. As a quantitative system, the system is sensible to the existence of fracture zones and other factors related to the repository safety.

3. The system allows integrating the result of different research activities performed during site characterization, and it is effective to have a first screening of suitable site.

4. It is usable either for the purpose of site-selecting or optimization of panel layout.
1. It does not preclude the application of other methods for evaluating the suitability of rock mass for disposal, like safety assessment, or structural geological interpretation.

2. Due to the limitation of available data, the parameter rating and suitability classification criterion at different scales are still open for further revision.

3. Further studies on the monitoring and influence of geochemical parameter during the construction and implementation stage are still necessary.
Beishan: the most potential site
Beishan …
Thanks!
Underground application of non-destructive geophysical methods (seismic, temperature, EMR, ERT) for site investigation


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Email: Patrick.Musmann@bgr.de

**Topic:** Site selection/site investigation methods and technologies (geophysical)

**Keywords:** geophysics, seismic, electro-magnetic reflection (EMR), electrical resistivity tomography (ERT), temperature, in-situ

**Abstract:** Non-destructive investigations of geological barriers of nuclear waste repositories are a particular important prerequisite for safety assessment. For this purpose, different geophysical exploration methods come into application. Each method is sensitive to different physical properties of the host rock and has its specific application, which, however, may fail in certain unfavorable geological situations. To overcome such an issue, the combination of several methods is advisable not only giving additional value but also enabling reliable interpretation of subsurface structures.

In the department “Geological-geotechnical Exploration” the Federal Institute for Geosciences and Natural Resources (BGR) applies and develops different non-destructive geophysical methods for site investigation and characterization. BGR’s expertise includes all host rocks that are relevant for nuclear waste disposals in deep geological formations, i.e. salt, claystone and crystalline rocks. In this talk, we present a broad spectrum of case studies on the application of different geophysical methods, like very high-resolution seismic investigations, electro-magnetic reflection methods (EMR), electrical resistivity tomography (ERT), and temperature measurements. Investigations were carried out by BGR’s scientists and were partly conducted in underground laboratories but also in existing repositories.
Underground application of non-destructive geophysical methods (seismic, temperature, EMR, ERT) for site investigation


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Overview

► Motivation
  ► Final disposal of radioactive waste
  ► Geophysical site exploration

► Case studies
  ► Electro-magnetic reflection (EMR) measurements for structural imaging
  ► High-resolution seismic and ultra-sonic in-situ measurements
  ► Application of direct current geoelectrics (ERT) for in-situ measurements
  ► Temperature measurements in boreholes

► Summary
Motivation: Final disposal of radioactive waste

- How can we safely dispose of radioactive waste?
Motivation: Geophysical site exploration

► Main focus
  ► In-situ measurements – closer to reality
  ► Structural exploration
  ► Geophysical/geotechnical characterization of host rocks – salt, claystone and crystalline rocks
  ► Application-oriented research – continuous adaptation and further development of materials and methods

► Applied geophysics
  ► Electro-magnetic reflection (EMR, Georadar)
  ► High-resolution seismic and ultra-sonic measurements
  ► Electrical resistivity tomography (ERT, Geoelectrics)
  ► Temperature measurements

Patrick.Musmann@bgr.de
International nuclear repository research: European co-operation projects & research sites

Grimsel
Äspö
Mol
Morsleben
Asse
Gorleben
Reiche Zeche
Mont Terri
Meuse/Haute Marne
Tournemire

salt rock
crystalline
claystone
Electro-magnetic reflection (EMR) measurements for structural imaging

V. Gundelach, U. Buschmann, C. Salat, A. Kellner, I. Ozer (BGR)
Electro-magnetic reflection (EMR) measurements for structural imaging

- 70-MHz antennas (shielded)
- P40 antennas (shielded) mounted side-ward on a vehicle.
- 50-MHz antennas and mobile registration unit.
- 50-MHz borehole tool (partly dismounted, length > 20 m)
Electro-magnetic reflection (EMR) measurements for structural imaging (Asse salt mine)
Electro-magnetic reflection (EMR) measurements for structural imaging (Asse salt mine)
Electro-magnetic reflection (EMR) measurements for structural imaging (Asse salt mine)
Application of high-resolution seismic and ultrasonic measurements for in-situ site investigation

Application of high-resolution seismic and ultra-sonic measurements for in-situ site investigation

- Sources: different pulse (~100 Hz – 2 kHz) and vibrator sources (500 Hz – 10 kHz) for high-resolution seismic measurements.

- Receivers: three-component piezo accelerometers and 8-channel ultra-sonic borehole probe (8KUBS).
Application of high-resolution seismic and ultra-sonic measurements for in-situ site investigation in claystone (URL Mont Terri):

BGR’s 8-channel ultrasonic borehole probe (8KUBS)

▲ 8-channel ultra-sonic borehole probe.

▼ Borehole camera photographs (~58x63 mm, fov ~77°).

Seismic constant offset section.

Patrick.Musmann@bgr.de
Application of high-resolution seismic and ultra-sonic measurements for in-situ site investigation in crystalline rocks (URL Grimsel):
Elastic properties from interval velocities measurements

<table>
<thead>
<tr>
<th>Depth [m]</th>
<th>Lithology &amp; core description</th>
<th>Seismic measurements: travel time [μs]</th>
<th>Seismic measurements: interval velocities $v_s$ [m/s], $v_p$ [m/s] and $v_p/v_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 – 15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 – 25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30 – 35</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Application of high-resolution seismic and ultra-sonic measurements for in-situ site investigation in crystalline rocks (URL Grimsel):
Elastic properties from interval velocities measurements

Patrick.Musmann@bgr.de
Application of high-resolution seismic and ultra-sonic measurements for in-situ site investigation in crystalline rocks (URL Grimsel):

Elastic properties from interval velocities measurements

Seismic measurements: travel time [μs]

Lithology & core description

Depth [m]


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Application of direct current geoelectrics (ERT) for in-situ measurements

M. FURCHE, K. SCHUSTER, C. CZORA, T. TIETZ, H. ALBERS, F. SCHULTE (BGR)
Application of direct current geoelectrics (ERT) for in-situ measurements

▲ Developing specialized borehole tools (Ø 80 mm, 50 electrodes with 15 mm spacing).

▲ ERT measurement in a salt mine, electrodes mounted on the wall.

Patrick.Musmann@bgr.de
Application of direct current geoelectrics (ERT) for in-situ measurements in claystone (URL Mont Terri): Engineered Barrier Emplacement Experiment

► 2001/2002: Excavation of EB-chamber, emplacement of dummy canister, bedded on bentonite blocks, chamber filled with granular bentonite, active saturation, first measurements

► 2012/2013: Monitoring of re-excavation, daily measurements

▲ EB experimental layout.

Photograph of re-excavated EB-chamber.
Application of direct current geoelectrics (ERT) for in-situ measurements in claystone (URL Mont Terri): Engineered Barrier Emplacement Experiment

- Resistivity (in-situ).
- Water content (in-situ).

Correlation of resistivity with water content (laboratory measurements by S. Kaufhold).
High-resolution temperature measurements in boreholes

M. Furché, C. Czora, T. Tietz (BGR)
High-resolution temperature measurements in boreholes

Technical equipment: borehole tool (3 wall sensors, 1 axial sensor), electric wire, digital voltmeter and controlling computer unit.
In-situ temperature measurements in 01YEA02/RB132.

Interruption of measurement: Retrieval and re-insertion of tool
High-resolution temperature measurements in boreholes (Gorleben salt mine): Numerical modelling

In-situ temperature measurements in 01YEA02/RB132.

Numerical modelling of the temperature field within EB1 (P. Vogel 2012).

- measured
- calculated
Summary

► Conclusions
  ► In-situ geophysical site investigation for (non-destructive) structural exploration
  ► In-situ geophysical site investigation for geophysical/geotechnical characterization of host rocks
  ► Different methods are sensitive to different physical parameters
  ► Different methods complement each other → increase reliability of interpretation

► Outlook
  ► High-resolution and ultrasonic reflection seismic processing and imaging
  ► R&D on broadband high-frequency seismic vibrator sources (and receivers)
  ► Continuation of EMR measurements in salt mines for structural exploration
  ► Correlation database of in-situ parameters (R, ρ, v_p, v_S, GRI, T, …)
  ► Continuous improvement of tools and methods
忠心感谢您的关注

Thank You for Your Attention

Danke für Ihre Aufmerksamkeit
Appendix
Motivation: Final disposal of radioactive waste

Possible locations / Host rocks

- Salt domes
  (after BGR-Study 1995)

- Crystalline rocks
  (after BGR-Study 1994)

- Claystone (Cretaceous/Jurassic)
  (after BGR-Study 2007)
Electro-magnetic reflection (EMR) measurements for structural imaging in crystalline rocks (URL Grimsel)
Langzeitentwicklung $v_p$, OPA - 45° & S/B – 1411 Tage (HE-E-Experiment)

4 Strahlwege im OPA – 45° tb
2 Starhlwege im S / B
Langzeitentwicklung \( v_p \), OPA - 45° & S/B – 1411 Tage

Entwicklung der EDZ / EdZ „Creation & Sealing“

Danke ...
Application of direct current geoelectrics (ERT) for in-situ measurements (Gorleben salt mine): Detection of hydrocarbons

- 80 electrodes, 0.25 m spacing, mounted on a wall
- 3 Wenner-α-profiles (each with 40 electrodes), one side overlapping
Application of direct current geoelectrics (ERT) for in-situ measurements (Gorleben salt mine):
Detection of hydrocarbons

- 80 electrodes, 0.25 m spacing, mounted on a wall
- 3 Wenner-α-profiles (each with 40 electrodes), one side overlapping

[Diagram showing resistivity and excavation damage zone with hydrocarbons]
Application of direct current geoelectrics (ERT) for in-situ measurements in claystone (URL Mont Terri): 
High-resolution borehole measurements: $\rho$ vs. $v_p$

![Graph showing resistivity and velocity profiles](image-url)

- **I** clayey facies
- **II** sandy/carbonate-rich facies
- **III** sandy facies
Application of direct current geoelectrics (ERT) for in-situ measurements in claystone (URL Mont Terri):
High-resolution borehole measurements: $\rho$ vs. GRI

![Graph showing resistivity (Ωm) vs. borehole length (m) with different facies]

I. clayey facies
II. sandy/carbonate-rich facies
III. sandy facies
Siting of clay formations as potential host rocks for HLW disposal repository in northwest China

Xiaodong Liu\textsuperscript{a,b}, Pinghui Liu, Chaocheng Dai, Shuai Liu, Weimin Zhang, Juzhi Deng, Zheng Yu
\textsuperscript{a} East China University of Technology, Nanchang, Jiangxi 330013, China.
\textsuperscript{b} Key Laboratory of Nuclear Resources and Environment, Ministry of Education, China
Email: liuof99@163.com

Abstract: The preliminary survey of clay formations as the host rock for high-level radioactive waste (HLW) disposal repository was conducted by East China University of Technology in 2007. The initial results of regional survey indicated that there are potential clay formations in several Mesozoic-Cenozoic sedimentary basins in Northwest China. Based on the experience of clay site selection in France and in Switzerland, and referring to the geological conditions of clay formations in the mainland of China, the following montmorillonite criteria for clay formation was suggested at the area survey stage of site selection project.

* Depth: 200m to 1000m
* Continuous thickness: > 100m
* Space extension along trending: > 5000m with small degrees in dip
* Contents of clay minerals: > 40%
* Low degree of metamorphism
* Stable in tectonic/structure

Supported by China Atomic Energy Authority, a new national program for siting of clay formation was granted in 2014, which highlights the beginning of site selection of clay formations for HLW disposal purpose in China. With the geological and hydrogeological survey in Northwest China currently, three candidate areas have been identified with the favorable clay formations which meet the site selection criteria above, including Nanbaxian area with N\textsubscript{1} Youshashan clay formation in North Chaidamu Basin, Northwest Qinghai province, Tamusu and Suhongtu areas with upper K\textsubscript{1} Bayingebi clay formation in east Bayingebi basin, Inner Mongolia Autonomous Region.

Based on the borehole information of exploration project for other commodities in Tamusu area, Bayingebi basin, there are two lacustrine face clay formations (K\textsubscript{1}b\textsuperscript{2-3} and K\textsubscript{1}b\textsuperscript{2-1}) partially with sandstone and siltstone interbeds. The thickness of upper K\textsubscript{1}b\textsuperscript{2-3} clay formation is about 300m to 600m with surface outcroppings, while the thickness for lower K\textsubscript{1}b\textsuperscript{2-1} clay formation is estimated more than 200m with the depth of about 550m below the surface. Initial mineralogical studies on clay samples from K\textsubscript{1}b\textsuperscript{2-3} and K\textsubscript{1}b\textsuperscript{2-1} formations indicated that the clay minerals with the concentration more than 45% are dominated by analcite, montmorillonite, kaolinite and little amount of illite.

In addition to the national expert’s consultation, the first international expert’s consultation under the support of Technical Cooperation Project of IAEA considered that Tamusu area in east Bayingebi basin, Inner Mongolia Autonomous Region, is a favorable candidate area for HLW disposal repository. However, it is necessary to conduct detail geological, hydrogeological, geophysical studies to select the favorable sectors or sites within the candidate areas.
Siting of Clay Formations as Potential Host Rocks for HLW Disposal Repository in Northwest China

Xiaodong Liu, Juzhi Deng

East China University of Technology

2017.05
Outline

1 Projects on Clays

2 Recommended Criteria for Screening of Clays as the Host Rocks

3 Progress of the Siting of Clays
1. Projects on Clays

Repository Site --- location?

What kind of host rock?

- crystalline rock
- argillaceous rock

Screening of host rocks including crystalline rocks, salt, and clays. The sitting have been conducted in China since 1986.

--- issued in 2006, by China Atomic Energy Authority (CAEA), MST and MEP.

Planed Project 3.6, in Subject 6.2.3 of the Guidelines:

Screening of other candidate sites and of other kind of host rocks (in addition to granite) for HLW repository.
First Project:

“Geological Survey of argilaceous rocks for HLW Disposal Repository in China”

--- approved and financed in 2009 by China Atomic Energy Authority (CAEA),
* Objectives:

* To draw up the general screening criteria for favorable clays

* To select 2 or 3 potential areas with favorable clays for further studies
Second national project:

“Sitting and Preliminary Evaluation of Clay formation in Northwest China as the Host Rocks for HLW Disposal Repository”

--- approved and financed by CAEA in 2015
* Objectives:

-- to complete the area survey stage studies of siting screening

-- to select 2 or 3 potential sectors of clay formation in Northwest China for further site characterization.
2 Recommended criteria in geology for screening of clays as the host rocks (draft)

* Depth: 200m to 1000m
* Thickness: single layer > 100m
* Extension: > 5000m with small degrees in dip
* Contents of clay minerals: > 40%
* Low degree of metamorphism
* Stable in tectonic/structure
3  Progress of the Siting of Clays

3.1 Area geological survey

Based on:

* overseas experiences (in France, in Switzerland)

* general screening criteria above

* regional geology information

(such as 1:200,000 geological survey)

Geological survey of clay formations have been conducted in Inner Mongolia, in Gangsu and Qinghai Provinces.
Target Areas

Mesozoic – Tertiary Sediment Basins (size: 2.4mkm²)
Distributions of Main Clay Formations
Five potential areas have been selected:
3.2 Nanbaxiang potential area

(in north Chaidamu basin, Qinghai province)
Stratum histogram in Nanbaxian

Upper Gangcaigou formation

Upper Youshashashang formation
Geological Profile in North Chaidamu Basin, Northwest Qinghai

Favorable clay layers: $N_{y(2)}$: Youshashan clay
$N_1$: Gangcaiguo clay
Clay on the surface near "Ghost City" in North Chaidamu basin
* Fold structures in Nanbaxian area

* Potential area for oil
3.3 Tamusu area in Bayingebi basin
(in Inner Mongolia Autonomous Region)

Field view of Tamusu area
Geological diagram of Tamusu area
Sedimentary phase diagram of upper Bayingebi formation
Profile of exploration line H16 in Tamusu area

River delta

Lacustrine face

\( k_1b^{2-3} \)

\( k_1b^{2-2} \)

\( k_1b^{2-1} \)
**Stratigraphic column**

<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>k₁b²⁻³</td>
<td>thickness more than 150m</td>
</tr>
<tr>
<td>k₁b²⁻¹</td>
<td></td>
</tr>
</tbody>
</table>

---

**Note:** The image shows a stratigraphic column with various layers and thicknesses, indicating geological features and sedimentary structures.
### Preliminary results of mineral composition

<table>
<thead>
<tr>
<th>Minerals</th>
<th>(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaolinite</td>
<td>0 ~ 8.04%</td>
</tr>
<tr>
<td>illite</td>
<td>8.36% ~ 15.54%</td>
</tr>
<tr>
<td>feldspar</td>
<td>21.7% ~ 43.47%</td>
</tr>
<tr>
<td>analcite</td>
<td>27.6% ~ 39.12%</td>
</tr>
<tr>
<td>dolomite</td>
<td>8.62% ~ 19.71%</td>
</tr>
<tr>
<td>others</td>
<td>0 ~ 13.12%</td>
</tr>
</tbody>
</table>
Micro-structure of clays

a, b: kaolinite,

kaolinite with illite

c, d: illite

e, analcite,
f, analcite with dolomite
Regional hydrogeological characters

1. basement rocks
2. water inflow < 10 m³/d
3. water inflow 10 - 100 m³/d
4. water inflow 100 - 500 m³/d
Delineated area and potential sector in Tamusu
Magnetotelluric (MT) survey in Tamusu area
Parameters for 3-D inversion

- **Stations**: 94
- **Frequency**: 320Hz ~ 0.035Hz, 26
- **Data set**: apparent resistivity, and impedance
- **Mesh generation**: 89×78×56
- **Starting model’s resistivity**: 10 Ω.m
- **Inversion method**: truncated Newton method (TRN)
- **Iterations**: 93
- **RMS**: 1.41
MT inversion result compared with seismic
Preliminary results of MT
Controlled Source Audio-frequency Magnetotellurics
Preliminary results of CSAMT
3.4 Suhongtu area in Bayingebi basin

Size: about 2700 km$^2$
Stratigraphic column

SZK1

clay of Suhongtu formation

SZK2

clay of Bayingebi formation
Sedimentary phase diagram of upper Bayingebi formation in Suhongtu area
Sedimentary phase diagram of Suhongtu formation in Suhongtu area
Delineated area and potential sector in Suhongtu

Preselected area

Recommend favorable sector
Magnetotelluric (MT) survey in Suhongtu area
Preliminary results of MT in Suhongtu
## General information on clays in different areas

<table>
<thead>
<tr>
<th>Area</th>
<th>Tamusu in Bayingebi</th>
<th>Suhongtu in Bayingebi</th>
<th>North Chaidamu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay Formation</td>
<td>Bayingebi</td>
<td>Sohongtu</td>
<td>Youshashan</td>
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<tr>
<td>Age of clay formation</td>
<td>$K_1b^2$</td>
<td>$K_1s$</td>
<td>$N_1$</td>
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<td>Depth (m)</td>
<td>50-450</td>
<td>50 - ?</td>
<td>0 - 400</td>
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<td></td>
<td>620-800(?)</td>
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<td>Thickness (m)</td>
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<td>&gt; 200</td>
<td>&gt; 200</td>
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<tr>
<td></td>
<td>&gt; 150</td>
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<tr>
<td>Clay minerals (%)</td>
<td>&gt; 35</td>
<td>?</td>
<td>&gt; 30</td>
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### 3.5 Preliminary Evaluation

<table>
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<tr>
<th>Survey Areas</th>
<th>Conditions in Geology</th>
<th>Conditions in Socieconomy</th>
<th>Comments</th>
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<tbody>
<tr>
<td>North Chaidamu Basin, Northwest Qinghai</td>
<td>?</td>
<td>√</td>
<td>Potential for oil and nature gas</td>
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<tr>
<td>Tamusu, Bayingebi basin, Inner Mongolia</td>
<td>√</td>
<td>√√</td>
<td>Potential area</td>
</tr>
<tr>
<td>Suhongtu, Bayingebi basin, Inner Mongolia</td>
<td>√</td>
<td>√√</td>
<td>Potential area</td>
</tr>
</tbody>
</table>

—stipulated the stages of site selection for HLW disposal facilities, the key factors and the general criteria for site selection. On the basis of granite as the host rocks

But for clay:

It is necessary to have the specific site selection criteria.

What and how to define?
Thank you!

Drill site in Tamusu
Concepts and emplacement technologies for an HLW repository in Germany

Niklas Joachim Bertrams

DBE TECHNOLOGY GmbH, Peine, Germany
Email: Niklas.Bertrams@dbe.de

Abstract: In the last decade, several repository concepts for high-level radioactive waste and spent fuel have been developed by DBE TECHNOLOGY GmbH on behalf of the German Ministry for Economic Affairs and Energy (BMWi) and the utility companies. Based on different container types, emplacement in drifts, in deep vertical boreholes, in horizontal boreholes as well as the direct disposal of transport and storage containers have been investigated.

The decade-long focus on rock salt as preferred host rock for such a repository has provided a good knowledge base in this area. Current R&D projects aim to close the gap between knowledge about repositories in rock salt and repositories in crystalline or argillaceous rock while not neglecting R&D on rock salt. Networking and consulting with radioactive waste management agencies abroad with experience in different host rocks due to advanced disposal programs or underground laboratories also is an important part of R&D work.

The development of a repository concept follows a standardized approach, which itself is subject to continuous development, especially with regard to necessary adaptations due to changing input data or improvements of the current state of technical and scientific knowledge. The input data that have to be compiled before the repository development process can be started, consist of three separate classes of information: First, regulations and requirements stemming from applicable laws, safety recommendations and engineering standards or the safety concept; second, geological data/modelling of the repository site, which for R&D purposes is mostly generic; and third, the prospective waste types and quantities. Based on this, the different disposal concepts can be developed into their respective underground repository layouts by first determining the suitable types of waste packages and their loadings. Then, the possible distribution patterns of the waste in the underground are determined by means of thermal calculations in order to not exceed critical temperatures in the host rock. Finally, shafts, drifts, emplacement areas etc. can be designed, taking into account the best practices of the mining industry as well as the special needs for such a repository as defined in specific regulations and the safety case.

This method of repository concept development has been applied to different R&D projects. Ongoing R&D projects like “KOSINA” and “KONEKD” provide the opportunity to exemplarily show the method’s implementation and interim results for bedded salt deposits and crystalline rock. Finalized projects like “ANSICHT” or “VSG” offer accomplished underground layouts for argillaceous rock and the Gorleben salt dome.

A major part in the development of a repository concept is the design of the emplacement technology. Several concepts have been developed by DBE TECHNOLOGY GmbH. Technologies for emplacement in drifts and in deep boreholes have undergone the whole process from planning to manufacturing to thorough testing.

The development of a repository concept pursues two objectives: demonstrating the technical feasibility of the concept itself and delivering data for long-term safety analyses.
Concepts and Emplacement Technologies for an HLW Repository in Germany

Niklas Bertrams
DBE TECHNOLOGY GmbH, Peine, Germany

3rd Sino-German Workshop on Radioactive Waste Disposal
Jiayuguan
May 2017, 16th – 19th
1. General approach of planning a repository concept

2. Design approach for a repository in crystalline rock

3. Knowledge base

4. First results of an R&D project (KONEKD)
1. General Approach of Planning a Repository Concept (simplified)

Compilation of basic data (Prospective waste quantities, geology, regulatory/safety requirements)

Draft design of repository mine openings (thermal calculations)

Design of emplacement and mining technology

Cross sections of drifts and emplacement drifts or boreholes

Final repository design
1a) Emplacement Technology – in Drifts

Demonstration test in 1:1 scale

Main waste cask:

2200 x POLLUX® -10, 65 t, with spent fuel elements
1a) Emplacement technology – in vertical boreholes

Demonstration test in 1:1 scale

Main waste cask:

7000 x BSK-V, 5.3 t, with spent fuel elements
1a) Emplacement technology – direct disposal of transport and storage casks

Conceptual design

Main waste cask:

1100 x CASTOR® casks
Diameter: 2.5 m
Length 6 m
Weight: 110 - 126 t
1a) Emplacement technology – in horizontal boreholes

Conceptual design

Main waste cask:

7000 x BSK, 5.3 t, with spent fuel elements
**1b) Underground Layouts**

**Gorleben salt dome**

- **Vertical boreholes in clay**
- **Horizontal boreholes in bedded salt**
2. Design Approach for a Repository in Crystalline Rock

- Compilation of basic data (Prospective waste quantities, geology, requirements)
- Draft design of repository mine openings (thermal calculations)
- Design of emplacement and mining technology
- Cross sections of drifts and emplacement drifts or boreholes
- Underground layout modules
3. Knowledge Base (Crystalline Rock)

Prospective waste quantities and requirements
- Amount and type very exactly know due to nuclear phase out
- waste casks? R&D activity to be launched

Geology:
- summary in R&D study Jobmann et al. 2016 (crystalline rock)
- parameters from underground laboratories

Transport, emplacement and mining technology
- Mining technology: state of the art
- Transport and Emplacement technology: built and tested or conceptual designs
4. First Results of an R&D Project (KONEKD)

List of modules (exemplary)

- Shaft for transportation of radioactive waste
- Ramp for transportation of radioactive waste (with cable car or rack and pinion?)
- Spiraling ramp for transportation of radioactive waste (with automotive transport?)
- Conventional drifts, ramps, blind shafts underground
- Emplacement boreholes

...
4. First Results of an R&D Project (KONEKD)

Starting Point: KBS-3 Concept (SKB)

Additional Requirements

- waste casks have to provide \(1,000,000\) years of containment
- retrievability during operational period

Technical Concept

- redundant copper shell (2x 25 mm) + clay buffer
- Borehole liner between buffer and waste cask
4. First Results of an R&D Project (KONEKD)

Alternativ Approach: Multiple CRZ

Additional Requirements
• waste casks provide containment until backfill and sealing elements are functional
• sealing elements provide containment until backfill is functional
• retrievability during operational period

Technical Concept
➢ single copper shell (5 mm)
➢ long term containment through backfill
➢ Borehole liner between buffer and waste cask
4. First Results of an R&D Project (KONEKD)

Alternativ Approach: CRZ in Sedimentary Overburden

Additional Requirements

- waste casks stays competent for recovery for 500 years
- backfill/seals underground provide obstruction for fluid migration

Technical Concept

- steel waste casks (POLLUX®- type)
- redundant und diverse sealing elements in the accesses to the surface provide long-term containment
Outlook

- Building modules
- arrange (some of) them to build an underground layout
- develop closure concept
- estimate ventilation requirements
- estimate time and cost requirements from planning to closure

- Relevance of KONEKD results:
  - preliminary Safety Concept (CHRISTA)
  - preliminary Disposal Concept (KONEKD)
  - Safety Concept + Disposal Concept (CHRISTA 2)
Thank you for your attention
Test of VCP glass in Beishan granite-GMZ bentonite barriers

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Abstract: Facilities known as “Pilot Repositories” are being set-up at the China Institute of Atomic Energy to simulate the conditions of bulk glass in repository environments. The experiment is designed to obtain the corrosion source-term from simulated VCP glass and to get the corrosion rates of the metal containers. The system consists of two connected vessels with a volume of 29 liters. One container holds the Beishan granite as host rock being evaluated and the other is used to simulate the repository tunnel in which a 2 kg glass column is surrounded by a metal plate of the same composition as the canister and GMZ bentonite backfill materials. Simulated groundwater from an anoxic glove box is transferred through the host rock container and then to the container with the bentonite, metal plate and the glass column. The permeate is then collected in an anoxic glove box to await analysis. It was found that the glass was corroded to a depth of 18μm and 30μm respectively at 70°C and 90°C for 900 days. The release rate of key elements in glass matrix was decreased to minimum after 200-400 days. The granite composition has influence on the U and Cs release in the deceasing order as Monzonitic granite, fissure granite and alteration granite. Addition of 5% of glass powder without radionuclide isotopes could effectively decrease the corrosion of VCP glass. The water content in the GMZ bentonite has a strong impact on the release of glass elements. Tests were conducted about the influence of the specific surface areas of glass to the volume of water(S/V) from 100 m⁻¹ to 6000 m⁻¹ to the disposal behaviour of glass. With the increase of S/V, the normalized leaching rate of glass elements increases while the corrosion rate of glass decreases. The corrosion depth was stabilized at 50μm for S/V of 100m⁻¹ for 720 days at 90°C.

Key words: VCP Glass, Beishan Granite, GMZ Bentonite, Repository, source-term, host rock.
Disposal without monitoring – Yin without Yang?

Karl-Heinz Lux

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Abstract: Regarding the disposal of high-level radioactive waste within a repository in deep geological formations, different concepts are discussed in the international community. These concepts are not only different because of different availability of host rock formations in different nations, but also due to different demands on a long-term monitoring option to check the repository’s behaviour over time. In Germany, according to its final report, the repository commission prefers a repository in deep geological formations guaranteeing long-term safety based on geologic, geotechnical as well as technical barriers. Additionally, reversibility of decisions as well as retrievability of waste canisters implied (1) by significant improvements of scientific knowledge and technology or (2) by an unexpected development of the repository system giving severe concern with respect to long-term safety should be possible for future generations. Therefore, a monitoring option should be implemented into the repository concept to provide data about the time-dependent physical as well as the chemical development within the repository system.

A long-term monitoring could be performed in different ways. First possibility is the installation of measurement devices in the repository without any further connections to monitoring stations outside of the emplacement area (no wirelines for energy supply or data transfer). But what to do in case of unexpected data or defects in energy supply? Second possibility is the monitoring only within special observation parts of the repository outside of the emplacement fields, like it is considered in the Swiss concept, but in this case there will not be any data available about the situation within the main part of the repository system. Due to these disadvantages of both concepts, a so-called direct long-term monitoring of at least preselected representative parts of the main repository could also be taken into account. This third approach is investigated in the framework of the ENTRIA-project additionally implementing a special monitoring level above the emplacement level in the repository construction. Within this project basic techniques regarding retrievability as well as the influence of a long-term monitoring concept on the repository systems load-bearing behaviour during operational phase and during a limited monitoring phase afterwards with special attention to geotechnical and monitoring aspects is analyzed by TU Braunschweig, whereas the fluid dynamic processes and the geologic barrier integrity in the nearfield of the emplacement drifts on the more local scale as well as in a representative part of the whole repository system on a more global scale are investigated by Chair in Waste Disposal and Geomechanics of Clausthal University of Technology. It has to be pointed out that in this concept the waste emplacement level and the monitoring level as well are part of the isolating rock mass zone.

In the framework of the ENTRIA-project the FTK-simulation tool is used for the numerical analysis. It combines the well-known software tools FLAC3D and TOUGH2 and enables the simulation of TH2M-coupled processes. These simulations can give an exemplary insight into the repository behaviour after emplacement of waste canisters with respect to natural and technological impacts. Furthermore, all these investigations contribute to improve the process as
well as system understanding and therefore supports the robustness of safety functions on the one hand and to increase acceptability of a repository installation on the other hand.

The analysis is focused on the time and space-dependent development of fluid dynamic processes occurring in the totally backfilled emplacement level for the two basic repository configurations (1) without monitoring level and (2) with implementation of a long-term monitoring option. The generic repositories are constructed either in a salt rock mass or in claystone formation. For this purpose simplified reference repository models are developed.

The presentation will discuss advantages and disadvantages of waste disposal without and with direct monitoring and give some insight in first results regarding repository behaviour in both configurations.

Selected results of the analysis performed so far are presented – exemplarily demonstrating the fluid dynamic behaviour and the thermomechanical behaviour of the repository in the long-term as well. These data together with state variables describing the mechanical behaviour could be used to perform safety analysis regarding barrier integrity as well as environmental safety in the planning phase and to compare them with data measured in the repository during operational or post-closure phase to evaluate the repository behaviour.

The availability of such a procedure may contribute to confidence building in the public already during the site-selection process perhaps starting in Germany in the next years. In this sense the final disposal of waste and the reliable monitoring of the repository behaviour are extremes which are calling for each other like yin and yang.
Disposal without monitoring?

Yin without Yang?

K.-H. Lux

3rd Sino-German Workshop on Radioactive Waste Disposal

Jiayuguan City, Gansu Province, China, 16-19 May, 2017
1) Aspects of recent situation in Germany

2) Yin - Thesis

3) Yang - Antithesis

4) Yin and Yang – Attempt of a synthesis

5) Outlook – History never ever repeats?
1) Aspects of recent situation in Germany
2) Yin - Thesis
3) Yang - Antithesis
4) Yin and Yang – Attempt of a synthesis
5) Outlook – History never ever repeats?
Recent situation in Germany – some main aspects

- **Law for new site selection process is in effect since 2017 (technical safety and societal justice)**
- **Reorganisation of institutions is on it‘s way (BfE-regulator, BGE-implementor)**
- **Implementation of reversibility in case of unexpected development is prescribed based on monitoring – observation beyond waste emplacement phase not fixed but may perhaps be demanded acc. to commission report (2016) during participation process**
- **Intensive participation of public during site-selection as well as disposal process is prescribed by law**
- **Repository for HAW is not well accepted in society at the moment – whereever it should be located in the future**
Recent situation of social conflict:

Thesis/Yin – reliable documentation of long-term safety is possible and convincing
→ final closure of repository as fast as possible
→ trust in long-term safety

Antithesis/Yang – Public mistrust in experty is based on experiences and therefore justified
→ monitoring of repository for some time
→ demonstration of safety is necessary

How can we find a balance between these conflictive forces?

Attempt of a synthesis?

Situation…
Basic objectives related to Final Disposal of HAW in deep underground formations

- Guarantee of operational safety
- Guarantee of long-term safety
- Acceptance of repository at site / in society based on technical safety as well as societal justice

based on the following boundary conditions:

- Design of repository following passive safety principle
- Realization of long-term safety by geological as well as geotechnical barriers (isolating rock mass concept)
- Maintenance-free behaviour in the long term after closure as well as according to site selection law (2017):
  - Reversibility of disposal process at any time (error correction)
  - Retrievability of waste part of repository design
How can the technical objective be achieved while maintaining the social agreement?
1) Aspects of recent situation in Germany
2) Yin - Thesis
3) Yang - Antithesis
4) Yin and Yang – Attempt of a synthesis
5) Outlook – History never ever repeats?
Thesis: Reliable documentation of long term safety is possible and well accepted

Arguments for a repository immediately sealed after end of disposal

• Trust in scientific-technical feasibility

• Reliability of prognosis of future repository behaviour is justified (basic and site-specific understanding, scientific knowledge, technical competence, management)

• Uncertainties in the development of social systems have to be obtained

• Intergenerational justice is fundamental (polluter pays principally)

• Long-term repository monitoring is not to be ensured

• Loss of competence may occur with time

• Loss of budget resources may occur with time

⇒ Necessity to guarantee passive safety of repository as soon as possible
Thesis – Final storage / immediate complete sealing

- no provisions for retrieval necessary
- no long-term monitoring of system behaviour necessary

How does this geotechnical system behave with respect to geotechnic as well as fluiddynamic development?

Reference simulation model with subcomponents (global model)

stylized disposal field model

complete stylized model
**Fundamentals:**
- reliable characterization of the storage site (ewG)
- extensive process understanding (TH2M as well as C, B, Mo …)

**FTK-Simulator**

**Host rock mass:**
- rock salt mass
- claystone formations

→ Verification und validation of process models (thermomechanical ↔ thermohydraulic)

**Prediction of**
- Geotechnical Behaviour (BM, BI)
- Fluiddynamic Behaviour (METI)
Visualisation of near-field processes / fluiddynamics und geotechnics / Rock Salt formation

State Variables:
- Temperature
- Saturation level
- Pore gas pressure
- Capillary pressure
- Groundwater pressure
- Compaction pressure
- Swelling pressure
- Displacements
- Stresses
- Radioactive radiation
- Chemotoxic pollution

t = 10 a after repository sealing
t = 100 a after repository sealing

Visualisation of near-field processes / fluiddynamics und geotechnics / Rock Salt formation
Visualisation of near-field processes / fluid dynamics and geotechnics / Rock Salt formation

- Further storage chambers in the 3rd panel
- 1st and 2nd panel

Volume flow rate (gas)

- ca. 0.1356 N·m³/a/m²
- ca. 0.0722 N·m³/a/m²
- ca. 0.035 N·m³/a/m²

Salinity (gas)

- Shaft

- Salt rock
- Corroding waste container
- Rocksalt filling
- Sealing structure

Univ.-Prof. Dr.-Ing. habil. Karl-Heinz Lux
Lehrstuhl für Deponietechnik und Geomechanik

3rd Sino-German Workshop on Radioactive Waste Disposal
Jiayuguan City, Gansu Province, China, 16-19 May, 2017
Salt rock mass / pressure-driven infiltration of gas into host rock

Visualisation of near-field processes / fluidodynamics und geotechnics / Rock Salt formation

gas infiltration front has arrived at top of salt
t = 10 a after repository sealing

Visualisation of near-field processes / fluid dynamics and geotechnics / Claystone formation

Thesis – multiphysical process simulation (3/1)
Visualisation of near-field processes / fluid dynamics and geotechnics / Claystone formation

$t = 100$ a after repository sealing
Visualisation of near-field processes / fluiddynamics und geotechnics / Claystone formation

t = 1,000 a after repository sealing
t = 10 a after repository sealing

Visualisation of near-field processes / fluiddynamics und geotechnics / / Claystone formation
t = 100 a after repository sealing

Visualisation of near-field processes / fluidodynamics und geotechnics / Claystone formation
t = 1.000 a after repository sealing

Visualisation of near-field processes / fluiddynamics und geotechnics / / Claystone formation
t = 10,000 a after repository sealing

<table>
<thead>
<tr>
<th>FLAC3D 5.01</th>
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<td>©2014 Itasca Consulting Group, Inc.</td>
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<table>
<thead>
<tr>
<th>Volume flow rate (gas)</th>
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<tbody>
<tr>
<td>↑ Shaft</td>
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<tr>
<td>ca. 0.07141 N·m⁻³/a/m²</td>
</tr>
<tr>
<td>ca. 0.04258 N·m⁻³/a/m²</td>
</tr>
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<td>ca. 0.04195 N·m⁻³/a/m²</td>
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Further storage chambers in the 3rd panel
1st and 2nd panel

Claystone | Corroding waste container | Bentonite filling | Sealing structure

Visualisation of near-field processes / fluiddynamics und geotechnics / Claystone formation
Overview

1) Aspects of recent situation in Germany

2) Yin - Thesis

3) Yang - Antithesis

4) Yin and Yang – Attempt of a synthesis

5) Outlook – History never ever repeats?
Antithesis: Reliable documentation of long term safety is not possible based on no/bad experiences and missing monitoring

Arguments against an immediately sealed repository

- Prognostic capacity about 1 million years not given in principle
- Black box-situation not acceptable
- No reliable direct proof for the long-term behaviour after sealing within the back-filled areas possible
- Rather bad experiences with repositories made in the past (A, K, M, G)
- Framework conditions of HAW repository even more complex (T)
- Further research required by implementor/regulator

consequences:

⇒ in light of diverse significant uncertainties no timely decision for final disposal
⇒ trust / hope in better knowledge as well as technical solutions in the future
1) Aspects of recent situation in Germany
2) Yin - Thesis
3) Yang - Antithesis
4) Yin and Yang – Attempt of a synthesis
5) Outlook – History never ever repeats?
Yin as well as Yang / Attempt at a synthesis

Consideration of Public concerns/ demands

(commission report/ law of site selection process)
- Transparency
- Participation
- Intergenerational justice
- Correctability of mistakes
- Reversibility during process (technically supported and prepared retrievability as far as possible without reduction of barrier integrity acc. to passive safety concept)
- Demonstration of repository safety in situ according to state variables regarding PA/safety case

Important components of an acceptance-focused final disposal process:

documentation of safety – fairness
(safety case) (justice)
Consideration of Public concerns/ demands

(commission report/ law of site selection process)
- Transparency
- Participation
- Intergenerational justice
- Correctability of mistakes
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\[\downarrow\]

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*documentation of safety* — *fairness* — *trust*

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Consideration of Public concerns/ demands

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- Transparency
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- Correctability of mistakes
- Reversibility during process (technically supported and prepared retrievability as far as possible without reduction of barrier integrity acc. to passive safety concept)
- Demonstration of repository safety in situ according to state variables regarding PA/safety case

central components of an acceptance-focused final disposal process:

*documentation of safety* — *fairness* — *trust* — *demonstration of (safety case)* (justice)

**Precondition:**
reliable monitoring of repository behaviour with respect to demonstrating safe evolution (observation of system behaviour)

- indirect monitoring
- direct monitoring

??
Monitoring during operation

? Post closure monitoring?

(a) Direct monitoring of repository behaviour without any accessibility to monitoring devices after their installation

EU-research programs
- MODERN
- MODERN 2020

Questions?
- Handling of confusing measurement data?
- Repair/substitution of failed measurement devices?
- Energy-supply?
- Wireless data transmission to surface?
Monitoring during operation

? Post closure monitoring?

(b) Indirect monitoring of repository behaviour in a special observation area outside waste emplacement panels → pilot plant concept / Switzerland

Disadvantages: transfer of pilot plant data to repository necessary - but:
Comparability of geotechnical situation in pilot plant area and disposal area (local geotechnic defects)
Basic concepts for Monitoring (3)

Monitoring during operation

? Post closure monitoring?
Possibility of error correction in principle

(c) Direct monitoring of repository behaviour with at least basic accessibility to monitoring devices even after installation as well as emplacement level closure

- Introduction of a 2-level mine concept composed of
  - upper-level: exploration/ventilation + monitoring
  - lower-level: emplacement of waste

→ Operational monitoring in already back-filled areas
→ Post closure monitoring
→ 2LL-monitoring concept
Existing 2-level-mine concepts

(a) Monitoring during in situ tests

(b) Exploration of emplacement level and ventilation of mine
Geological repository with direct 2 level-long term (2LL) monitoring

**conceptional configurative design**

2-level mine within isolating rock mass zone including observation boreholes

*above - monitoring level*

*below - emplacement level*
Advantages and disadvantages of direct 2-level longterm monitoring

(a) Advantages
- Immedeate selective / areal observation of the repository behaviour
- Reliable collection of decision-making relevant data
- Replacement of defective measuring equipment
- Timely recognition of undesirable development of the repository
- Verified decision-making basis for final storage or recovery of waste
- Stepwise approach towards the final implementation of the repository with verified possibilities for error correction
- No irreversible decision from the very beginning as to include future generations
- Greatest possible amount of safety as well as flexibility, while keeping within an inter-generational democratic framework
- Maintaining of participation opportunities for future generations

(b) Disadvantages
- More space required to accommodate the isolating rock mass zone
- Long-term technogenic interference within the rock mass close to the repository due to excavation and operation of the monitoring level in increased operational risk with time
- Additional influence on the surrounding geological area of the emplacement level within / outside of the isolating rock mass zone in additional damage to geologic barrier
- Additional back-filling / sealing measures with respect to drilling holes / excavations at monitoring level

(c) Additional advantages
- Option to directly observe / verify the functionality of geotechnical barriers
- Option to prove the functionality of geotechnical barriers even during the monitoring period
  - Prerequisite for that is the development / design of geotechnical barriers with a timely development of hydraulic effectiveness
Scope of work related to direct 2LL-monitoring:

- Reduced technical safety $\Leftrightarrow$ increased public acceptability?
- How big is the possible loss in technical safety? (preservation of barrier integrity / guarantee of migration safety)
- Which data can be obtained by measurements in situ?
- How can a basis for assessment of measurement data be developed?
- What amount of additional underground space is necessary?
- Is there any influence on the site-selection process?

**Decision making in uncertain circumstances**

→ reduction of uncertainties – as far as possible
→ improvement of robustness of safety functions

→ improvement of decision-making basis?
preservation of barrier integrity ← TH2M-processes → fluidodynamics / no inadmissible release

Process analysis of the 2 level repository system (1/2)

Process analysis of the 2 level repository system (2/2)
Investigations regarding long-term safety – TH2M-processes / claystone

**FLAC3D 5.01**
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Volume flow rate (gas)

$t = 10 \text{ a after sealing}$

Synthesis – direct 2LL-monitoring

Visualisation of near-field fluiddynamics
Investigations regarding long-term safety– TH2M-processes / claystone

**FLAC3D 5.01**

©2014 Itasca Consulting Group, Inc.

<table>
<thead>
<tr>
<th>Volume flow rate (gas) [N·m³/a/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum: 0.00487795</td>
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<tr>
<td>Scale: 500 (Einlagerungssohle)</td>
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<tr>
<td>Maximum: 0</td>
</tr>
<tr>
<td>Scale: 5000 (Überführungssohle)</td>
</tr>
<tr>
<td>Maximum: 0</td>
</tr>
<tr>
<td>Scale: 50 (Bohrlöcher)</td>
</tr>
<tr>
<td>2.5000E-03</td>
</tr>
<tr>
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<td>2.2000E-03</td>
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<td>2.0000E-03</td>
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<td>1.8000E-03</td>
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<tr>
<td>2.0000E-04</td>
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<td>0.0000E+00</td>
</tr>
</tbody>
</table>

**Volume flow rate (gas)**

$t = 100$ a after sealing

Visualisation of near-field fluidynamics
Investigations regarding long-term safety – TH2M-processes / claystone

**FLAC3D 5.01**

©2014 Itasca Consulting Group, Inc.

Volume flow rate (gas)

$t = 1.000 \text{ a after sealing}$

**Synthesis – direct 2LL-monitoring**

Visualization of near-field fluid dynamics
Synthesis – direct 2LL-monitoring

Investigations regarding long-term safety – TH2M-processes / claystone

Volume flow rate (gas) $t = 10,000\text{ a after sealing}$

<table>
<thead>
<tr>
<th>FLAC3D 5.01</th>
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</thead>
<tbody>
<tr>
<td>©2014 Itasca Consulting Group, Inc.</td>
</tr>
<tr>
<td>Volumenstrom (Gas) [N·m⁻³/a/m²]</td>
</tr>
<tr>
<td>Maximum: 0.0643413</td>
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<tr>
<td>Scale: 250 (Einlagerungsohle)</td>
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<tr>
<td>Maximum: 0.0353121</td>
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<tr>
<td>Scale: 500 (Überfahrungssohle)</td>
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<tr>
<td>Maximum: 1.74398</td>
</tr>
<tr>
<td>Scale: 5 (Bohrlocher)</td>
</tr>
</tbody>
</table>

- 2.5000E-03
- 2.4000E-03
- 2.2000E-03
- 2.0000E-03
- 1.8000E-03
- 1.6000E-03
- 1.4000E-03
- 1.2000E-03
- 1.0000E-03
- 8.0000E-04
- 6.0000E-04
- 4.0000E-04
- 2.0000E-04
- 0.0000E+00

Ca. $1,7440\text{ N·m}^{-3}\text{ a/m}^2$
Ca. $0,17\text{ N·m}^{-3}\text{ a}$
Ca. $1,7008\text{ N·m}^{-3}\text{ a/m}^2$
Ca. $0,17\text{ N·m}^{-3}\text{ a}$

$t = 10,000\text{ a after sealing}$

(Einlagerungsohle)
(Überfahrungssohle)
(Bohrlocher)

- Corroding waste container
- Bentonite filling
- Sealing structure
- Access level
- Drilling hole

Visualisation of near-field fluidodynamics
Development of selected state variables in a stylized repository / claystone

State variables = measurement variables?
(temperature, degree of saturation, pore gas pressure, capillary pressure, displacements, swelling pressure, …)
**Advanced science and technology (Yin) ↔ sceptical public (Yang)**

- Basis for principal understanding of physical processes as well as system behaviour
- Basis for the identification of planned development (safe) / unplanned development (unsafe)
- Basis for development of monitoring concepts as well as monitoring programs
- Basis for decision-making regarding final storage or retrieval
- Basis for advanced acceptability → **transdisciplinarity**
  (active involvement of civil society just from the beginning)
- Trust and mistrust ↔ Yin and Yang → balance of opposing forces possible? →

**Documentation of safety**
- fairness in process - trust in competence
  but - demonstration of safety necessary?

**Question:** Which extend of in situ demonstration is necessary to gain the acceptance needed for implementing the repository facility?
Overview

1) Aspects of recent situation in Germany
2) Yin - Thesis
3) Yang - Antithesis
4) Yin and Yang – Attempt of a synthesis
5) Outlook – History never ever repeats?
technical safety as main requirement until year 2000 + fairness – trust – demonstration as additional public demands since year 2000

1977

but

2017

Source: "Dorf und Turm könnt ihr zerstören, aber nicht unsere Kraft, die es schuf!", 40 Jahre Anti-Atom-Protest Gorleben, Deutschlandradio Kultur. („Village and tower you may destroy but not our power that build it!“ 40 years of anti-atomic-protests in Gorleben)

Since we do not want such a confrontation between state and public in the future ⇒

Source: „Resolution der Niederbayern-Landräte: Kein Atommüllendlager im Woid“, hogn.de. („Resolution of the lower-bavarian councils: no repository for radioactive waste in Woid“)
Some conclusions for further procedure:

- **Disposal and long-term direct monitoring – Yin as well as Yang**
- **Guarantee repository safety as best as possible!**
- **Attempt of social acceptance as far as possible!**
- **Implement public acceptability by monitoring / reversibility without significant loss of safety!**
- **Investigate advantages/disadvantages of direct 2LL-monitoring regarding geomechanic / fluiddynamic aspects!**
- **Introduce transdisciplinary elements in site selection process!**
- **Try to get back public confidence by transparency, participation, monitoring/demonstration of safety!**
- **Ask public for their opinions / demands!**
- **Include monitoring / demonstration of safety already in the site selection process!**
ENTRIA-options and the power of facts ⇒
The initial „either-or“ steadily turns into an „as-well-as“

Synthesis:
documentation of safety – fairness –
thrust – demonstration of safety

Research items for

VP 7
Long-term direct 2LL-monitoring
• Design and requirement of underground space?
• Loss of technical safety?
• Possibilities of measurements in situ?
• Representative state variables?
• Monitoring concepts?
• Retrieval concepts?
• Increase in procedural fairness?
• Demands of public regarding demonstration of safety?
• Recovery of confidence?
Thank you for your attention!
Long-term performance of GMZ-bentonite as buffer material for HLW repository in China

Yuemiao Liu

Beijing Research Institute of Uranium Geology, P O Box 9818, 10029 Beijing, China

Email: liuyuemiao@163.com

Abstract: Gaomiaozi (GMZ) bentonite is currently considered as the candidate buffer and backfill material for the disposal project in China. Based on the extensive experimental investigations, thermal, hydraulic, mechanical and physic-chemical properties for its use as a buffer material have been obtained.

According to the preliminary concept of the high-level radioactive waste (HLW) repository in China, the large scale China-Mock-up test, intended to study the Thermal-Hydro-Mechanical-Chemical (THMC) behavior of Gaomiaozi (GMZ) bentonite was built. The temperature of heater was increased progressively to 90°C which is the maximum temperature expected on the canister surface in China. The hydration with the underground water from the host granite rock at the depth 524.24m in Beishan site, NW China was initially controlled by a water injection rate, and then controlled by water pressure 0.2MPa to 2MPa with the water consumption rate decrease. Several aspects, including temperature, relative humidity (RH) and stress in the compacted bentonite were recorded continuously since 1st January 2011. It has been operated well for more than 4 years. A lot of valuable data about the evolutions of temperature, RH and stress in compacted bentonite and experience about how to evaluate the suitability of buffer material in long-term under THMC coupled condition have been obtained for the first time.

The temperature of compacted bentonite increased quickly and then increased slowly with heating and hydration. The highest temperature 64.9°C was recorded by sensor 18 located at section V after 540 days heating. RH recorded by the sensors in the bentonite blocks indicated that the compacted bentonite was progressively saturated. But with the water sucking and increasing stress in the bentonite steadily, it implies the compacted bentonite is unsaturated until now. Temperature and RH evolution in the compacted bentonite induced by heating and hydration could be influenced by each other. The stress evolution in the compacted bentonite may be influenced by the gravity of heater and water, the thermal expansion induced by high temperature, the swelling pressure of bentonite generated by water penetration. The highest vertical stress 3.8 MPa is recorded in the section VI located on the top of heater after 1512 days. The relatively low temperature and stress releasing may be attributed to the existence of installation space between the heater/steel tuck and compacted GMZ blocks which was filled by the pellets with lower dry density 1.3 g/cm³, as well as the gaps between the sensors and the blocks separately.

The experiment results evaluated the THMC processes occurring in the compacted bentonite-buffer during the early stage of HLW disposal and could provide a reliable database for the design of HLW repository.
Long-term Performance of GMZ-Bentonite as Buffer Material for HLW Repository in China

Yuemiao Liu

Beijing Research Institute of Uranium Geology
Outline

• The Current Status of Buffer material study for HLW Geological Disposal in China

• THMC China-Mock-up Test on Compacted Bentonite-Buffer

• Current Research work
  ---- Manufacture bentonite blocks
Introduction

Preliminary conceptual model for China’s HLW repository

Host rock
Vitrified waste
Canister
Buffer
Bentonite

Engineering barrier
Hydraulic barrier
Chemical barrier
Thermal conductor
我国缓冲/回填材料30年研究进展
CHINESE BUFFER/BACKFILL MATERIAL STUDY IN 30 YEARS

1986
缓冲材料与膨润土矿床选择
Buffer material and Bentonite deposit selection
膨润土矿床筛选依据
Bentonite mine selection
- 矿床规模 Scale
- 矿石质量 Quality
- 开采条件及成本 Mining condition & cost
- 交通运输条件 Transportation

1996
高庙子钙基膨润土性能研究
Study on GMZ Ca-bentonite

2001
高庙子钠基膨润土性能和长期性能研究
Study on GMZ Na-bentonite

已开展的缓冲材料性能研究
Research work about buffer material
- 化学成分和矿物组成研究 Chemical and Mineral characteristics
- 热传导性能研究 Thermal conductivity
- 渗透特性研究 Hydraulic conductivity
- 力学特性研究 Mechanical property
- 化学缓冲性能研究 Water-bentonite reaction
- 核素迁移研究 Nuclide migration
- 添加剂研究 Additive
- 多场耦合特性试验研究 Mock-up test
- 多场耦合数值模型研究 Numerical modeling
- 缓冲材料的制备 Buffer Fabrication

核工业北京地质研究院环境工程研究所
Division of Environment Engineering, BRIUG/CNNC
Bentonite preparation

Raw ores

Bentonite power
### Basic properties of GMZ bentonite

#### Mineralogical composition (%)

<table>
<thead>
<tr>
<th>Mineral</th>
<th>GMZ (China)</th>
<th>MX-80 (USA)</th>
<th>FEBEX (Spain)</th>
<th>Montigel (Switzerland)</th>
<th>Avonseal (Canada)</th>
<th>Kunigel-V1 (Japan)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Montmorillonite</td>
<td>75.4</td>
<td>65-82</td>
<td>92 ± 3</td>
<td>66</td>
<td>79</td>
<td>47</td>
</tr>
<tr>
<td>Quartz</td>
<td>11.7</td>
<td>4-12</td>
<td>2 ± 1</td>
<td>8.3</td>
<td>5</td>
<td>0.6</td>
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<tr>
<td>Feldspar</td>
<td>4.3</td>
<td>5-8</td>
<td>2-4</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plagioclase</td>
<td>8.2 ± 2.7</td>
<td>2 ± 1</td>
<td></td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Cristobalite</td>
<td>7.3</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Kaolinite</td>
<td>0.8</td>
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<tr>
<td>Chalcedony</td>
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<td></td>
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<td>37</td>
</tr>
</tbody>
</table>

(Bradbury and Baeyens 2002; Komine 2004; Wen 2005; Lloret and Villar 2007)
## Basic properties of GMZ bentonite

### Cation exchange capacity

<table>
<thead>
<tr>
<th>Sample</th>
<th>CEC (meq/100 g)</th>
<th>Exchangeable cation (meq/100 g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>E(K⁺)</td>
</tr>
<tr>
<td>GMZ China</td>
<td>77.30</td>
<td>2.51</td>
</tr>
<tr>
<td>MX-80 USA</td>
<td>78.7 ± 4.8</td>
<td>1.3 ± 0.2</td>
</tr>
<tr>
<td>FEBEX Spain</td>
<td>111 ± 9</td>
<td>22.2 ± 1.8</td>
</tr>
<tr>
<td>Montigel Switzerland</td>
<td>62</td>
<td>0.2</td>
</tr>
<tr>
<td>Avonseal Canada</td>
<td>82</td>
<td>0.7</td>
</tr>
<tr>
<td>Kunigel-V1 Japan</td>
<td>73.2</td>
<td>0.9</td>
</tr>
</tbody>
</table>

(Bradbury and Baeyens 2002; Komine 2004; Wen 2005; Lloret and Villar 2007)
Preliminary assessment

The ideal bentonite (at the moment) should be/have

Chinese bentonite

1- free of calcite & gypsum  ✔
2- Ca/Mg dominated montm.  ±
3- moderate structural Fe  ✔

Very interesting material

Detachment of colloidal particles should be considered

... to be continued ...
Strength characteristics of GMZ bentonite

Dry density 1.4g/cm³

- Water content 9.5%
- Water content 14.5%
- Water content 19%
- Water content 25%

Dry density 1.6g/cm³

- Water content 9.4%
- Water content 14.5%
- Water content 19%
- Water content 25%

Stress [MPa] vs Strain [%]

Stress [MPa] vs Strain [%]
Thermal characteristics of GMZ bentonite

Hot Disk Thermal Constants Analyser

![Graph 1](image1)

![Graph 2](image2)

![Graph 3](image3)

![Graph 4](image4)
Swelling and hydraulic behaviors

Test conditions
- Temperature: RT ~ 90°C
- Water pressure: 0~2MPa
- Initial dry density: 1.0~2.0g/cm³

Swelling pressure and permeability test system

Data Log & control system

Pressure vessel

Patent

Swelling pressure/MPa

Time/day

Temperature/℃

Increasing temperature

Decreasing temperature

Swelling pressure/MPa

Time/day

#1(\(\rho_d=1.79\) g/cm³)
#2(\(\rho_d=1.78\) g/cm³)
#3(\(\rho_d=1.61\) g/cm³)
#4(\(\rho_d=1.80\) g/cm³)
Chemical buffering properties

Batch test in low-oxygen glove

![Laboratory setup and graph showing concentration of elements vs. solid/liquid ratio. The graph includes lines for Al, Ca, Fe, K, Mg, Cl⁻, Na, Si, and SO₄²⁻, with a curve for Na and a dashed line for SO₄²⁻.](image)
THM-mock-up tests

- To study the properties of GMZ bentonite under coupled THM conditions
- To establish the methods and techniques for conducting large-scale mock-up tests
- To verify the reliability of sensors
Coupled THM bentonite-granite test

![Image of coupled THM bentonite-granite test setup]

- Water
- Bentonite
- Stress sensor
- Granite

Graph showing swelling pressure over time:

- Swelling pressure (MPa) vs. Time (h)
- Data points showing swelling pressure increase over time.
Design since 2005, Constructed on Sep. 10, 2010
Hydration and heating since July 8, 2011
The main objective of China-Mock-up

- 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.
Scale: 1:2 Preliminary repository concept of HLW in China
_compacted bentonite blocks

- Compacted bentonite block samples

Dry density
A, B, C, D - 1.71 g/cm³
E - 1.3 g/cm³ (1.9)
Total density 1.6 g/cm³

For crushing
Thermal conductivity exhibits a different distribution on the three different measurement surfaces.

Side surface > top surface > bottom surface

Density of the bentonite blocks is inhomogeneous.
Heater and temperature control system

- Weight 1T, pressure at the bottom 1.24MPa
- Temperature controlled: room temperature - 90°C
- Heater power 1000W
- Thermal insulation layer
  FUMEISI— I Rubber
Groundwater from Beishan site

<table>
<thead>
<tr>
<th></th>
<th>Na$^+$</th>
<th>NH$_4^+$</th>
<th>Ca$^{2+}$</th>
<th>K$^+$</th>
<th>Mg$^{2+}$</th>
<th>pH</th>
<th>Fe$^{2+}$</th>
<th>Al$^{3+}$</th>
<th>Mn$^{2+}$</th>
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<td>0.12</td>
<td>183.0</td>
<td>15.95</td>
<td>50.40</td>
<td>7.56</td>
<td>0.033</td>
<td>0.06</td>
<td>0.022</td>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>SO$_4^{2-}$</th>
<th>Cl$^-$</th>
<th>HCO$_3^-$</th>
<th>NO$_3^-$</th>
<th>F$^-$</th>
<th>Br$^-$</th>
<th>Li$^+$</th>
<th>Sr$^{2+}$</th>
<th>Cu$^{2+}$</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>941.1</td>
<td>1193</td>
<td>130.9</td>
<td>32.60</td>
<td>2.20</td>
<td>0.0001</td>
<td>0.0112</td>
<td>0.715</td>
<td>0.0001</td>
</tr>
</tbody>
</table>
Sensor Types

10 kinds of sensors are installed in the China-mock-up.
inside 113, outside 52, total 165

temperature sensor (28 + 2), humidity (RH) sensor (24 + 4), stress sensor (37),
pore water pressure sensor (8), LVDT displacement sensor (6) and electrochemical corrosion sensor (10), FBG strain sensor (28), strain gauge (15), micrometer caliper (1) and flowmeter (2).
Test schedule

- Controlled by injection pressure
  - T=90°C
  - 2013.8

- Controlled by injection rate
  - T=30°C~90°C
  - 2011.12
  - 2011.7
  - 2011.4
  - 2010.9

- No water supply

- Construction
  - 2011.4
  - 2011.7
  - 2010.9

1. T=30°C
2. T=30°C~90°C
3. T=90°C
T, RH & Stress evolution and Displacement evolution of the heater
Stress evolution in China-Mock-up
Distribution of T and RH

Distribution of T (2012.7.8)

Distribution of RH (2012.7.8)
Distribution of the Stress

- Vertical stress
- Radial stress
- Hoop stress

- High Stress Zone
- Low Stress Zone

Graphs showing stress distribution over time:
- July 8, 2012
- Oct. 8, 2013
- July 8, 2014

Stress/MPa:
- 0~0.5
- 0.5~1.0
- 1.0~1.5
- 1.5~2.0
- 2.0~2.5
- >2.5

Graph showing sensor locations:
- Hoop Sensor
- Radial Sensor
- Vertical Sensor
## Performance of Sensors

<table>
<thead>
<tr>
<th>No.</th>
<th>Sensor type</th>
<th>Total number/out of work</th>
<th>Distribution of the out of work sensors</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Temperature</td>
<td>28/10</td>
<td>2/I,1/II,1/III,2/IV,2/V,2/VI</td>
</tr>
<tr>
<td>2</td>
<td>Relative Humidity/Temperature</td>
<td>24/24</td>
<td>1/III,1/IV,2/V</td>
</tr>
<tr>
<td>3</td>
<td>Soil pressure</td>
<td>37/0</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Pore water pressure</td>
<td>8/0</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>LVDT</td>
<td>6/3</td>
<td>3/Top of the heater</td>
</tr>
<tr>
<td>6</td>
<td>Electro-chemical corrosive sensor</td>
<td>10/0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>113/37</td>
<td></td>
</tr>
</tbody>
</table>
Numerical modelling

- Vapor flux \( \text{(diffusion)} \)
- Heat flux \( \text{(convection)} \)
- Liquid flux \( \text{(advection)} \)
- Heat flux \( \text{(conduction and convection)} \)

Water in

GAS

Solid

90°C

20°C

Evaporation

Condensation

Coupling

Mechanical behaviors
Initial condition
\( e=0.57, s_i=49\%, P_c=80\text{MPa} \)

2D-axisymetric
Numerical results - temperature

Temperature evolution

Temperature evolution over time for different periods:
- 1 month
- 1 year
- 3 years

Temperature evolution graph showing:
- Test
- Model

Temperature (°C) vs. Time (d)
Numerical results - hydration pressure and RH

Hydraulic pressure evolution

1 month 1 year 3 years
核地研自主设计

我国首台高放废物缓冲材料大型试验台架正式启动运行

为高放废物地质处置库工程屏障设计提供可靠依据
PEBS Project Meeting, Beijing, May 23-27
Compact machine for bentonite blocks

Peak load: 200,000kN (2000T)

Platen: 2000 × 2000mm
Manufacture bentonite blocks

試制大型膨潤土塊

Diameter 1600mm column

Diameter 1600 × 600mm circle

核工业北京地质研究院，Beijing Research Institute of Uranium Geology
Thanks for your attention!
Laboratory investigations of HLRW bentonites

Kaufhold Stephan

Federal Institute for Geosciences and natural Resources, Hannover, Germany

Email: Stephan.Kaufhold@bgr.de

Abstract: In some concepts for the encapsulation of high level radioactive waste (HLRW) bentonite will be used to isolate the canister from the host rock. This is particularly important in the case of fractured host rocks, as commonly observed for granite. To date it is not clear, however, if all bentonites can be used in this new application. All commercial bentonites have a large content of swellable clay minerals (smectites) but the properties vary significantly from one type of bentonite to another. BGR established a bentonite sample set consisting of 40 different materials (including 2 illite-smectite clays). The bentonites vary with respect to smectite content (60 – 95 %), layer charge density of the smectites (0.18 – 0.38 eq/FU), CEC (65 – 110 meq/100g), portion of exchangeable Na⁺ (0 – 100 %), pH of a 2 % dispersion (4 – 10), portion of tetrahedral charge (10 – 65 %), Fe content (1 – 16 % oxide), carbonate abundance (0 – 10 %), and specific surface area (7 – 130 m²/g). In the bentonite industry different bentonites from different locations are compared with respect to the quality determining parameters of a product (e.g. water uptake capacity of cat litter). The quality determining parameters of HLRW bentonites are, however, not defined yet. BGR identified 10 key parameters which have to be considered with respect to HLRW bentonite quality: 1) sealing capacity, 2) stability against drying, 3) stability against cementitious solutions, 4) extent of corrosion at the metal bentonite interface, 5) erosion at the rock interface, 6) stability against salt solutions / rock water, 7) retention capacity, 8) canister displacement, 9) thermal conductivity, and 10) stability against radioactive radiation. Both a literature study as well as comparative laboratory studies were conducted. The results were discussed by Kaufhold & Dohrmann (2016). Despite the complexity of the system and the difficulty to compare different quality determining parameters it turned out to be possible to provide some general recommendations for the selection of a HLRW bentonite. First of all the content of soluble or at least partly soluble components should be low. Also the content of possibly reactive phases such as pyrite or organic matter should be low. Fe in the structure of the smectite increases the reactivity of smectites. Smectites with Fe can participate in redox reactions and even improve microbiological viability. Hence the content of Fe should be low or at least moderate. The type of exchangeable cation, however, which is commonly one of the most important variables in the bentonite business, does not play a significant role because the different performance of e.g. Na- and Ca-rich bentonites disappears at high densities which result from block production. In addition the exchangeable cation population is expected to equilibrate with the rock water within a few years or decades (during water uptake). Kaufhold et al. (2015) showed that the corrosion of Fe is faster in the case of low charged smectites. If Fe canisters are used smectites with larger layer charge density should be used.

Current laboratory investigations focus on the identification of reaction mechanisms. On the one hand the corrosion mechanisms of bentonite/iron and bentonite/copper are investigated. On the other hand the Mg enrichment observed in almost all large scale field tests is investigated further because this was not yet observed in dynamic (shaking) laboratory experiments.

References:

Kaufhold, S., Dohrmann, R. (2016) Distinguishing between more and less suitable bentonites
Laboratory investigation of HLRW bentonites

Stephan Kaufhold, Reiner Dohrmann, Kristian Ufer

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Bentonites in HLRW-systems

Bentonites are highly variable materials

Implication for HLRW-systems?

They will perform differently !!!

Which properties are favorable and which not ??
Laboratory investigation of HLRW bentonites

The BGR bentonite sample set used for the tests (first 40 samples)
Laboratory investigation of HLRW bentonites

Variability of the BGR samples set (1st 40 samples)

- Smectite content: 60 – 95 mass% (without ill/smt clays)
- LCD: 0.18 – 0.38 eq/FU
- CEC: 65 – 110 meq/100 g
- %/CEC Na+: 0 – 100 %
- pH: 4 - 10
- %tet-charge: 10 – 65 %
- Fe-content: 1 – 16 mass% Fe₂O₃
- Carbonates: 0 – 10 mass% (Cc-eq)
- SSA: 7 – 130 m²/g

Different smectite morphology (sample with fibrous smt)
Different submicron particle size distribution (50 vs. 150 nm)
Bentonites in HLRW-systems

What's the job of the bentonite??

+ stability : cement water
+ stability : drying (T)
+ sealing (swelling capacity)
+ stability : radiation
+ T conductivity (radionuclide adsorption)
+ retention (radionuclide adsorption)
- canister displacement
- erosion
- corrosion
+ stability : salt solutions

1 2 3 4 5 6 7 8 9 10
Sealing (hydraulic conductivity and self sealing ability) depend on swelling pressure

Swelling pressure depends on compaction (measured as dry density)

Differences can be explained by
- uncompactable pores
- light minerals (zeolites)
- smectite content
(Kaufhold et al., 2014)

The sealing / swelling pressure of bentonites depends more on production than on material properties
Bentonites may be affected by extensive drying (irreversible collapse of interlayer)

2 tests (Kaufhold & Dohrmann, 2010; 90-120°C, 1.5 – 4.5 years) proved that all bentonites lose some swelling capacity (CEC) (about 10 %)

Bivalent cations are fixed (cannot be exchanged or hydrated anymore)

Some bentonites lose more CEC upon heating than others (reason?), but the extent of cation fixation is similar the process is limited

Cement/bentonite reaction is difficult to assess because of chemical diversity (Kaufhold & Dohrmann, 2011)

Cement/bentonite interface is limited to a few mm, chemical impact (e.g. cation exchange) a few cm (FEBEX project, unpublished data)

Excess silica reduces the extent of smectite dissolution at the interface (unpublished data, already modelled by Arthur&Savage, 2016)

Bentonites with “reactive silica components” (e.g. cristobalite) are preferable; irrelevant if low pH cements are used.
Corrosion proceeds unaerobically (even in lab) Fe-layered silicates form (berthierine / chlorite)

7 corrosion tests, 60°C, unaerobically, 5 months each

Bentonites with low charged smectites are more corrosive
5] Erosion

Colloidal particles may detach from the bentonite surface

Detached colloids (which “survived” 46,000 g centrifugation) were mainly smectite

Na-bentonites tend to liberate colloidal particles (more than Ca)
6] Stability in salt solutions

NaCl: mainly cation exchange (Kauf & Doh, 2009)

KCl: „illitization“ (Kaufhold & Dohrmann, 2010)
- Significant loss of the CEC
- Soluble silica increases
- real illite, smectite with non-exchangeable K, non-swellable smectite, and exchangeable K-smectite have to be distinguished

The loss of swelling depends on the LCD, but is reversible
The degree to which the CEC was reduced (cations fixed + phase transition) differs from one bentonite to another (reason ??)

Interestingly: correlation of CEC drop after dry heating and KCl-tests – is there a general trend / reason for the tendency to lose some CEC?
All bentonites (smt) do have permanent negative charges \(\Rightarrow\) similar adsorption behaviour

Selectivity may vary with chemical composition

Main point: To distinguish more suitable „retention bentonites“ from less suitable ones, most important radionuclides have to be defined (no bentonite will adsorb all of them)

\[ ^{129}\text{I} \] is one of the worst \(\Rightarrow\) bentonite can be improved with respect to its iodide retention capacity (Kaufhold et al., 2007; Riebe et al. 2005)
A minimum of swelling pressure is needed to keep the canister in place (0.1 MPa, Sellin & Leupin, 2014).

All bentonites will show sufficient swelling pressure to keep the canister in place.
9] Thermal conductivity

As high as possible

Thermal conductivity depends on amount of gas filled pores (water content + compaction) and quartz content

If necessary, bentonites with large quartz contents can be selected (those will have lower swelling capacity…)

The thermal conductivity of bentonites depends more on the production (initial water content + compaction) than on the different types of bentonites (although illite and quartz rich materials will have larger thermal conductivity)
Stability against radiation

A lot of studies prove, that dose must be much higher than expected to cause structural damage.

However, Fe-rich bentonites are known to be more sensitive towards radiation damages (Plötze et al., 2002).

Fe-rich bentonites are less stable against radiation
!! Mineralogical/chemical aspects have to be distinguished from engineering aspects !!

In other words: some parameters (as thermal conductivity) depend more on production than on bentonite differences

Some conclusions can, however, be drawn!
1) Absence of reactive components

Componentes which can be dissolved and/or reduced/oxidized should be absent

Pyrite, organic matter, sulphate, carbonates (least critical)

This specification is well established for landfill bentonites (they should at least apply for radioactive material as well)
2) Low (moderate) Fe-content

Fe-bentonites are less stable with respect to:
- Solubility
- Thermal load
- Radioactive radiation

They provide possibilities for redox-reactions (even for micobiological processes)
3) Moderate – high layer charge density

Low charged smectites have larger Fe-corrosion rate than high charged ones.

Does only apply for Fe as canister material.
### BGR mineralogical/chemical data GMZ bentonite

<table>
<thead>
<tr>
<th>Gaomiaozi bentonite</th>
<th>SK-IB-59</th>
<th>SK-IB-60</th>
<th>SK-IB-61</th>
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<tbody>
<tr>
<td>BGR samples</td>
<td>China GMZ-Ca</td>
<td>China GMZ-zeolite</td>
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<table>
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<tr>
<th>CEC</th>
<th>Na⁺ [meq/100g]</th>
<th>K⁺ [meq/100g]</th>
<th>Mg²⁺ [meq/100g]</th>
<th>Ca²⁺ [meq/100g]</th>
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<table>
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<tr>
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<th>XRF</th>
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<th>TiO₂ %</th>
<th>Al₂O₃ %</th>
<th>Fe₂O₃ %</th>
<th>MnO %</th>
<th>MgO %</th>
<th>CaO %</th>
<th>Na₂O %</th>
<th>K₂O %</th>
<th>P₂O₅ %</th>
<th>(SO₃)₁₁ %</th>
<th>(Cl)₁₁ %</th>
<th>(F)₁₁ %</th>
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<tr>
<td>SK-IB-59</td>
<td>66.4</td>
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<td>0.1</td>
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</tr>
<tr>
<td>Ccarb [mass%]</td>
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<tr>
<td>Sges [mass%]</td>
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<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
</tbody>
</table>

Layer charge density information is missing.

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3rd Sino-German Workshop
Some basic specifications can be given (no reactive phases)

Further specifications depend on the concept (materials to be used, e.g. Fe / Cu)
and on the type of host rock (and the water expected)

Additional detailed comparative work will lead to more specifications (DD/SW.P., different smectite reactivity)

Experience with a given material should not be forgotten
Optimum waste repository bentonite???

More?

A bentonite with lower sensitivity towards swelling pressure changes caused by dry density changes would be perfect – additional investigations are required!!!
Advances on investigations into chemo-mechanical coupling effects on the volume change behavior of compacted GMZ01 bentonite

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**Key words:** GMZ01 bentonite; deep geological repository; chemo-mechanical coupling; swelling behavior; compressibility; salinization-desalinization cycles

**Abstract:** Based on the existing results from literature, contributions on the chemo-mechanical coupling effects on the volume change behavior of compacted GMZ01 bentonite are reviewed and presented in this paper. Results show that the swelling pressure and swelling strain of the GMZ01 bentonite decrease with the increase of concentrations of salt solutions. For a given concentration of CaCl\textsubscript{2} solution cyclically infiltrated, the total vertical displacement of the GMZ01 bentonite specimen mainly happens in the first salinization-desalinization cycle. The plastic compressibility parameter decreases as the concentration of NaCl solution increases, the vertical stress applied during the saturation process has negligible influence on the compressibility parameter; while the yield stress increases as the concentration of NaCl solution or the vertical stress applied on saturation increases. Clearly, investigations on cyclically salinization-desalinization with multiple cations solutions, the mechanism of micro-structure and the multi-field coupling tests with consideration of chemical effect should be conducted in the future.
Sealing performance of clay-based materials

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Abstract: In the framework of the European Full-Scale Demonstration of Plugs and Seals project (DOPAS) during the time period of 2012 to 2016, GRS investigated clay-based materials for sealing repositories in clay formations. In most of the seal concepts developed by many countries, bentonite and bentonite-sand mixtures are chosen to ensure certain swelling pressures to compress the surrounding damaged rock and to achieve low hydraulic conductivity of the entire plug/seal system. As an alternative, crushed claystone produced by repository excavation was taken into account and intensively investigated in our program.

The Callovo-Oxfordian claystone excavated from the Bure-URL was taken and mixed with bentonite for the experiments. The claystone-bentonite and bentonite-based mixtures were examined with respect to the safety relevant properties such as compacted density, water uptake and retention capacity, swelling potential, hydraulic conductivity, and gas migration.

The experiments indicated a favorable sealing performance of the claystone-bentonite mixture with small bentonite contents less than 40%. While this mixture is comparable with the other materials in terms of compacted density, water permeability, and swelling pressure, it shows a particularly low gas breakthrough pressure after water saturation. In contrast, the gas breakthrough pressures of the compacted bentonite and the bentonite-sand mixture (70%/30%) were found to be quite high, either at the swelling or confining pressures or even above. The major concern about high gas pressures compromising the integrity of the geological-engineered barrier system can thus be disregarded utilizing claystone-bentonite mixtures for sealing.

Based on the experimental results, adequate constitutive models and parameters were derived for the sealing materials. Their hydro-mechanical behavior observed in the experiments was modelled using CODE_BRIGHT. The models and parameters adopted for the mixtures were then used for a preliminary prediction of the long-term performance of a drift seal. Water saturation and swelling pressure in the seal and the deformation and porewater pressure in the surrounding rock were calculated in a hydro-mechanical coupling way.

Main findings from the experimental investigation and the modelling exercises will be presented on the 3rd Chinese-German Workshop on Radioactive Waste Disposal.
Sealing Performance of Clay-Based Materials

Laboratory Investigations in the European Project DOPAS
(09. 2012 – 08. 2016)

Chun-Liang Zhang
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS), Germany
DOPAS: Full-Scale Demonstration of Plugs and Seals for safe sealing repositories in different host rocks

- Dome Plug (Sweden)
- Deposition Tunnel Plug (Finland)
- Pressure/Sealing Plug (Czech)
- Drift Seal (France)
- Shaft Seal (Germany)

Seal materials
Reference Drift Backfilling/Sealing Concept (Andra, France)

- Backfilling excavated claystone
- Sealing bentonite pellets + powder
- Sealing bentonite-sand blocks

Low hydraulic conductivity (<$10^{-11}$ m/s)
Certain swelling pressure (< 7 MPa)

GRS investigated compacted claystone-bentonite mixture for drift sealing
Main Objective

Characterization of claystone-bentonite mixture in comparison with bentonite-sand mixture with respect of safe sealing properties

➢ High density to ensure the required hydro-mechanical properties

➢ High mechanical stiffness to guarantee the stability

➢ Certain swelling capacity to seal gaps in the seal system and to support the EDZ against further damage propagation and for enhancement of its sealing

➢ Low water permeability to limit advective water transport and to retard migration of radionuclides

➢ Low gas entry pressure to allow discharge of gases produced within repository without damaging the multi-barrier-system
Seal Materials

Crushed claystone COX (URL Bure)

Claystone-Bentonite (20/80; 60/40)

Bentonite MX80

Bentonite-Sand (70/30)

Experiments

- Compacted Density
- Mechanical stiffness
- Water retention
- Swelling capacity
- Water permeability
- Gas migration
Compacted Density

D = 280 mm  H = 200 mm

Claystone 2.00 g/cm³

CB (60/40) 1.85 g/cm³

BS (70/30) 1.80 g/cm³

Bentonite 1.65 g/cm³
Mechanical Stiffness

Compaction behaviour

Elastic bulk modulus

claystone-bentonite-mixtures show higher density and higher stiffness
Water retention

Wetting at null suction

Drying at suction = 140 MPa
**Water content – suction relationship (water retention curve)**

### Bentonite

Bentonite-Sand (70/30)

![Graph showing water content vs. suction for Bentonite-Sand (70/30) with data points and curves indicating different materials and their dry densities.]

- 70MX80+30Sand confined, dry density = 1.81 g/cm³
- MX80 bentonite unconfined, dry density = 1.15 g/cm³
- MX80 bentonite unconfined: dry density = 1.64 g/cm³

**Water content (%):**
- 48%
- 32%

### Claystone-Bentonite

(60/40; 80/20)

![Graph showing water content vs. suction for Claystone-Bentonite (60/40; 80/20) with data points and curves indicating different materials and their dry densities.]

- 60COX+40MX80 confined, dry density = 1.89 g/cm³
- 60COX+40MX80 confined, dry density = 1.81 g/cm³
- 60COX+40MX80 unconfined: dry density = 1.88 g/cm³
- 80COX+20MX80 unconfined: dry density = 1.95 g/cm³

**Water content (%):**
- 28%
- 20%
Free swelling

Compacted samples
D = 50 mm; H = 20 mm

In humid air conditions (RH = 96-100 %)

- Claystone-Bentonite (80/20) dry density = 1.95 g/cm³
- Claystone-Bentonite (60/40) dry density = 1.88 g/cm³
- MX80 bentonite dry density = 1.64 g/cm³

unconfined samples
T = 25°C / RH = 96%

- COX crushed claystone: dry density = 2.05 g/cm³
- 80COX+20MX80 mixture: dry density = 1.95 g/cm³

Crushed claystone 2.05 g/cm³
Swelling pressure

Bentonite-sand (70/30)  
$\rho_d = 1.82 \text{ g/cm}^3$

Claystone-bentonite (60/40)  
$\rho_d = 1.86 \text{ g/cm}^3$

BS (70/30): $\rho_d = 1.82 \text{ g/cm}^3$

CB (60/40): $\rho_d = 1.86 \text{ g/cm}^3$
Water permeability

Measurement of water flow

**CB (80/20)**
- $\rho_d = 1.86–1.90$ g/cm$^3$
- $K_w = 2 \cdot 10^{-19} – 1 \cdot 10^{-19}$ m$^2$

**CB (60/40)**
- $\rho_d = 1.86–1.92$ g/cm$^3$
- $K_w = 1 \cdot 10^{-19} – 3 \cdot 10^{-20}$ m$^2$

**BS (70/30)**
- $\rho_d = 1.82$ g/cm$^3$
- $K_w = 2 \cdot 10^{-20}$ m$^2$

**Requirement**
- $\leq 10^{-18}$ m$^2$
  (Andra)
Gas Migration

Claystone-bentonite-mixture allows for gas flow at low pressures.
Borehole sealing

BS Blocks (70/30) 1.80 g/cm³

CB Blocks (60/40) 1.85 g/cm³
**Swelling pressure**

- **Swelling pressure** 2 MPa

**Water permeability**

- **BS (70/30):** $K_w = 2 \cdot 10^{-20} \text{ m}^2$
- **CB (60/40):** $K_w = 1 \cdot 10^{-19} \text{ m}^2$

**Requirement** $\leq 10^{-18} \text{ m}^2$ (Andra)

**Gas breakthrough pressure**

- **BS (70/30):** $P_b = 8 \text{ MPa}$
- **CB (60/40):** $P_b = 4 \text{ MPa}$
## Conclusions

All the compacted mixtures have favourable sealing properties; The claystone-bentonite mixtures allow gas flow at low pressures.

<table>
<thead>
<tr>
<th>Sealing properties</th>
<th>Crushed claystone COX</th>
<th>Claystone-bentonite (80/20)</th>
<th>Claystone-bentonite (60/40)</th>
<th>Bentonite-sand (70/30)</th>
<th>Bentonite MX80</th>
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<tbody>
<tr>
<td>Dry density (g/cm$^3$)</td>
<td>2.00</td>
<td>1.95</td>
<td>1.90</td>
<td>1.80</td>
<td>1.60</td>
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<tr>
<td>Bulk modulus (MPa)</td>
<td>-</td>
<td>1400</td>
<td>1200</td>
<td>600</td>
<td>-</td>
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<tr>
<td>Water permeability (m$^2$)</td>
<td>$5\cdot10^{-20}$</td>
<td>$1\cdot10^{-19}$</td>
<td>$5\cdot10^{-20}$</td>
<td>$2\cdot10^{-20}$</td>
<td>$1\cdot10^{-20}$</td>
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<tr>
<td>Swelling pressure (MPa)</td>
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<td>Gas break. pressure (MPa)</td>
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<td>1.2</td>
<td>2.5</td>
<td>$\geq 6.0$</td>
<td>$\geq 7.5$</td>
</tr>
</tbody>
</table>
Thank you for your attention!

感谢您的关注！
Corrosion study of low alloy steel based on the effect of trace dissolved oxygen in HLW geological disposal repository

Junhua Dong

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Abstract: The engineering barrier system for HLW geological disposal is composed of the solidified glass, metal overpack and buffer materials. Among these, overpack is the first artificial barrier to isolate HLW from the biosphere for long-term. Due to the advantages such as anti-irradiation, high strength, welding performance, carbon steel has been selected as the candidate material in some countries. However, the corrosion mode and corrosion rate are strongly affected by the dissolved oxygen, compositions of groundwater and buffer material in the deep geological disposal environment. With the consumption of the residual oxygen, the environment will become reducing condition. Previous studies suggested that the corrosion of carbon steel was active dissolution driven by hydrogen evolution reaction (HER) in anaerobic environment. However, the dissolved oxygen is difficult to be depleted completely in the actual repository. A small amount of dissolved oxygen may still have a strong impact on the corrosion of carbon steel during the long-term disposal. The feasibility of low carbon steel used for manufacturing the overpack of HLW geological disposal needs further study.

The current work has firstly focused on investigating the tendency of active dissolution or quasi-passivation of low carbon steel in deaerated solutions. The results showed that the corrosion mode of low carbon steel was active dissolution in the initial stage. With extending the immersion time, the open circuit potential (OCP) was significantly increased under the effect of corrosion product, inducing the low carbon steel in a quasi-passivation state. The corrosion products were mainly composed of α-FeOOH, Fe$_3$O$_4$ and Fe$_6$(OH)$_{12}$CO$_3$, and the cathodic reaction transformed from HER to the reduction of α-FeOOH. As the environments containing chloride, the low carbon steel was prone to suffer from the localized corrosion and the corrosion rate was accelerated. Therefore, the low carbon steel is not considered to be suitable for manufacturing the overpack. Thereafter, by alloying with a small amount of Ni and Cu in the low carbon steel, it is found that NiCu steel present a similar corrosion behavior with that of low carbon steel. However, its corrosion rate was obviously decreased and it was less prone to suffer from the localized corrosion in the simulated environments. Hopefully, it is possible to consider using NiCu steel as the candidate material for manufacturing the overpack of HLW for geological disposal.
Benchmark project for flow and transport in fractured rock and coupled THM processes in bentonite

Hua Shao

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Abstract: To understand and simulate the fully coupled THMC processes occurred in the construction, implementation and post-closure phase of a deep geological repository for radioactive waste, numerical codes are developed and applied. Because such a numerical code is a highly complicated software product, it is necessary to verify and validate the code against the experimental data and compare the results with other codes used to guarantee the quality of the outcomes. This is an important way to increase the confidence building.

Two cases will be presented concerning the disposal concept in the fractured rock: 1) flow and solute transport in the fractured rock and 2) coupled thermo-hydro-mechanical processes in bentonite buffer material. Both cases were intensively studied within the framework of the DECOVALEX project (www.decoval.org), which is an international cooperative project focusing on the development, verification, calibration and validation of a numerical code against the experimental data from either laboratory experiments or large-scale in-situ experiments.

In the first case, the transit time distribution on inflow rate and stable isotopes of water discharging to individual fractures and fracture networks were numerically analyzed in a well-defined real-case benchmark abstracted from the Bedrichov site in the Czech Republic. Using three-dimensional fracture/matrix models, tracer transport process in which transport in fracture networks is affected by rapid advection in fractures and diffusion into and out of adjacent intact lower-permeability matrix, can well be interpreted.

The second one is dealing with a laboratory heating and hydration experiment on the MX-80 bentonite pellets to simulate bentonite behavior under the canister-emplacement conditions in a real repository. To understand the strong interaction between thermal, hydraulic and mechanic processes, a fully coupled THM code taking into consideration saturation-dependent thermal conductivity and temperature-dependent retention behavior for the bentonite is needed.
Benchmark Project for Flow and Transport in Fractured Rock and Coupled Processes in Bentonite

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Benchmark Project

- A measurement of the **quality**
- **Comparison** with standard ones
- **Objectives** are to:
  - determine w&w improvements
  - analyze how others achieve high performance
  - use this information to improve performance
- **Numerical Code** – complicated software **Product**
- **Quality management (QM)** and **confidence building**
DECOVALEX – 25 years

- Increase the basic **Understanding** of coupled THM and THMC processes in **geological host rocks and geotechnical buffer materials**
- Exchange experimental data and improve the understanding of the **constitutive behaviors**
- **Develop, verify and validate** computer codes against field experiments
- Investigate the **predictive capabilities**
Real-case benchmark for flow and tracer transport in the fractured rock

Bedrichov – Tunnel (CZ)

(Final report D2015)
Real-case benchmark for flow and tracer transport in the fractured rock - Characterisation

(Final report D2015)
Real-case benchmark for flow and tracer transport in the fractured rock - Codes

TUL (FLOW123)  BGR/UFZ (OGS)  SANDIA (PFLOTRAN)

(Hokr et al. 2016)
Real-case benchmark for flow and tracer transport in the fractured rock - Properties

(Final report D2015)
Real-case benchmark for flow and tracer transport in the fractured rock - Application

(Hokr et al. 2016)
Laboratory THM experiment – Bentonite pellets

No flux boundary

$T_{bc} = 21.5 \, ^{\circ}C$

Heat power:

$W(t) = 5.25 \quad 0 \, \text{–} \, 3524 \, \text{h}$

$W(t) = 7.7 \quad 3524 \, \text{–} \, 5015 \, \text{h}$

$P_w = 0.1 \text{ bar after 5015 h}$
Laboratory THM experiment – Processes

- **T**: Linear heat transport

- **H²**: Non-isothermal multiphase flow

- **M**: Elastic constitutive model

\[ \Delta \sigma^{sw} = \sigma_m \Delta s^I \]
Laboratory THM experiment – Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bentonite $\lambda_{\text{sat}}/\lambda_{\text{unsa}}$</th>
<th>Teflon</th>
<th>Wool</th>
<th>Insulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity [W/(m·K)]</td>
<td>1/0.3</td>
<td>0.25</td>
<td>0.04</td>
<td>0.034</td>
</tr>
<tr>
<td>Specific heat [J/(kg·K)]</td>
<td></td>
<td>950</td>
<td>960</td>
<td>1220</td>
</tr>
<tr>
<td>Thermal expansion [K⁻¹]</td>
<td>1e-5</td>
<td>1e-6</td>
<td>9.6e-6</td>
<td>-</td>
</tr>
</tbody>
</table>

- Temperature dependent water retention

- Saturation dependent thermal conductivity

- Relative permeability:
  \[
  k_{rw} = S_e^5
  \]
  \[
  k_{rg} = (1 - S_e)^5
  \]
Laboratory THM experiment – Temperature

Heating – Heating & hydration

(Graupner et al. 2016)
Laboratory THM experiment – Humidity

- Temperature dependent water retention behaviour

constant water retention  temperature dependent
Lessons learned from benchmark project

➢ Analyze jointly same cases
➢ Minimize error sources
➢ Increase understanding of complicated system
➢ Keep state-of-the-art in both experiment and modelling
➢ Exchange know-how between (international) partners
➢ Build confidence for the public
Thank you for your attention!


Analysis of discontinuities based on the integration of measurements, experiments and modeling

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Abstract: Whether a fault zone is a conduit or barrier to flow is determined by the ratio of damage zone to clay core. How is the development of fault gauge in the fault zone of different scales?

1st order fault in Beishan site: Fault gouge, revealed by exploratory trenches, can be up to a few tens of centimeters wide, thus forms an efficient barrier to transverse fluid flow. There is a combined barrier-conduit effect, which has been confirmed by ground water monitoring. In the contrast, in the 2nd order fault zones with several km long and minor horizontal dislocation, the clay content is absent or only a few millimeters, therefore, no obvious barrier effect on fluid flow.

On the typical exposure, different structural components can be found and classified. Then, the fracture patterns and densities in different fault architectural components, which control their hydraulic properties, have been identified and documented in detail. For the further identification of the internal structure and its mechanism, the 3D Cautious Exploration Trenches (3DCET) and related more detailed characterization are needed.

The intrinsic permeability of the fault architectural components 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 behavior of the fault zone.

By systematic and detailed measurements, the influence range of fault zone has been be determined.

Different grades of structural planes play different roles in stability, therefore, different evaluation methods have been analyzed for four grades of structural planes. The preferential structural plane in stability controlling has been identified. It is found that the deformation and damage of surrounding rockmass are mainly controlled by preferential structural planes.

We have developed an Air +Outcrop +Borehole +Tunnel combined photogrammetry and integrated fracture parameter determination system. With the AOBT system, the absolute high precision 3D coordinates of fractures can be determined with precision of centimeter level.

Usually, it is assumed that fractures occur randomly, the midpoints of trace lengths are uniformly distributed. On the basis of fine measurements and statistical analyses, non uniform joint set has been identified.

Homogeneity zonation was firstly and carefully analyzed. Then the influence of undulation of outcrop surface was modified.

By comparison with in situ packer-test. The Deterministic-Stochastic integrated fracture Network (DSN) model is in better agreement with the measured results than simple stochastic model.

Cautious sampling, detailed identification and characterization of faulted rocks have been carried out, employing multiple observation, scanning instruments.

Firstly, the spatial probability distribution of rockmass factors, like RQD, JRC and so on, are determined. Then, the mechanical parameters of rockmass, like cohesion, frictional angle of rockmass, have been determined employing GSI criterion and Bayesian inference method.
Abstract: In Germany, radioactive waste is foreseen to be disposed in deep geological formations with very low hydraulic conductivities, e.g. rock salt, claystone and crystalline rock. Safety assessment is focused here on the safe containment of the radioactive waste within a specifically defined zone in the host rock over a period of one million years. Long term safety assessment for such a repository requires a comprehensive system understanding which in turn requires, among other things, exemplary numerical investigations with qualified high-performance tools. These tools have to be able to describe all relevant processes concerning radionuclide transport in the host rock and subsequently in the overburden.

To meet the needs of modelling groundwater flow and nuclide transport, the computer codes d³f (distributed density-driven flow) and r³t (radio-nuclides, reaction, retardation and transport) had been developed in the early nineties based on version 3 of the UG Toolbox. Afterwards, these codes were substantially advanced and continuously adapted to the state-of-the-art of science and technology.

However, in the original design of the UG library – codes such as d³f and r³t have been built as separate applications based on the core libraries – the coupling and thereby simultaneous simulation of flow field and species transport was not natively supported. This has changed with the new version UG4 where coupling of different equations is now implemented as a standard procedure. Based on this coupling mechanism the codes d³f and r³t have been combined to the new conjoint code d³f++ which allows for the simultaneous simulation of density-driven groundwater flow and pollutant transport.

This powerful tool is able to handle salt, heat and pollutant transport as well as free groundwater surface in the far field of a geological repository. Furthermore it can be applied to different kinds of deep geological formations such as the overburden of a salt dome, clay formations, or fractured crystalline rock, respectively. Besides long-term safety analyses for nuclear waste repositories d³f++ has also successfully been used to reproduce or to predict laboratory and field experiments as well as flow in coastal aquifers.
d³f++ —
modelling tools for
density-driven flow and transport

Hong Zhao, Anke Schneider, Klaus-Peter Kröhn, Anne Gehrke,
Jens Wolf, GRS
3rd Chinese-German Workshop on Radioactive Waste Disposal
Jiayuguan, China, May 16th 2017
Motivation – far field modeling

disposal of nuclear waste in deep geological formations
salt, clay, crystalline rock

- safe containment in the host rock
- 1 million years
- radionuclide release scenarios
- 2d/3d geosphere modelling
  - groundwater flow in porous/fractured media
  - thermohaline flow
  - nuclide transport
  - large regions, complex geology
- development of the codes $d^3f$ (distributed density-driven flow) and $r^3t$ (radionuclide, reaction, retardation, and transport) from 1995
- now: $d^3f++$

high-level waste repository
far field
developing a modelling tool

1995 –

**UG3**

- Uni Erlangen
  - P. Knabner
  - discretisation error estimators
  - (until 1998)
- Uni Hannover
  - W. Zielke
  - preprocessing
  - (until 1998)
- UFZ Leipzig
  - O. Kolditz
  - benchmarking
- Uni Jena
  - S. Attinger
  - inhomogeneities upscaling uncertainties

1998 –

**d³f**

- fractures
- heat transport
- phreatic flow
- inhomogeneities
- adaptive fractures
- speed-up

**r³t**

- qualification
- GRS
  - E. Fein
  - project management
- Uni Stuttgart/Heidelberg/Frankfurt
  - G. Wittum
  - numerics
- Uni Heidelberg/ETH Zurich
  - W. Kinzelbach
  - physical model
  - (until 2003)
- Uni Freiburg
  - D. Kröner
  - Uni Bonn
  - M. Rumpf
  - postprocessor
- funded by BMBF/BMWi

2013 –

**UG4**

**d³f++**

- free surface flow
- smart \( K_d \)
- colloidal transport
- ↔ PHREEQC
**d³f++: distributed density-driven flow**

- density-driven groundwater flow
- salt and heat transport
- fluid density and viscosity depending on salt concentration and temperature
- porous and fractured media
- free groundwater surface – levelset function
- sources and sinks

- transport of radionuclides
- radioactive decay
- equilibrium and kinetically controlled sorption
- precipitation/dissolution
- diffusion into immobile pore water
- complexation
- colloid-borne transport
- smart $K_d$ concept
- PHREEQC-coupling
Equations of thermohaline flow

\[ \partial_t (\phi \rho) + \text{div} (\rho \mathbf{q}) = 0 \]

mass conservation of the fluid

\[ \partial_t (\phi \rho \omega) + \text{div} (\rho \omega \mathbf{q} + \mathbf{J}_\omega) = 0 \]

mass conservation of the brine

\[ \mathbf{J}_\omega = -\rho \mathbf{D} \nabla \omega \]

Fick’s law

\[ \partial_t \left[ \left( \phi \rho C_f + (1 - \phi) \rho_s C_s \right) T \right] + \text{div} \left( \rho C_f T \mathbf{q} + \mathbf{J}_T \right) = 0 \]

heat conservation

\[ \mathbf{J}_T = -\Lambda \nabla T \]

Fourier’s law

\[ \mathbf{q} = -\frac{k}{\mu} (\nabla p - \rho g) \]

Darcy’s law

\(\phi\) effective porosity

\(C_f\) heat capacity of the fluid

\(C_s\) heat capacity of the solid (rock)

\(\rho_s\) rock density

\(\Lambda\) hydrodynamic thermal dispersion tensor

\(\omega\) mass fraction of the brine

\(p\) pressure

\(T\) temperature

\(\mathbf{q}\) Darcy velocity

\(\rho = \rho(\omega, T)\) fluid density

\(\mu = \mu(\omega, T)\) viscosity
Equations of nuclide transport

$$\partial_t \left( \phi \rho \chi_i \right) + \text{div} \left( \rho \chi_i \mathbf{q} + \mathbf{J}_{\chi_i} \right) = Q_i$$

mass conservation of the contaminant

$$\mathbf{J}_{\chi_i} = -\rho \mathbf{D} \nabla \chi_i$$

Fick’s law

$$\partial_t \left( \phi \rho \chi_i^l + \phi \rho \chi_i^p + (1 - \phi) \rho \chi_i^{ad} \right) + \text{div} \left( \rho \chi_i^l \mathbf{q} + \mathbf{J}_{\chi_i} \right) = Q_i$$

$\chi_i$ mass fraction of the $i^{th}$ radionuclide (contaminant)

$\chi_i^l$ mass fraction of the dissolved nuclide

$\chi_i^p$ mass fraction of the precipitated nuclide

$\chi_i^{ad}$ mass fraction of the adsorbed nuclide

$Q_i$ source term of the $i^{th}$ nuclide

$$Q_i = \phi \sum_k R_k \lambda_k c_k$$

$\lambda_k$ the decay constant of radionuclide $k$

$c_k$ the concentration of radionuclide $k$
Numerics

- based on UG4 (G-CSC University Frankfurt)
- finite volume discretisation
- grids
  - unstructured
  - tetrahedral or prism elements
  - fractures lower dimensional
- upwind strategies
- linear geometric and algebraic multigrid solvers
- completely parallelised
- interactive, graphical pre- and postprocessors
- grid generator ProMesh (Sebastian Reiter, G-CSC, [www.promesh3d.com](http://www.promesh3d.com))
Applications of $d^3f++$

- **Porous media**, overburden of host formations
  - *Gorleben Site*: 2D density driven flow and RN transport in high saline environment
  - *Wipp Site*: 3D density driven flow
  - *Cape Cod*: 2D contaminant transport with pH-dependent sorption

- **Low permeable media**
  - *Generic German Site in clay*: 3D diffusive transport in a low permeable anisotropic clay formation

- **Fractured media**
  - *Yeniseysky site*: Flow and transport in fractured rock
  - *Grimsel*: Colloid-facilitated transport in clay
  - *Äspö*: Flow in the repository near field
Hard Rock Laboratory at Äspö

Only suitable host rock in Sweden: granite

Hard Rock Laboratory at Äspö
Collaboration of GRS and SKB
Äspö Hard Rock Laboratory

Field data from the Swedish Hard Rock Laboratory at Äspö: Prototype Repository

Model geometry domain
- Model size 150m x 200m x 50m

Geotechnical openings
- 4 tunnels (+2 extensions)
- 6 deposition holes

Additional features
- Matrix, skin, fractures
- 3 major, 6 minor fractures

Numerical grid
- 31388 vertices, 131242 volumes
Boundary conditions:

- Outer model boundary: *prescribed pressure*  
  *rock temperature* (15°C)
- Tunnel surface:  
  *atmospheric pressure*  
  *temperature outflow*
- Borehole surface:  
  *atmospheric pressure*  
  *time-dependent temperature*
Flow at medium scale, checking the model concept: Prototype Repository
Thermo-hydraulic flow at the prototype Repository
\(t=300, 900, 3600\) days
Thermo-hydraulic flow at the Prototype Repository
$t=300, 900, 3600$ days
Numerical realization of lower-dimensional fractures in $d^3f++$

3 nodes
- orthogonal to the fracture plane
- at infinitesimal short distance to each other

epecially challenging: intersections
1D-fractures in 2D-space

2D-fractures in 3D-space
Thank you for your attention!

Thanks especially to colleagues of group Prof. Wittum, G-CSC Frankfurt
3D geological model of URL in Xinchang preselected site

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Abstract: China's high-level radioactive waste disposal research began in 1985. Since then, we have obtained a large number of engineering geological characteristics information of Beishan pre-selected area in Gansu province. Based on the multi-source data obtained from these disciplines and multi-methods, the three-dimensional geological model of the rock mass in the underground laboratory preselected site is established, and the deep geological environment and characteristics such as scale, integrity and fracture structure distribution are expressed.

The geological model of the Xinchang preselected site consists of two submodels: the lithological model and the faults model. The Xinchang preselected site has a model area of 36 km², which is located in the east-west direction. The north and south sides of the rock are separated from the metamorphic strata by the E-W trending faults. The lithologic units of granite from north to south are: Hongliujingnanshan unit’s gneissic granodiorite (Pt2-H), Xinchang unit’s monzonitic granite (O1-x), Jijinggou unit’s granodiorite (O1-J), and Yuanyanggou unit’s gneissic monzonite granite (Pt2-Y). Xinchang preselected site is located in the clamping site between the E-W trending regional faults in north and south sides of Xinchang block and a series of N-E trending local faults. The inner part of the rock mass is broken into different sizes of the block, forming a number of “structural security island.”

The 3D geological modeling of Xinchang preselected site can make the exploration data more lifelike manifestation, it is helpful in the inference, forecasts and grasps of its distribution rule in the research region, and provides a model for geologic numerical analysis. Furthermore, it can also provide the basis for the subsequent engineering design of underground laboratories.

Key words: 3D geological modeling; high-level waste disposal; underground research laboratory; deep geological environmental
3D geological model of URL in Xinchang
preselected site

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Beijing Research Institute of Uranium Geology, CNNC
Outline

- Background
- Modeling methods and Procedure
- Geological Site model
The site selection and site characterization activities conducted in the past 30 years has resulted in the identification of 11 preselected sub-areas for China’s geological repository. Based on this, 9 sites for URL were selected.
4 preselected sites have been selected from the previous 9 candidate sites, i.e. the Xinchang, Shazaoyuan sites in Gansu province; the Yamansu site in Xinjiang; Nuorigong site in Inner Mongolia.
Guided by the “Site selection plan for an URL of geological disposal of high level radioactive waste in China” and the “Site selection criteria for an URL for geological disposal of high level radioactive waste in China”

Finally, according to the recommendation of a widely representative expert group, the Xinchang site in Gansu province is recommended as the preferred site for URL.

The report has a detailed description——
Since 1985, we have obtained a large number of engineering geological characteristics information of Xinchang.

Topographic data (1:5000);
Geological map (1:50000);
14 boreholes’ catalog data (600m, 5 incline boreholes);
19 boreholes’ catalog data (100m, 16 incline boreholes);
1 boreholes’ catalog data (1000m, still drilling);
11 geophysical profiles (electromagnetic);
borehole measurement data;
borehole hydraulic test;
BHTV logging;
borehole radar;
borehole compostive measurements (resistivity, density, natural gamma).
Based on the multi-source data obtained from these disciplines and multi-methods, the three-dimensional geological model of the rock mass in the underground laboratory preselected site will be built, and the deep geological environment and characteristics such as scale, integrity and fracture structure distribution are expressed.

The 3D geological modeling of Xinchang URL site can make the exploration data more lifelike manifestation, it is helpful in the inference, forecasts and grasps of its distribution rule in the research region, and provides a model for geologic numerical analysis. Furthermore, it can also provide the basis for the subsequent engineering design of underground laboratories.
procedure of modeling

- Model area is 36 km²
- The depth of the model is 1 km
- Lithological units together with major fault systems will be modeled
Procedure

- Import surface data
- Import the borehole data and draw Cross well profiles
- Interpretation of geophysical profiles
- Build the fault model based on the data of surface geological survey and borehole data
- Draw horizontal profiles of different depth, and build the lithological model
- Embed this two models together, and get a 3D GSM of Xinchang
Import surface data

Topographic: Elevation range is 1632 m ~ 1770m

Geological map

Superimposed remote sensing data
Import borehole data
Cross well profile
Cross well profile

12 cross well profiles
Interpretation of geophysical profiles

11 geophysical profiles
After analyzing and interpreting the geophysical profiles, we have obtained 11 corresponding geological profiles.
Fault model
## Fault Characteristic Table

<table>
<thead>
<tr>
<th>ID</th>
<th>Length /km</th>
<th>Inclined/dip (survey)</th>
<th>Inclined/dip (modeling)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>F7</td>
<td>5.6</td>
<td>180° ≤ 70°</td>
<td>180° ≤ 70°</td>
<td>Survey point.</td>
</tr>
<tr>
<td>F8</td>
<td>4.0</td>
<td>180° ≤ 60°</td>
<td>180° ≤ 60°</td>
<td>Survey point.</td>
</tr>
<tr>
<td>F29</td>
<td>3.0</td>
<td>320° ≤ 64°</td>
<td>320° ≤ 64°</td>
<td>Survey point.</td>
</tr>
<tr>
<td>F29-1</td>
<td>2.2</td>
<td>195° ≤ 85°</td>
<td>195° ≤ 60°</td>
<td>Survey point、BSQ07。</td>
</tr>
<tr>
<td>F30</td>
<td>1.8</td>
<td>288° ≤ 80°</td>
<td>288° ≤ 80°</td>
<td>Survey point。</td>
</tr>
<tr>
<td>F31</td>
<td>5.5</td>
<td>290° ~ 305° ≤ 70° ~ 83°</td>
<td>290° ~ 80°</td>
<td>Survey point、2 exploratory trench、BSQ04、BSQ05、BSQ06、BS35、BS36。</td>
</tr>
<tr>
<td>F32</td>
<td>6.1</td>
<td>260° ~ 290° ≤ 60° ~ 82°</td>
<td>(above 200m) 280° ≤ 70°, (below 200m) 280° ≤ 75°</td>
<td>Survey point、1 exploratory trench、BSQ09、BSQ11、BSQ12。</td>
</tr>
<tr>
<td>F32-1</td>
<td>4.7</td>
<td>60° ~ 70° ≤ 70° ~ 79°</td>
<td>65° ≤ 75°</td>
<td>Survey point、1 exploratory trench。</td>
</tr>
<tr>
<td>F33</td>
<td>5.1</td>
<td>280° ~ 300° ≤ 68° ~ 75°</td>
<td>290° ≤ 68°</td>
<td>Survey point、1 exploratory trench、BSQ08、BSQ10、BS38、BS39。</td>
</tr>
<tr>
<td>F34</td>
<td>4.6</td>
<td>310° ~ 320° ≤ 72° ~ 86°</td>
<td>(above 200m) 315° ≤ 75°, (below 200m) 315° ≤ 84°</td>
<td>Survey point、2 exploratory trench、BSQ01、BSQ02、BSQ03、BS37。</td>
</tr>
<tr>
<td>F34-1</td>
<td>0.8</td>
<td>120° ≤ 82°</td>
<td>120° ≤ 82°</td>
<td>Survey point。</td>
</tr>
<tr>
<td>F34-2</td>
<td>1.1</td>
<td>320° ~ 330° ≤ 60° ~ 80°</td>
<td>330° ≤ 70°</td>
<td>Survey point、BSQ16。</td>
</tr>
<tr>
<td>F34-3</td>
<td>1.9</td>
<td>340° ≤ 60°</td>
<td>340° ≤ 60°</td>
<td>Survey point。</td>
</tr>
<tr>
<td>F35</td>
<td>2.6</td>
<td>320° ≤ 66°</td>
<td>320° ≤ 66°</td>
<td>Survey point、2 exploratory trench。</td>
</tr>
</tbody>
</table>
F31

NW290° ~ 305°, 70° ~ 83°; length is 5.5km, width is 1.0~2.5m.

We designed BSQ04, BSQ05, BSQ06, BS35, BS36 to expose the fracture characteristics. BSQ04 reveals the depth of the fault is 138.50 ~ 141.77m, BSQ05 reveals the depth of the fault is 101.20 ~ 115.90m, BSQ06 reveals the depth of the fault is 79.83 ~ 92.40m, BS35 reveals the depth of the fault is 609.7 ~ 617.3m, BS36 reveals the depth of the fault is 497.20 ~ 501.1 m.
Fault model
Fault model

F33
Fault model

F34
Fault model
Fault model

F29-1
Fracture model of Xinchang preselected site
12 pieces nearly E-W direction vertical profile,
11 pieces nearly S-N direction vertical profile,
We draw eight horizontal profiles at different depths (elevation 550m, 700m, 850m, 1000m, 1150m, 1300m, 1450m, 1600m).
Lithologic model
Xinchang preselected site is located in the clamping site between the E-W trending regional faults in north and south sides of Xinchang block and a series of NE trending local faults. The inner part of the rock mass is divided into different sizes of parts, forming a number of "structural security island."
Thanks for your attention.
Simulation of density-driven flow in heterogeneous and fractured porous media

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Abstract: The study of fractured porous media is an important and challenging problem in hydrogeology. One of the difficulties is that mathematical models have to account for heterogeneity introduced by fractures in hydrogeological media. Heterogeneity may strongly influence the physical processes taking place in these media. Moreover, the thickness of the fractures, which is usually negligible in comparison with the size of the whole domain, and the complicated geometry of fracture networks reduce essentially the efficiency of numerical methods. In order to overcome these difficulties, fractures are sometimes considered as objects of reduced dimensionality (surfaces in three dimensions), and the field equations are averaged along the fracture width.

Fractures are assumed to be thin regions of space filled with a porous material whose properties differ from those of the porous medium enclosing them. The interfaces separating the fractures from the embedding medium are assumed to be ideal. We consider two approaches:

(i) the fractures have the same dimension, d, as the embedding medium and are said to be d-dimensional;
(ii) the fractures are considered as (d-1)-dimensional manifolds, and the equations of density-driven flow are found by averaging the d-dimensional laws over the fracture width.

We show that the second approach is a valid alternative to the first one. For this purpose, we perform numerical experiments using a finite volume discretization for both approaches. The results obtained by the two methods are in good agreement with each other.

We derive a criterion for the validity of the simplified representation. The criterion characterizes the transition of a mainly parallel flow to a rotational flow, which can not be reasonably approximated using a d-1 dimensional representation. We further present a numerical algorithm using adaptive dimensional representation.

References


Simulation of density driven flow in heterogeneous and fractured porous media

Arne Nägel, Sebastian Reiter, Andreas Vogel, Gabriel Wittum
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LARGE SCALE SIMULATION

Adaptivity

Parallelism

Robust Multigrid

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Adaptivity

- Refine grid where needed
Distributed Density Driven Flow $D^3F$

- Saltwater intrusion
- Upconing
- Flow around salt domes

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\textbf{D}^3\textbf{F}

- Distributed Density Driven Flow

\[
\frac{\partial (n\rho(c))}{\partial t} + \nabla \cdot (\rho(c)\vec{v}) = Q_p(c),
\]

\[
\frac{\partial (n\rho(c)c)}{\partial t} + \nabla \cdot (\rho(c)(c\vec{v} - \mathbb{D}\nabla c)) = Q_c(c)
\]

+ b.c.; with \( \vec{v} = -K/\mu(c)(\nabla p - \rho(c)\vec{g}) \),

\[
\mathbb{D}(\vec{v}) := D_m\mathbb{I} + \alpha_t |\vec{v}|\mathbb{I} + (\alpha_l - \alpha_t)\vec{v}\vec{v}/|\vec{v}|,
\]

\[
\frac{1}{\rho} := \left(1 - \frac{c}{c_{\text{max}}} \right) \frac{1}{\rho_f} + \frac{c}{c_{\text{max}} \rho_s}
\]

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D$^3$F

- Distributed Density Driven Flow (d$^3$f)
  Solver for density driven flow based on *UG3*, 1999
- Radionuclides, Reaction, Retardation and transport (r$^3$t), based on *UG3*, 2004
- Distributed Density Driven Flow ++, (d$^3$f++)
  Solver for density driven flow based on *UG4*, 2015
**Validation**

- Extensive validation

**Especially designed experiments (saltpool)**


**Field cases measured (Cape Cod, E. Fein, K.-P. Kröhn)**
$D^3F$

- complicated domains w. unstructured grids ($\Omega_G$)
$D^3F$

- Full density dependent non-linear dispersion
- fully parallel adaptive
Adaptivity and Paralleism

- Parallel efficiency > 1/2, $p \leq 1024$
- Gain by adaptivity up to $10^4$
- Vogel, Andreas; Reiter, Sebastian; Rupp, Martin; Nägel, Arne; Wittum, Gabriel: UG 4..., *Comput Vis Sci*, 16 (4), pp 165-179, 2014.
Elder‘s Problem

- Boundary Conditions:
  \[ p=0, \ (\omega q - D \nabla \omega) \cdot n = 0 \]

- Model: Boussinesq - Approximation

- Discretization: vertex-centered finite volume

- Upwinding: exponential

- Time-stepping: fully implicit

- Newton-Method with assembled Jacobian

- Solver: BiCGStab with GMG Preconditioner with ILU Smoother
Elder Scaling study (GMG)  

A. Vogel

<table>
<thead>
<tr>
<th>( p_e )</th>
<th>( L )</th>
<th>( \text{DoFs} )</th>
<th>( N_{\text{iter}} )</th>
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Scaling study on JuQueen for the weak scaling of Elder’s problem in 2d. Initial grid with 8x2 quadrilaterals and uniform refinement for each grid level. Solution of the non-linear problem using Newton-iteration. Linearized problems are solved using a BiCGStab solver with geometric multigrid preconditioner and ILU smoother.

(Abbreviations are: \( PE \) = Processing entities (cores), \( \text{DoF} \) = Degrees of Freedom; \( T_{\text{assemble}} \) = time for assembling of system matrix and coarse grid matrices, \( T_{\text{linSolver}} \) = time for linear solver within newton iteration)
LIMEX  Deuflhard et al 1987

- IVP:
  \[
  \frac{du}{dt} = F(u) \quad u(0) = u_0
  \]

- LIMEX (Linear implicit method with extrapolation) (Deuflhard et al, 1987)
  - Separate stiff components.
  - Coupling time step and non-linear iteration (restricts the time step)
  - Extrapolation increases time accuracy and allows larger time steps.
Results: LIMEX can compete with Full Newton (Elder Problem, w/ exact solver)

- Full Newton (179 iter/44 steps)
- Linear Implicit (44 iter/ 44 steps)
Results: LIMEX for Density Driven Flow (w/ inexact solver)

- Neglecting convection is not admissible, BUT:
  - Omitting related derivatives is beneficial for linear solver

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LIMEX

- Limex (all terms)
- Limex (simple convection)
- Limex (no convection)
Modified Elder

- Modified BC resulting in a unique time development

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Modified Elder (3d)

<table>
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<th>Method</th>
<th>Time steps</th>
<th>Linear solver</th>
<th>Timing</th>
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<td>LIMEX_2 (full)</td>
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<td>LIMEX_3 (full)</td>
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<td>590</td>
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<table>
<thead>
<tr>
<th>Method</th>
<th>Time steps</th>
<th>Linear solver</th>
<th>Timing</th>
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<tr>
<td>LIMEX_2 (no deriv)</td>
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<tr>
<td>LIMEX_3 (no deriv)</td>
<td>26</td>
<td>33</td>
<td>0.51</td>
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</tbody>
</table>

Similar results for 3D
Fully non-linear problem
• Based on Gorleben Saltdome
• Large anisotropy
• High contrast
• High dispersion
• Coarse mesh, large grid Peclet number

Solver Setup:
• LIMEX (TOL=0.1 for concentration; absolute!)
• Exact Jacobian, but: w/o Dispersion
• MG V(2,2)-cycle with element GS

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Solver Test Case

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A. Nägel

Smoother Performance

ILU > Element GS  >> Jacobi

Channel inflow

Channel backflow
Smoother Comparison

A. Nägel

Test 4 (Gorleben problem).

• Additional complexity due to the dispersive terms (5).
• Formulation as in previous sections requires more potent smoothers.
• $\text{ILU} > \text{element GS} > \text{node GS}$
• $\text{Jac}$

Disabling derivatives of dispersion mitigates problems (and allows for $\text{Jacobi}$ smoothing).

Figure 8: Test 4 – Truncated Gorleben: Time step size [yrs] vs. simulated time [yrs] for various smoothers.
WIPP

- Waste Isolation Pilot Plant (New Mexico)
- Detailed model of flow and transport
- 100,000 years
WIPP - Geometry

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S. Reiter
WIPP - Geometry and Grid

S. Reiter
WIPP Salt Mass Fraction

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S. Reiter
Fractured Porous Media

- Flow through fractures and matrix
- Full dimensional: resolving the fractures in detail
- Low dimensional: pcsw. 2d representation of fractures
- For larger fractures density driven flow may cause vorticity in the fracture => large error for low dimensional rep.

Adaptive dimensional approach:

Compute

\[ \theta = \frac{\epsilon |\omega_f|}{\|v_\theta\|} \frac{K_f}{K_m} \frac{c_f}{c_\theta} \]

\[ \text{max } \theta > \theta_0 \Rightarrow \text{full dimensional} \]

\[ \text{max } \theta \leq \theta_0 \Rightarrow \text{low dimensional} \]
Weak Scaling UG4

- Robust GMG solver for transdermal drug delivery problem (JuQueen) > 10^9 unknowns

\[\text{wall clock time [s]}\]
\[\text{#Procs}\]

\begin{align*}
16 & \quad 128 & \quad 1.024 & \quad 8.192 & \quad 65.536 \\
10 & \quad 20 & \quad 30 & \quad 40
\end{align*}

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Skin Problem: TKD

- Base solver UG4: Parallel adaptive multigrid
  - acceleration from $10^2$ to $10^6$ by adaptivity
Parallel Adaptivity

- Base solver UG4: Parallel adaptive mg
  - acceleration by 512 by adaptivity

- Importance of adaptivity increases with problem size!

<table>
<thead>
<tr>
<th>Resolution [nm]</th>
<th>uniform</th>
<th>adaptive</th>
</tr>
</thead>
<tbody>
<tr>
<td>uniform L13</td>
<td>33,554,432 cores</td>
<td></td>
</tr>
<tr>
<td>adaptive L13</td>
<td>65536 cores</td>
<td></td>
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<tr>
<td>factor</td>
<td>512 (99.5%) in CPU time and in power consumpt.</td>
<td></td>
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</tbody>
</table>

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Parallel Adaptivity

- Key strategy for
  - saving CPU time (99.5%),
  - saving power (99.5%),
  - improving accuracy
    (uniform needs 3 more levels to reach same error)
- Higher order effect without additional smoothness
- Importance of adaptivity increases with problem size!
- Multi-scale modeling necessary.
谢谢
Discrete fracture network modeling of host rock for high-level radioactive waste disposal

Jian Liu, Liang Chen, Chunping Wang, Yawei Li, Ju Wang

Beijing Research Institute of Uranium Geology, P O Box 9818, 10029 Beijing, China

Email: liujian0430@163.com

Abstract: For a high-level radioactive waste (HLW) disposal repository built in granite, the discrete fracture network (DFN) in the host rock might form potential pathways of nuclide migration from the engineered barriers to the biosphere. Building the DFN model of the surrounding rock is a prerequisite for the nuclide migration simulation and the safety assessment of the repository. Some improvements of DFN modeling technique in China’s HLW disposal project were presented in this study.

1. The 3D laser scanning technique was firstly imported into the field mapping of outcrop and tunnel. The trace-length data of fractures was successfully identified based on the high-resolution data-cloud.

2. In order to launch the dynamic clustering of fractures according to the occurrence, a modified max-min distance method of selecting initial cluster centers was proposed. The reliability of different validity indexes was then tested under different distance measures by using stochastic approximation method and an optimal combination of validity index and distance measure was proposed. With these proposed algorithms, more reasonable dominant occurrences were obtained.

3. By establishing a new criterion for searching optimal bin-width of fracture trace-lengths, a method of estimating the distribution characteristics of fracture trace-length and diameter was proposed. The estimation of truncation of trace-length was also successfully realized in this method.

4. An indoor apparatus of testing the mechanical behavior of natural fracture was developed and a preliminary method of numerically defining the shear properties was proposed.

5. A 3D DFN modeling software is currently being developed by packaging the above improved algorithms and methods.
Discrete Fracture Network (DFN) Modeling of Host Rock for Geological Disposal

LIU Jian, CHEN Liang
WANG Chunping, LI Yawei, WANG Ju

CNNC Beijing Research Institute of Uranium Geology (Briug)
Outline

1. Background
   - Why is the DFN modeling used?

2. State of the art
   - What is the DFN modeling?
   - What are the problems?

3. Progresses
   - How to improve this technique?

4. Conclusions and perspectives
1. Background
   - Why is the DFN modeling used?

2. State of the art
   - What is the DFN modeling?
   - What are the problems?

3. Progresses
   - How to improve this technique?

4. Conclusions and perspectives
1. Background – Geological disposal

The host rock is the last barrier to isolate HLW from biosphere.

"Multi-barrier System"

- Host Rock
- Backfill Material
- Buffer Material
- Canister
- Waste Form

Natural Barrier

Engineered Barriers

The host rock is the last barrier to isolate HLW from biosphere.
1. Background – Fracture network

The fracture network in granite is one key factor for the stability even the long-term safety of the repository.
1. Background – How to get 3D info.?

Borehole/borecore investigation

Outcrop investigation

1D Info.

2D Info.

3D Info.
1. Background
   - Why is the DFN modeling used?

2. State of the art
   - What is the DFN modeling?
   - What are the problems?

3. Progresses
   - How to improve this technique?

4. Conclusions and perspectives
2. State of the art – DFN modeling

Field investigation → Fracture clustering → Statistical analysis

Application ← Visualization ← Monte-Carlo

Probability density

Set 1
Set 2
Set 3
N
S
W
E

0
0.02
0.04
0.06
0.08
0.1
0.12
0 20 40 60

2. State of the art – DFN modeling

- **Field investigation**
  - Manual measurement → Imprecise basic data
  - Subjective judgments → Arbitrary clustering

- **Statistical analysis**
  - Theoretical problems → Inappropriate models
  - High technical requirements → Lack of special module for geological disposal

- **Application**
  - Unreliable hydrologic and mechanical properties → Limited in application

- **Visualization**
  - Probability density
  - Manual measurement → Imprecise basic data
  - Subjective judgments → Arbitrary clustering

- **Monte-Carlo**
  - Monte Carlo Visualization
  - Application
  - Statistical analysis
Outline

1. Background
   - Why is the DFN modeling used?

2. State of the art
   - What is the DFN modeling?
   - What are the problems?

3. Progresses
   - How to improve this technique?

4. Conclusions and perspectives
3. Progresses – Improvement list

Field investigation

- Increase precision of field investigation → Import 3D laser scanning technique

Fracture clustering

- Replace subjective judgments → Propose automatic clustering method

Statistical analysis

- Avoid theory contradiction → Propose new theoretical criteria

Application

- Obtain mechanical properties of fracture → Propose a testing method of shear properties

Visualization

- Realize visual post-treatment → Develop post-treatment module by implementing typical disposal concepts

Monte-Carlo
3. Progresses – Field investigation

Increase precision of field investigation → Import 3D laser scanning technique

Field investigation → Fracture clustering → Statistical analysis

Replace subjective judgments → Propose automatic clustering method

Avoid theory contradiction → Propose new theoretical criteria

Application → Visualization → Monte-Carlo

Obtain mechanical properties of fracture → Propose a testing method of shear properties

Realize visual post-treatment → Develop post-treatment module by implementing typical disposal concepts
Key fractures have been successfully identified under a resolution of millimeter and a semi-automatic method of identifying the fractures is being developed.
3. Progresses – Fracture clustering

Field investigation

- Increase precision of field investigation
  - Import 3D laser scanning technique

Fracture clustering

- Replace subjective judgments
  - Propose automatic clustering method

Statistical analysis

- Avoid theory contradiction
  - Propose new theoretical criteria

Application

- Obtain mechanical properties of fracture
  - Propose a testing method of shear properties

Visualization

- Realize visual post-treatment
  - Develop post-treatment module by implementing typical disposal concepts

Monte-Carlo
3. Progresses – Fracture clustering

**Objective selection of initial centers**

\[
d^*_\text{max} = \max_{v_i \in D} \left\{ \rho_i \min_{v_s \in I} \{ d(v_i, v_s) \} \right\}
\]

- \(v_i, v_s\) → Vector of occurrence
- \(d(v_i, v_s)\) → Distance between occurrences
- \(\rho_i\) → Density of occurrence

**Selection of initial dominant occurrences**

A new objective criterion of defining the initial dominant fractures has been proposed.
A criterion of automatically determining fracture set number has been proposed.

### 3. Progresses – Fracture clustering

#### Objective selection of initial centers

Correlation coefficient $R^2$ between objective function and validation index

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<th>Validation index</th>
<th>$D$</th>
<th>$I$</th>
<th>$DB$</th>
<th>$CH$</th>
<th>$XB$</th>
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<td>Minimum arc-length</td>
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<td>0.004</td>
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<td><strong>0.940</strong></td>
<td></td>
<td>0.897</td>
<td>--</td>
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</table>

- **Progresses – Fracture clustering**
- **Objective selection of initial centers**
Compared to traditional methods, the new criteria give more reasonable clustering results.

- Initial clustering results of fractures from a cupper mine
  
  [Shanley et al. 1976, Kose et al. 2006, …]
  
  \(I=0.06241, \ E=53.35\)

- Clustering results with improved method
  
  \(I=0.06494, \ E=51.28\)

Validity test
3. Progresses – Statistical analysis

Field investigation

Increase precision of field investigation
→ Import 3D laser scanning technique

Fracture clustering

Replace subjective judgments
→ Propose automatic clustering method

Statistical analysis

Avoid theory contradiction
→ Propose new theoretical criteria

Application

Obtain mechanical properties of fracture
→ Propose a testing method of shear properties

Visualization

Realize visual post-treatment
→ Develop post-treatment module by implementing typical disposal concepts

Monte-Carlo
3. Progresses – Statistical analysis

- Automatically selecting optimal bin-width

\[ \beta_{optimal} = \min_{\beta} \{ \text{mean}(\Delta f_i) \} \]

Automatically balancing the “randomly sampling fluctuation” and “local density-variation”.

\[ \Delta f_i = |f(4i-3)\beta/4 - f(2i-1)\beta/2| = |f(4i-1)\beta/4 - f(2i-1)\beta/2| \]

\[ \Delta f_{i+1} = |f(4i+1)\beta/4 - f(2i+1)\beta/2| = |f(4i+3)\beta/4 - f(2i+1)\beta/2| \]

A simple criterion of selecting optimal bin-width of histogram has been proposed.
The conventional statistical laws have been proven to be unsuitable for describing trace-length data.
A method of estimating diameter has been established based on the supposition & verification strategy.

Suppose a distribution law of diameter.

Calculate trace-length distribution function by forming explicit solution of Washburnton’s equation.

Compare the calculated results to the measured results of trace-length distribution.

Consider the supposed law as the diameter distribution law.

Not accordant

Accordant

A method of estimating diameter has been established based on the supposition & verification strategy.
3. Progresses – Visualization

Field investigation
Increase precision of field investigation
→ Import 3D laser scanning technique

Fracture clustering
Replace subjective judgments
→ Propose automatic clustering method

Statistical analysis
Avoid theory contradiction
→ Propose new theoretical criteria

Application
Obtain mechanical properties of fracture
→ Propose a testing method of shear properties

Visualization
Realize visual post-treatment
→ Develop post-treatment module by implementing typical disposal concepts

Monte-Carlo
The typical disposal concepts have been implemented in the software.

3. Progresses – Visualization

- Software with visual post-treatment module
The optimal direction of disposal hole can be been recommended by searching minimum fracture density of disposal holes in different directions.
3. Progresses – Application

Increase precision of field investigation → Import 3D laser scanning technique

Replace subjective judgments → Propose automatic clustering method

Avoid theory contradiction → Propose new theoretical criteria

Field investigation → Fracture clustering → Statistical analysis

Application → Visualization → Monte-Carlo

Obtain mechanical properties of fracture → Propose a testing method of shear properties

Realize visual post-treatment → Develop post-treatment module by implementing typical disposal concepts
3. Progresses – Application

- Testing mechanical properties of natural fracture

The indoor tests can give similar results about shear strength of different samples from the same fracture.

\[ \tau = \tan(30.4^\circ) \cdot \sigma_N + 1.86 \]

\[ R^2 = 0.6895 \]
1. Background
   - Why is the DFN modeling used?

2. State of the art
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   - What are the problems?

3. Progresses
   - How to improve this technique?

4. Conclusions and perspectives
Some basic algorithms of DFN modeling have been improved and the reliability of the DFN model has been increased.

- Establishment of basic algorithms for modeling non-flat fractures
- Research on hydrologic properties of natural fracture
- ......
Thanks for your attention!
Continuous workflows for process analysis in radioactive waste disposals

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Abstract: Planning, design and construction of radioactive waste disposals (RWDs) is huge and complex challenge for scientists and engineers as well as stakeholders and authorities in this century worldwide. Therefore, appropriate design tools need to be established for different disposal scenarios and verified against as much as possible data sets from all over the world. The latter is related to international efforts such as the DECOVALEX initiative for validating physical process simulation tools. As many countries, such as Germany and China, are looking for different options of potential host rocks (salt, clay, crystalline formations), the design tools for site selection measures must be versatile and flexible. However the main steps at least for data analysis and model predictions for RWDs are universal and independent from the specific scenario under consideration. Therefore, we propose the development of “Continuous Workflows for Process Analysis in Radioactive Waste Disposals”. These generic workflows contain all required works steps for comprehensive analysis of RWDs, e.g. complete geometric descriptions of all relevant geotechnical elements and geological structures of RWDs as well as monitoring infrastructures, numerical simulation tools for of thermo-hydro-mechanical-chemical analysis during RWD construction (near-field processes) and in the far-field through to modern visual analytics platforms (i.e. scientific visualization). Some key features of those generic workflows are interoperability and open source, i.e. modules for all workflow steps must be exchangeable via common interfaces, main software developments must be reproducible and extendable according to developing IT standards. A generic sketch of those continuous workflows is illustrated in Figure left. This workflow concept has been successfully implemented within the OpenGeoSys Virtual Reality Framework (OGDVRF) and recently tested in first applications for water resources management and geothermal energy utilization. We will present a concept of continuous workflow development for RWD analysis and illustrate based on data from different research sites (e.g. Mont Terri, Switzerland) and recent results from the DECOVALEX projects.
Sources:
Topic 3: Modelling
Continuous Workflows
for Process Analysis in Radioactive Waste Disposals

Olaf Kolditz, SHAO Haibing, SHAO Hua, Thomas Nagel

Helmholtz Centre for Environmental Research – UFZ
Technische Universität Dresden – TUDD
Trinity College Dublin – TCD
Technische Universität Freiberg – TUBAF
Bundesanstalt für Geowissenschaften und Rohstoffe – BGR

Talk structure

1. Continuous Workflow Concept > Geotechnics (Kolditz)
3. Opportunities for Cooperation - ”Belt & Road” (TBD)
1.

Introduction
Helmholtz Association

- 18 Research Centres (National Labs)
- 36,000 Employees
- 12,700 Scientists and Technicians
- 6,600 PhD Students
- Budget: 3.8 Billion Euro per year
- Programs "Earth & Environment", "Energy"
Department for Environmental Informatics
ENVINF: 20 Scientists, 4 Workgroups

Managing Water Resources for Urban Catchments – Chaohu

COMPUTATIONAL ENERGY SYSTEMS
A workshop at the Department of Environmental Informatics

GEOTHERMAL SYSTEMS ANALYSIS
Optimization of geothermal system design for utilizing fully exploited reservoir models

TESSIN VISLab
Visualization of Terrestrial Environments

JProf. Marc Walther  Dr. Thomas Nagel  JProf. Haibing Shao  Lars Bilke, MSc
2. Continuous Workflows
Continuous Workflows

Concept < Basic Idea

DataAnalysis WorkFlows

Systems-Analysis

Monitoring
Data Integration
Model Generation
Process Analysis
Data Analytics
Experimental Design

Continuous Workflows

Examples from > Hydrology and of > Geothermal Systems

- Hydrosystems (surface and groundwater)
- Geothermics (shallow and deep geothermal systems)
- Geotechnical applications ...
Continuous Workflows
Geotechnical Applications

Sources: BGR, UFZ-VISLAB, OGS, swisstopo
3.

THMC Processes in Waste Repositories
<table>
<thead>
<tr>
<th>Wirtsgestein:</th>
<th>Salzgestein</th>
<th>Tongestein</th>
<th>Kristallines Gestein</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materialverhalten</td>
<td>Visko-Plastisch Verheilung</td>
<td>Elasto-Plastisch Quellen/Schrumpfen</td>
<td>Elastisch/Plastisch Klüfte</td>
</tr>
<tr>
<td>Experiment</td>
<td>BGR</td>
<td>IfG</td>
<td>TU BA Freiberg</td>
</tr>
<tr>
<td>Modellierung Simulation</td>
<td>UFZ # IfG</td>
<td>UFZ</td>
<td>Uni Stuttgart</td>
</tr>
</tbody>
</table>
New models and numerical methods in OGS-6

Provide modelling capabilities for major types of host rock for deep geological repositories:

\[
\psi(C, d, \text{grad } d) \quad u(x) = \sum_{i=1}^{m} N^i \hat{u}^i + \sum_{j=1}^{n} N^j \sum_{k=1}^{o} \tilde{N}^k \hat{a}^k \quad \bar{u}(x) = \int_{\Omega} u(\xi) \, d\xi
\]
Dr. Thomas Nagel, Helmholtz Centre for Environmental Research – UFZ, Leipzig, Germany.

Fault slip experiments in URL

\[ u(x) = \sum_{i=1}^{m} N_i(x) \hat{\gamma}^i + \sum_{j=1}^{n} N_j(x) \sum_{k=1}^{o} \tilde{N}_k(x) \tilde{a}^k \]

\[ \phi(x) = \| x - x^*_r \| \text{sign} \left[ n_r \cdot (x - x^*_r) \right] \]

\[ \tilde{N}_{\text{strong}}(x) = H(\phi(x)) - H(\phi(x')) \]

\[ \tilde{N}_{\text{weak}}(x) = |\phi(x)| - |\phi(x')| \]

\[ \tilde{N}_{\text{tip}}(x) = \{ \text{asymptotic near-tip displacement field} \} \]

Extended implementation based on Watanabe et al., 2012.

Zieflle, Nagel, Naumov et al.

OpenGeoSys
Continuous Workflow Implementation (Generic)
Simulation Platform: OpenGeoSys (OGS)

In summary:

- Work flow concept
- Research code for THM/C in PFM
- High-Performance-Computing (HPC)
- Data integration and visualization

Additional information:

- www.opengeosys.org
- www.youtube.com/user/OpenGeoSys
- https://github.com/ufz/ogs

Thank you for your attention
Media on Workflow Development and Training
Books | Tutorials | Platforms ... (www.opengeosys.org)

Benchmarking

Tutorials

Platforms
opengeosys.org | docs.opengeosys.org

Hydrosystems
Energy Systems
Geothermal Systems
Geotechnical Systems
Modelling and Software Development for Nuclear Waste Disposal—Current Developments in OpenGeoSys

Thomas Nagel¹,², Jobst Maßmann³, Hua Shao³, Wenqing Wang¹, Gesa Ziefle³, Olaf Kolditz¹,⁴
¹) Helmholtz-Centre for Environmental Research – UFZ, Germany
²) Trinity College Dublin, Ireland
³) Federal Institute for Geosciences and Natural Resources (BGR), Germany
⁴) Technische Universität Dresden, Germany

3rd Sino-German Workshop on Radioactive Waste Disposal
May 15 – 19, 2017, Jiayuguan, China.

Visit
www.ufz.de/environmental-geotechnics
www.ufz.de/comp-energy-sys
New models and numerical methods in OGS-6

Provide modelling capabilities for major types of host rock for deep geological repositories:

\[
\psi(C, d, \text{grad } d) = u(x) = \sum_{i=1}^{m} N^i \hat{u}^i + \sum_{j=1}^{n} N^j \sum_{k=1}^{o} \bar{N}^k \hat{a}^j \]

\[
\bar{u}(x) = \int_{\Omega_i} u(x + \xi) \omega(\xi) \, d\Omega
\]
Upscaling heater experiments in URL

- THM-behaviour of Callovo-Oxfordian clay stone
- Interpretive and predictive modelling of URL experiments from small scale to repository scale
- Decovalex teams: ANDRA, Quintessa, LBNL, UFZ/BGR

Meuse/Haute Marne URL
Small-scale heater experiment (TED)
Real-scale heater experiment (ALC)

THM processes

- Mechanical (THM) behavior of the COx is of great importance in what concern the design and safety level waste management.
- Moreover, thermal loading may provoke thermomechanical stresses in the media due to boundary conditions.

Concerning the high level waste (HLW), the interpretation and modeling of a full experimental program consists of:

- The second step consists in upscaling THM modeling from small size experiments (THM) to real scale cell (some ten cubic meters) and to scale of the waste repository (cubic kilometers).
- The interpretation and modeling of a full experimental program consists of:
  - Meuse/Haute Marne URL plan and  principal stress directions.
  - Small-scale heater experiment (TED) on the basis of model calibrations of the thermal loading on the steel structure. The extent of the heat emitted from the wastes provokes a pore pressure increase (they appeared to be defective).
  - Real-scale heater experiment (ALC) and ALC1616 with 5 chambers, ALC1617 and ALC1618 with 3 chambers.

Each section includes:
- 6 strain gauge sectors at the intrados, with an axial gauge and a circumferential gauge for measuring the horizontal and vertical strain. (they appeared to be defective).
- 3 sensors at each connection between two elements to control the heating.
- 3 displacement sensors to measure the spatial variation taking a measurement in the annular clearance measurement sensors sectors, one at horizontal and at a 45° angle horizontally and at a 45° angle
- 2 boreholes on the TED platform (bottom) and the perpendicular NRD boreholes for liquid pressure and temperature measurement (ALC4005 to ALC4002)

Timeline of the TED experiment with experimental program consists of:

- 4.1: Main objectives
- 4.2: THM processes
- 5.1: Results

DeCOVALEX 2019
www.decovalex.org
Upscaling heater experiments in URL

The initial HM state is obtained by the modelling of excavation.

Temperature evolution at measurement points

Temperature distribution in the domain

Pore pressure evolution at measurement points

Pore pressure distribution in the domain

Deformation variable evolution at measurement points

Distribution of displacement magnitude and stress in the domain

Concluding remarks

Wang et al. (2017)
Fault slip experiments in URL

Figure 1. Mt Terri fault activation experiment setting (Guglielmi, 2016). A – Mt Terri main fault with the location of the experiment (red squares- seismic sensors, blue squares-piezometers, blue rectangles-injection and monitoring intervals). B – Cross section of the Main Fault with the locations of the packed-off sections.

- HM behaviour of fractured Opalinus clay
- Interpretive modelling of fault activation
- Different constitutive formulations for aperture change etc.
- Decovalex teams: ENSI, INER, KAERI, LBNL, CNSC, UFZ/BGR

www.decovalex.org; Ziefle et al. (2017)
Fault slip experiments in URL

\[
\begin{align*}
    u(\mathbf{x}) &= \sum_{i=1}^{m} N^i(\mathbf{x}) \hat{u}^i + \sum_{j=1}^{n} N^j(\mathbf{x}) \sum_{k=1}^{o} \bar{N}^k(\mathbf{x}) \hat{a}^{jk} \\
    \phi(\mathbf{x}) &= \| \mathbf{x} - \mathbf{x}_{\Gamma}^* \| \text{sign} [ \mathbf{n}_{\Gamma} \cdot (\mathbf{x} - \mathbf{x}_{\Gamma}^*) ] \\
    \bar{N}_{\text{strong}}(\mathbf{x}) &= H(\phi(\mathbf{x})) - H(\phi(\mathbf{x}^i)) \\
    \bar{N}_{\text{weak}}(\mathbf{x}) &= |\phi(\mathbf{x})| - |\phi(\mathbf{x}^i)| \\
    \bar{N}^k_{\text{tip}}(\mathbf{x}) &= \{ \text{asymptotic near-tip displacement field} \}
\end{align*}
\]

Extended implementation based on Watanabe et al., 2012.

Ziefle, Nagel, Naumov et al.
Fault slip experiments in URL

\[
u(x) = \sum_{i=1}^{m} N^i(x) \hat{u}^i + \sum_{j=1}^{n} N^j(x) \sum_{k=1}^{o} \tilde{N}^k(x) \hat{a}^j k
\]

\[
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\[
\tilde{N}_{\text{strong}}(x) = H(\phi(x)) - H(\phi(x^j))
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\]

Extended implementation based on Watanabe et al., 2012.

Ziefle, Nagel, Naumov et al.
Current implementation: phase-field modeling of crack propagation

Free Helmholtz energy density:
\[
\psi = \left[ (1 - d)^2 + \eta \right] \psi_0^+ + \psi_0^- + \frac{G_c}{2\epsilon} d^2 + \frac{G_c\epsilon}{2} |\text{grad } d|^2
\]

PDE governing Crack field is similar to the Ginzburg-Landau/Allen-Cahn equation:
\[
M \dot{d} = G_c \epsilon \text{div } \text{grad } d - \frac{G_c}{\epsilon} d + 2(d - 1) \max_{\tau \in [0,t]} \psi_0^+(\tau)
\]

Possibility to simulate complex crack patterns, including coalescence and branching.

Image from Bourdin et al., 2014.
Phase-field models for discontinuity propagation: M

- Crack-propagation
- Crack-driving forces and physical forces
Elements of code QA

- Code is open-source
- Development discussion is public
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- Automated compilation & testing on different platforms
- Complex testing in intervals (e.g. memory leaks, runtime checks)
- Automated deployment of binaries
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- Automated & manual documentation

For Users

For Developers

Trinity College Dublin
Coláiste na Trionóide, Baile Átha Cliath
The University of Dublin
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- Results of benchmarks published
- Tutorials published → international training courses
- Community contributions
- ...

Trinity College Dublin
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The University of Dublin
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- Antje Wörner
- Lin Zhang
- Tianyuan Zheng
- Gesa Ziefle
References I


References II


Modelling workflow

balance laws
- mass balance(s)
- linear and angular momentum balance(s)
- energy balance(s)
- entropy balance

constitutive relations
- mass transport (Darcy, Forchheimer, ...)
- heat transport (Fourier, radiation, ...)
- reaction/sorption equilibrium (van't Hoff, Dubinin, ...)
- reaction/sorption kinetics (linear driving force, logarithmic driving force, ...)
- state-dependencies (e.g. conversion-dependent heat capacity)
- mixture rules (effective properties of multiphase media)
- constraints (e.g. incompressibility)
- ...

reference solutions
- analytical solutions
- manufactured solutions

numerical method
- FEM
- FDM
- FVM
- ...

numerical model

system dependent

boundary and initial conditions

from Nagel et al. (2016).
Hydraulic characterization of Xinchang site

Ruili Ji

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Email: ruili_ji@139.com

**Topic:** Site selection/site investigation methods and technologies (Hydrogeology)

**Keywords:** Xinchang site, hydraulic test, lower permeability

**Abstract:** Hydrogeological property of fractured granite is one of the key factor for site characterization in Beishan area. To evaluate permeability of candidate sites for geological disposal of radioactive waste, hydraulic tests and groundwater level monitoring in boreholes were performed in Beishan area since 2003.

Xinchang site is one of the granite candidate sites in Beishan Area. Three main deformation zone trending roughly east located in north and south boundary of granite in the site. Secondary structures in Xinchang site striking NNE are tensor-shear deformation zone. Inclined boreholes crossing these NNE deformation zones are drilling in 2016 to characterize the main hydraulic conductor domain, and vertical boreholes were drilled to measure permeability of hydraulic rock domain.

Water lifting tests and pumping tests needed in the section in which water sample can be taken from (hydraulic conductivity equal to or more than $10^{-6}$ m/s) during drilling. Hydrogeochemical parameter of groundwater was measured at the outlet to make it sure that hydrogeochemical condition were stable in the period of pumping test. Groundwater samples were collected when concentration of uranine in groundwater lower than 1% of the initial concentration in drilling water.

After the borehole finished, constant head injection tests and/or pulse tests by using double packer hydraulic test equipment were performed. Length of test section was first set as 12m and then 3m only for 12m-sections where hydraulic conductivity more than $10^{-8}$ m/s. Hydraulic tests in vertical boreholes were almost finished in 2016. Data interpretation tool Hytool was used to analysis pulse tests and Aqtesolv was used to analysis other tests.

Under geological environment in Xinchang site, fracture density in shallow part of NNE deformation zones is higher than the density in deep part, and fracture density in north part is also higher than south part. Many fractures in footwall of NNE deformation zone are open. Core recording and water lifting tests confirm that north part of NNE deformation zones were main hydraulic conductor domain in Xinchang site and groundwater are mainly stored in shallow and/or footwall of the deformation zones.

Cumulative percent of interpretation results shows that 80% of hydraulic conductivity of packer-off test sections lower than $10^{-8}$ m/s, which confirmed lower permeability of granite in Xinchang site. The location of section more than $10^{-8}$ m/s showed that: (1) hydraulic conductivity of fractured granite decrease with depth from surface to 200m underground, (2) permeability of granite from 200m to 600m underground almost lower than $10^{-8}$ m/s, (3) vertical fractures zone in few boreholes seems to be hydraulic conductor zone from 400m to 600m underground, (4) groundwater level were found decrease from surface to underground in some boreholes which may located at watershed in Xinchang site.
Hydraulic Characterization of Xinchang Site

Ruili JI (jiruili@briug.cn)
Beijing Research Institute of Uranium Geology
Outline

• Geological & Hydrogeological Background of Xinchang Area

• Hydraulic tests and monitoring in boreholes

• Hydrogeological property of deformation zone & fractured granite

• Groundwater level distribution in fractured aquifer

• Conclusion
Geological map of Xinchang Site (partly)

- **Pull**
- **Push**
- **ductile shear zone**
- **Well**
- **F31 (Tensor Shear)**

Image description:
- Map highlighting geological features and shear zones.
- Markings for pull and push directions.
- Identification of ductile shear zones and wells.
Geological and hydrogeological background in Xinchang Site

- NNE deformation zone been controlled by ductile shear zones on north and south boundary of granite
- Width of NNE deformation zone increases from south to north
- More open fractures in footwall than in hanging wall in NNE deformation zone
- Precipitation is one of the major groundwater recharge resource
Hydraulic tests and monitoring in boreholes

• During drilling process
  • 0.5ppm uranine in drilling water as tracer
  • Dynamic water level monitoring per attack
  • Water consumption every 10m drilling length
  • Water lifting test when reach certain drilling length
  • Pumping test for groundwater sampling if possible

• After finishing drilling of borehole
  • Hydraulic test by using double packer equipment
  • Constant head injection tests more frequently
  • Groundwater level monitoring
3rd Chinese-German Workshop on Radioactive Waste Disposal

Start Drilling

- Water Lifting Test Every 100m, 200m, ...
- Dynamic Water Level
- Water Consumption

Steady

Yes

- Continue
- dynamic Water Level
- Water Consumption

No

- Pumping Test
- K \geq 10^{-6} M/S

Yes

- Finishing Drilling
- Water Sampling
- Uranine < 5 ppb

No

- Groundwater Monitoring

Hydrogeological Monitoring and tests during drilling
Dynamic water level monitoring and statistics of water consumption

Water consumption per 10m

Dynamic water level
3rd Chinese-German Workshop on Radioactive Waste Disposal

Pumping test and hydrogeochemical monitoring
Borehole: BSQ05/BSQ06  
Length: 120.00m/99.60m  
Dip: 7°/ 10°  
Length of Breccia: 14.70m/12.57m  
K_B: 4.11E-8m/s

Borehole: BS35  
Length: 628.47m  
Dip: 11°  
Length of Breccia: 7.60m  
K_B: 1.16E-8m/s

Borehole: BSQ04  
Length: 145.30m  
Dip: 12°  
Length of Breccia: 3.27m  
K in DZ: 2.41E-10m/s

Borehole: BSQ04  
Length: 145.30m  
Dip: 12°  
Length of Breccia: 3.27m  
K_B: 5.55E-11m/s

Borehole: BS36  
Length: 607.78m  
Dip: 12°  
Length of Breccia: 3.90m/4.20m  
K_B: 5.55E-11m/s
Groundwater level monitoring during hydraulic test in BS26

Green: Above test section
Red: Test Section
Blue: Below test section

30 meter
Water level difference in boreholes

Blue+Red: WL below test section decrease
Green+Red: WL above test section Increase
In-situ Hydraulic Tests

- Methods including: slug test, pumping test, constant injection test and pulse test
- Prefer constant head injection test
- Test equipment:
  - Golder Associates GmbH (depth ≤ 600m)
  - Solexperts AG (600 ≤ depth ≤ 1000m)
- Data interpretation: type curve matching (Aqtesolv & Hytool)
K value distribution in borehole BS32
Water level difference in boreholes

BS33, BS34, BS17, BS26, BS27
Core of test53 in borehole BS26

205.31m →

BS26-Test53  $Kr=3.26\times10^{-7}$ m/s

← 208.79m
Conclusion (1)

- Hydraulic property of NNE deformation zone
  - Permeability increase from south to north, from deep to shallow
  - Hangingwall of NNE deformation zone can be treated as no flow boundary except shallow section in north
  - Groundwater mainly stored in shallow section and or footwall of NNE deformation zone
Conclusion (2)

- Hydraulic property of fractured granite
  - Permeability of fractured granite decreases with depth from surface to 200m underground
  - Granite 200 ~ 400m below surface where fewer steep dip fractures can be treated as aquitard.
- Aquifer located in steep dip fracture zone may connect shallow section to deep section
Hydrogeological Investigation On the Way...
ReSUS: a new probabilistic and sensitivity analysis software tool and its test problems

Xiaoshuo Li, Klaus-Jürgen Röhlig

Institute of Disposal Research, Clausthal University of Technology, Clausthal-Zellerfeld, Germany
Email: xiaoshuo.li@tu-clausthal.de

Abstract: Release and transport of radioactive nuclides is one of the most important processes which need to be analyzed in safety assessment for high level radioactive waste disposal. In this research work, a 3-D global model for a whole high level waste disposal system in a clay formation has been built to analyze its long term THM coupled two-phase flow processes and the corresponding nuclide transport processes. TOUGH2-EOS9nT[1] is a module of the TOUGH2 program family for the simulation of radionuclide chain transport. TOUGH2-FLAC is a linked application of two established codes TOUGH2 and FLAC3D, which is a pragmatic tool to model coupled multiphase flow, heat transport and geomechanics[2]. We modified the TOUGH2-EOS9nT source code to couple it with the TOUGH-FLAC program. According to the two-phase flow field of the 3-D global model, the transport process of radionuclide chain was simulated and analyzed by the modified TOUGH2-EOS9nT program. An example of the simulation results can be seen in Figure 1.

Moreover, due to the parameter uncertainty of the adsorption isotherm in clay stone, we are performing probabilistic analysis with probabilistically sampled variable adsorption values using the software platform ReSUS[3]. ReSUS is a software platform with the full name “Repository Simulation, Uncertainty propagation and Sensitivity Analysis” which is developed by Institute of Disposal Research, Clausthal University of Technology. The result of the analysis can look like in Figure 2. The calculations serve evaluating the system behavior under different assumptions as well as demonstrating of the capabilities of the newly developed ReSUS software platform.

References:

ReSUS: A new probabilistic and sensitivity analysis software tool and its test problems

Dr. Xiaoshuo Li
Prof. Dr. Klaus-Jürgen Röhlig

Institute of Disposal Research,
Clausthal University of Technology

3rd Chinese-German Workshop on Radioactive Waste Disposal
Jiayuguan City, China, 15-19 May 2017
Table of Contents

▪ Introduction

▪ Software design and working procedure

▪ Test examples of simulations and Analysis

▪ Conclusion & Outlook
Introduction

Institute of Disposal Research:

- Repository systems  
  Prof. Dr. Klaus-Jürgen Röhlig

- Geochemistry  
  Prof. Dr. Kurt Mengel

- Mineral Resources  
  Prof. Dr. Bernd Lehmann

- Hydrogeology  
  Prof. Dr. Wolfgang van Berk

Cooperating Institute:

Institute of Waste Disposal and Geomechanics  
Prof. Dr. habil. Karl-Heinz Lux, Prof. Dr. Uwe Düsterloh
Introduction

OECD/NEA project
MeSA: Generic safety assessment flowchart
Introduction

OECD/NEA project
MeSA: Generic safety assessment flowchart
Introduction

- A Repository system:
  - Long term safety to be demonstrated (post-closure phase)
  - Complex processes (thermal, hydraulical, mechanical and chemical)
  - High uncertainty of parameters

Modeling

- Process-level models
- Integrated or system models
**Introduction**

- Integrated model: GoldSim
- Process level model: TOUGH2, PHREEQC/PHAST, OpenGeoSys/Rockflow, FLAC3D, ...

**ReSUS**: Repository Simulation, Uncertainty propagation and Sensitivity Analysis

Aim: a userfriendly platform for uncertainty and sensitivity analysis with the flexibility of using the external numerical codes applicable for research and education.
Table of Contents

- Introduction
- Software design and working procedure
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Software design and working procedure
Software design and working procedure

Template file based method

```plaintext
#SOIL_PROPERTIES
2
1.0
0
<$1$
1.0
0
0
0.0
0 0

<$2$
0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0; k-S function
0.0; p-S function

<$3$
0.0
0.0 0.0
2000.0 0.0
0 0.0
```

; dimension
; area
; porosity model
; porosity
; tortuosity
; mobile immobile model
; lithological component
; maximum sorption model
; nonlinear flow parameter
; storativity
; permeability model, permeability tensor
; permeability
; mass dispersion parameters
; heat dispersion parameters
; rock density, heat capacity
; heat conductivity parameters
Software design and working procedure
Software design and working procedure

Realization i

Realization i+1

Result Parameter
Output
Input

Sub-Model 1
External code

Sub-Model 2
External code

Sub-Model 3
External code

Result Parameter
Output
Input
Table of Contents

▪ Introduction

▪ Software design and working procedure

▪ Test examples of simulations and Analysis

▪ Conclusion & Outlook
Test Model 1: a process level model
Test Model 1: a process level model

- FLAC-TOUGH2-coupled simulator (FTK-Simulator)
- TH2M coupled process
- TOUGH2-EOS9nT
  - Nuclide chain migration
- Simulating the nuclide migration process in TH2M conditions
Test Model 1: a process level model

Am-243, Pu-239, U-235, Pa-231 are considered
Test Model 1: a process level model

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Distribution</th>
<th>Mean</th>
<th>Stdv</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solubility of Am-243</td>
<td>normal</td>
<td>0.00155</td>
<td>1.e-4</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Solubility of Pu-239</td>
<td>normal</td>
<td>1.16e-5</td>
<td>1.16e-6</td>
<td>kg/m³</td>
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<tr>
<td>Solubility of U-235</td>
<td>normal</td>
<td>6.86e-6</td>
<td>6.0e-7</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Kd value of Am-243 in clay</td>
<td>normal</td>
<td>0.00423</td>
<td>0.001</td>
<td>m³/kg</td>
</tr>
<tr>
<td>Kd value of Pu-239 in clay</td>
<td>normal</td>
<td>0.00435</td>
<td>0.001</td>
<td>m³/kg</td>
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<tr>
<td>Kd value of U-235 in clay</td>
<td>normal</td>
<td>0.00431</td>
<td>0.01</td>
<td>m³/kg</td>
</tr>
</tbody>
</table>

sampling size = 100
Test Model 1: a process level model

Evolution of the Uranium-235 concentrations at an observation point with a distance = 5 m to the boreholes
Test Model 1: a process level model

Histogram of the maximal Uranium-235 concentration at the observation point with a distance = 5 m to the boreholes
Test Model 1: a process level model

Scatter plot showing the dependence of the logarithmically transformed maximal uranium-235 concentrations at the observation point with a distance = 5 m on the Kd values of the clay host rock.
Test Model 1: a process level model

Scatter plot showing the dependence of the maximal uranium-235 concentrations at the observation point with a distance = 5 m on the Uranium solubility in the clay host rock.
Test Model 2: an integrated model

Disposal in crystalline host rock

Submodel 1
- Length: 1000 m
- Width: 2 m
- Pressure: 5 MPa
- Uranium: 6.8e-8 kg/m³

Submodel 2
- Length: 1000 m
- Pressure: 4.9 MPa

Drinking water well
- Pressure: 4.89 MPa
Test Model 2: an integrated model
Test Model 2: an integrated model

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Distribution</th>
<th>Belongs to</th>
<th>Min</th>
<th>Max</th>
<th>Unit</th>
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<tbody>
<tr>
<td>Permeability of fracture</td>
<td>Log_Uniform</td>
<td>Submodel 1</td>
<td>1.e-10</td>
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<td>Porosity_matrix</td>
<td>Uniform</td>
<td>Submodel 1</td>
<td>0.2</td>
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<tr>
<td>Sorption coefficient</td>
<td>Uniform</td>
<td>Submodel 1</td>
<td>5.e-05</td>
<td>5.e-04</td>
<td>kg/kg</td>
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<tr>
<td>Porosity overburden</td>
<td>Uniform</td>
<td>Submodel 2</td>
<td>0.05</td>
<td>0.4</td>
<td>-</td>
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<tr>
<td>Permeability</td>
<td>Log_Uniform</td>
<td>Submodel 2</td>
<td>1.e-13</td>
<td>1.e-11</td>
<td>m2</td>
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<tr>
<td>Dispersion length</td>
<td>Uniform</td>
<td>Submodel 2</td>
<td>5</td>
<td>10</td>
<td>m</td>
</tr>
<tr>
<td>Sorption coefficient</td>
<td>Uniform</td>
<td>Submodel 2</td>
<td>5.e-05</td>
<td>5.e-04</td>
<td>kg/kg</td>
</tr>
</tbody>
</table>

Sampling size = 100
Test Model 2: an integrated model

Scatter plot showing the dependence of the maximal uranium-235 concentrations on the permeability of the main fracture in the granite rock.
Test Model 2: an integrated model

Scatter plot showing the dependence of the maximal uranium-235 concentrations on the porosity of the formations over the granite host rock

Scatter plot showing the dependence of the maximal uranium-235 concentrations on the Kd values of the fracture in the granite host rock
Conclusions

ReSUS:

▪ Ability to run various THMC and other assessment codes automatically from a graphic user interface

▪ Options to couple two or more THMC codes (weak coupling, i.e. by the transfer of I/O data), and

▪ The Input/Output files must be in Ascii-Format
Outlook

We are still developing the ReSUS platform further

Possible enhancements include:

- Introduction of additional sampling schemes
- Calculation of additional sensitivity measures
- Portability to different hard- and software environments
Acknowledgement

This software development and simulation work is financed and supported by the German Federal Ministry of Education and Research (BMBF) in frame of the “ENTRIA” project platform – 02S9082A

www.entria.de
Thank you for your attention!
Coupled processes controlling radionuclide behaviour in nuclear waste repository compartments

Thorsten Schäfer, Horst Geckeis

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Email: Horst.geckeis@kit.edu

Abstract: Waste forms, technical and geotechnical barriers change over time during the different periods of repository evolution. Saturation of geotechnical barriers (e.g. bentonite), container and concrete corrosion combined with secondary phase formation (magnetite, CSH phases), hydrogen evolution and pH plume propagation and the temporary impact of elevated temperatures modify radionuclide retention relevant hydrogeological and geochemical parameters in the repository nearfield. Geotechnical barrier erosion upon interaction with intruding glacial meltwater might have an impact on radionuclide migration in the far field of a repository in crystalline rock.

Within this contribution, some relevant processes are exemplary investigated:

- Upon container corrosion, Fe(II) containing mineral phases such as magnetite form. By direct sorption of various radionuclides to such phases such corrosion phases exhibit a significant chemical barrier function. Dissolved Fe(II) interacts with clay minerals in forming Fe(II) rich secondary clay minerals, being as well active as redox active sorbents.

- Due to the geochemical gradients establishing at repository near field interfaces such as the argillaceous rock/concrete contact zone secondary phase precipitation may have a significant impact on porosity and permeability of the barrier matrix. In depth understanding of nucleation processes and the potential evolution of hydrogeochemistry in such regions is still insufficient. Model system investigations aim at examining the pore structure evolution and notably the potential of complete pore clogging in such systems and their modeling.

- Poorly mineralized glacial meltwater intrusion is considered a relevant scenario in crystalline rock repositories. Concomitant bentonite erosion, clay colloid release and colloid mediated radionuclide mobilization is investigated within the Colloid Formation and Migration experiment (CFM) at the underground rock laboratory at the Grimsel Test Site (GTS). A focus is set on the quantification of kinetics of clay colloid release and radionuclide/clay colloid interaction. Kinetic parameters are mandatory for modeling and assessing such processes.
Coupled processes controlling radionuclide behavior in nuclear waste repository compartments

Horst Geckais & Thorsten Schäfer

3rd Chinese-German Workshop on Radioactive Waste Disposal, May 15-19 2017, Jiahuguan (China)
Coupled THCM processes

Operational period
TUNNEL CLOSURE

Post closure period
REPOSITORY CLOSURE

1
10
100
1000
10000
100000
10^6 years

Thermal phase
Natural geothermal conditions

Hydraulic transient phase
Hydraulic equilibrium

Hydraulic transient

Oxidizing conditions
Reducing conditions

Metal liner corrosion
Metal sleeve corrosion
Production of H₂ from corrosion
Container corrosion
SF assembly dissolution
Concrete degradation
Alkaline perturbation of argilites and bentonite components

Variation of creep velocity of argilites

Initial stress release EDZ formation
Lining failure
Canister failure ➔ RN release

Dossier argille (2005)

INSTITUTE FOR NUCLEAR WASTE DISPOSAL (INE)
Steel corrosion

-Magnetite system-
Steel corrosion: **Secondary phase formation**

- **Steel corrosion**
- **Fe(II) release**
  - Fe-Oxide formation
- **Cation exchange processes**
- **Fe(II) smectite Ca-carbonate formation**

**Radionuclide retention**
- Surface complexation
- Isotope exchange
- Co-precipitation
- Solid-solution formation

**Radionuclide mobilization**
- Colloid/nanoparticle transport

$t_{\text{react}} = 193\text{d}$
Barrier function of canister corrosion products
- Interaction of trivalent actinide ions with magnetite -

Surface sorption complex structure of Pu(III) or Am(III) on edge-sharing FeO$_6$-octahedral
New detector developments @ INE

γ = 1.5 eV

U(IV)

U(VI)

Absorption (arb. units)

Energy (eV)

X-ray energy: > 20 keV (L1-edges of actinides)

Photon flux: \( \sim 10^{14} \) ph/sec/1%BW (20 keV)

I. Pidchenko, T. Vitova, K. Kvashnina, 2015
Surface induced reduction reactions
-Example: U(VI) coprecipitated with Fe$_3$O$_4$ -

Initially sorbed U(VI) species recrystallize to nonstoichiometric UO$_{2+x}$ nanoparticles. U(V) incorporated in octahedral sites.

Pidchenko, Vitova et al., 2017 ES&T 51, 2217
Secondary phase formation

=> retroaction on transport
Gradients of chemical and physical properties


Archie’s law:

$$D_e = \varepsilon^m \cdot D_0$$

- Mineral transformation (dissolution/precipitation)
- RN speciation (solid-solution formation, RN redox state)

Secondary phase formation

TRANSPORT (diffusion controlled)

C-H coupling

- Effect of precipitation on transport parameters & RN speciation

Counter diffusion experiment

Chagneau, Claret, Enzmann, Kersten, Heck, Made, Schäfer *Geochem Trans* 2015, 16, (13), 015-0027.

\[ 2 Na^+ + SO_4^{2-} + Sr^{2+} + 2 Cl^- \rightarrow 2 Na^+ + 2 Cl^- + SrSO_4 \downarrow \text{(Celestite)} \]

Counter-diffusing solutions each 0.5 M of Na$_2$SO$_4$ and SrCl$_2$

Celestite: 20 ± 3 mg (µCT)
22 mg (leaching)

ε$_{\text{min}}$: 28 ± 3 % (reduction of 38 ± 6 %)
1D Continuum model: **CRUNCHFLOW**, with multi component diffusion

Model parameters:
- **Pure transport parameter of porous media (no clogging)**
- **30% (CT data in the precipitation zone)** or
- **Minimum porosity of 1% (best fit)**
- **Discrepancies**: HTO flux or mass of precipitate (about 4 to 7 times bigger)

The 1D continuum model **can fit** the experimental data, but **cannot reproduce** the clogging experiment parameters satisfactorily.

---

Colloid mediated radionuclide mobilization
(CFM, Grimsel Test Site)
Reference scenario of future glaciation and melt water intrusion

Where do we find glacial melt water conditions? Grimsel Test Site (GTS), CH


**Water type A:** Dilute 0.5-2 g/L TDS; $\delta^{18}O = -11.7$ to $-9.5$ ‰ SMOW; Na-HCO$_3$; mainly Meteoric

**Main reactions:** Weathering, ion exchange, dissolution of calcite, redox reactions, microbial reactions

**Redox conditions:** Oxidising - reducing

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

Research within URL projects (e.g. CFM)

- **Integrity of the geo-engineered barrier**
- **Upscaling** from laboratory to field
- Colloid **migration** (filtration)
- Colloid associated **RN transport**

Particle trace snapshots showing the heterogeneous spreading due to flow velocity variability.
Bentonite barrier integrity

Crystalline host rock
Bentonite
Canister
Dilute glacial Melt water

Colloid generation & quantification by LIBD

Nanoparticle Mobility:
Roughness & surface charge dependent $\alpha$

Actinide Mobility in URL:
Nanoparticle Sorption reversibility kinetics

Bentonite saturation & swelling/erosion

1d
200d
Processes investigated

Model implementation in COFRAME
Redox and colloid desorption kinetics have to be considered in models to describe field observations.
COFRAME: Long-term $^{243}$Am/$^{242}$Pu breakthrough

Accelerator Mass Spectrometry (AMS)

Dissolved species

ppm parts per million ($10^{-6}$)
ppb parts per billion ($10^{-9}$)
ppt parts per trillion ($10^{-12}$)
ppq parts per quadrillion ($10^{-15}$)

Nuclear weapons test fallout
Mobility in fracture systems

COFRAME: Long-term $^{243}\text{Am}/^{242}\text{Pu}$ breakthrough

Lower dissolved Am/Pu concentration than expected by our model:

a) colloid filtration

b) Very slow desorption kinetics

Conclusions

- Secondary phases of canister corrosion (i.e. magnetite) reveal strong sorption capacities and evidence structural incorporation currently not considered as RN retention process.

- Limits of 1D reactive transport single continuum model to describe porous media clogging with realistic parameters demonstrated; 2D/3D approaches to be implemented.

- Clay colloid retention even under „unfavorable“ glacial melt water conditions triggered by surface roughness.

- New AMS protocol developed for simultaneous analysis of U, Np, Pu, Am and Cm isotopes.

- AMS perfect tool to investigate the slow desorption kinetics occurring in natural systems to reduce uncertainties in long-term RN mobility predictions.

*Everything should be made as simple as possible, but not simpler.* (Albert Einstein)
Looking forward to a continuing excellent Chinese-German cooperation…

Vitrification project China (VPC) as mentioned by Mr. Lixin Chen

… from vitrification technology issues

… to nuclear waste disposal research topics
Acknowledgement

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Peter Vilks (OPG)
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Kotaro Nakata (CRIEPI)
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thank you for your attention
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- This work has been partially funded by the European Atomic Energy Community’s Seventh Framework Programme (FP7/2007-2011) under grant agreement no. 295487 (BELBar Project) “Bentonite Erosion: effects on the Long term performance of the engineered Barrier and Radionuclide transport”
CFM current actions: **Long-Term In situ Test (LIT)**

start-up **May 2014** (at GTS)

16 glass vials filled with $^{45}$Ca, $^{75}$Se, $^{99}$Tc, $^{233}$U, $^{237}$Np, $^{241}$Am, $^{242}$Pu, **Amino-G** and synthetic Ni- montmorillonite.

Near-field water chemistry:
- pH: 9.6 $\rightarrow$ 9.0
- $s_{pec}$: 60 $\rightarrow$ 170 µS/cm
- $E_{h}$ ($SHE$): $-220$ mV $\rightarrow$ $+170$ mV

Tc
Upscaling: Reference case for a generic German repository in crystalline rock TRAPIC/ COFRAME

Variation of the desorption rate

\[ Da = \frac{L}{v} \]

Da > 50 equilibrium assumption
WARNING: not necessarily conservative!

Da < 1/50: assumption of irreversible sorption

KIT scientific report 7645 (2014)
Research on EDZ characterization technology for URL:
Field EDZ monitoring experiment at BET

Chunhe Yang, Guibin Wang, Shiwan Chen
Institute of Rock and Soil Mechanics, CAS; Chongqing University
Email: chyang@whrsm.ac.cn

Abstract: With drill-blast experiment in Beishan Exploration Tunnel (BET), the inspecting range and precision of different Excavation Damage Zone (EDZ) monitoring techniques are systematically tested and analyzed, and the feasibility and suitability of these techniques for characterization EDZ is evaluated. An EDZ evaluating system for URL in Beishan area is finally proposed.

A wide range of techniques is used to investigate the Excavation Damage Zone at BET. The methods include 1) Borehole core drilling and logging before and after excavation, and laboratory test of borehole cores for physical and mechanical properties. 2) Ultrasonic wave velocity measurement, borehole TV logging, borehole radar and ground penetrating radar (GPR) survey before and after excavation. 3) Micro Seismic and Acoustic Emission online monitoring during and after excavation.

The original state before excavation, the extent and property change of EDZ after excavation are obtained by these techniques. The location, property and intensity of micro crack are inferred from MS and AE monitoring data. The origination and evolution EDZ is determined by the magnitude, concentrations and density of the micro crack.

Single-borehole ultrasonic wave velocity and the images of ultrasonic wave tomography reveal that wave velocity decreased significantly (more than 20%) in the zone, 20cm-50cm from the excavation surface, which is defined as EDZ.

Remarkable increase of AE hits was observed at the moment of blasting, and then AE hits rate hold high for 1 hour, indicating progressive damage of rock-mass caused by blasting. AE events were clustered within 30cm to 100 cm from excavation surface.

Clear images of borehole TV were obtained, which is difficult to applied to quantify the extent of EDZ, but helpful for the interpretation of wave velocity.

Strong reflection signals were detected in the range of 10cm to 25 cm by GPR, indicating significant changes of physical properties of rock-mass in the zone. EDZ identified by GPR is smaller than the zone identified by ultrasonic wave velocity.

Effective and efficient EDZ monitoring techniques are screened out. Reliable data interpretation and EDZ evaluating methodology for URL in Beishan area is established. The extent and property change of EDZ to the surrounding rock in the construction of URL could be more predictable.
Research on Excavation Damage Zone (EDZ) characterization technology for URL:
Field EDZ monitoring experiment at BET

Chunhe Yang
Guibin Wang  Shiwan Chen

Institute of Rock and Soil Mechanics, CAS
Chongqing University
Outline

- EDZ Roles & definition
- Overview of EDZ studies in URLs
- Field experiment Design & Objective
- Implementation & data interpretation
- Discussion and Conclusion
EDZ definition

➢ John A. Hudson (2009)
around an underground excavation where irreversible changes have taken place.

➢ Tsang et al. (2005)
EDZ: hydro-mechanical and geochemical modifications induce significant changes in flow and transport properties.

➢ Backblom et al. (2004)
has suffered irreversible deformation where shearing of existing fractures as well as propagation or development of new fractures has occurred.
The potential role of the EDZ in system performance (Zuidema 2005):

- The EDZ may form a potential pathway for migration of radionuclides from the waste emplacement rooms to the surface environment.
- The EDZ may affect the hydrogeological, geochemical, geo-mechanical and thermal conditions, but it may also be favorable to system performance for release of gas generated within the repository.
EDZ Studies

Excavation Damage Zone

Rock mass response to tunneling

Excavation method

Characterization methods

Hudson et al. 2008
EDZ Studies

- EDZ forming process
- Suitable Characterization methods
- The geometry of EDZ (Thickness, Radial profile, continuity)
- Influence factors and controlling methods
- Hydraulic characteristics of EDZ, radioactive transport characteristics of EDZ
- The potential evolution of T-H-M-C-B (thermal, mechanical, hydraulic and chemical/biological) processes
- A basis for the requirements and compliance criteria for the excavation damaged and disturbed zone
- …

After McEwen 2005 and Bäckblom 2008
Outline

EDZ Roles & definition

Overview of EDZ studies in URLs

Field experiment Plan & Objective

Implementation & data interpretation

Discussion and Conclusion
EDZ Studies in Sweden

Stripa Experiment 1986-92
- Hydraulic testing,
- EDZ grouting test

ZEDEX, 1996
- Seismic tomography,
- Hydraulic testing,
- AE monitoring (11 methods)

APSE 2006 (TASQ tunnel)
- Temperature,
- AE, monitoring,
- Displacement

TASS tunnel, 2009
- Rock sawing,
- Fracture investigation,
- 3D modeling
**EDZ Studies in Canada**

**Room 209 & 213 test, 1991**
Excavation response and permeability test
vacuum permeability EDA packer

**MBE& HFT**
1989-1995 & 1993-1996 extensometers,
AE monitoring (11 methods)

**ESS & TSX**
1995-1997
Tunnel Sealing Experiment
Temperature, AE monitoring, Displacement

**BDA**
2003
MVP, borehole camera, AE monitoring
EDZ Studies in Finland

EDZ Programme
2007-2008
GPR
Seismic survey,
Predict EDZ

EDZ09 Project,
2008-2010
GPR,
Seismic survey,
Hydraulic testing
Predict EDZ

POSE
2012
GPR
hydraulic testing
Temperature
AE monitoring

Summary

EDZ Programme

EDZ09 Project,

POSE

EDZ test site (ONK-TKU-3620)
Planned length 59 m

Tomographic reconstruction

Figure 8.4b. The normalized GPR dispersion model: a slice at the ONK-PP202
PZ02C location on the wall. The lithology, natural fractures, crossing artifacts ONK,
PZ02C and difference in the acoustic impedance Napoleon are shown on the delimit.

Figure 5.5. Longitudinal GPR profiles (frequency interval 3.045-1.659 MHz) from
down measurement lines of heights 5.8m, 1.7m and 0.3m from the floor level with
the GPR data is in red (on the right), the right side is in meters calculated with the dielectric
value of the material. 

Figure 4.4. Measurement scheme from period 3, ONK-PP208, ONK-PP210 and ONK-
PP217 from left to right. O-ring packers in ONK-PP208 and ONK-PP210. PFL DIFF
probe in ONK-PP217.
EDZ Studies

### Methods

- AE/MS
- Seismic velocity tomography
- GPR/Borehole radar
- Fracture mapping
- Flow measurement
- Blasting vibration
- 14C-PMMA autoradiography
- Borehole TV
- Displacement/ stress
- Goodman jack
- SEPPi

---

**EDZ studies in crystalline rock**

*Figure 7-10. Modelled blast (red) and blast-induced (yellow) fractures.*
Outline

1. EDZ Roles & Definition
2. Overview of EDZ studies in URLs
3. Field experiment Plan & Objective
4. Implementation & data interpretation
5. Discussion and Conclusion
Objectives of EDZ study in BET

1) To improve the understanding of EDZ with respect to its development, character and extent.

2) To evaluate the capability of used techniques in characterizing EDZ.

3) To propose an effective EDZ technique system for future URL in Beishan.
At the end of this ramp and near to the drill and blast experiment tunnel.

Field work was conducted from April to August in 2016.
Different colored volumes represent five blasting rounds.

The EDZ monitoring tunnel consists of a tunnel perpendicular to the blasting test tunnel, called TL1; And a parallel to the blasting tunnel, called TL2.
Field experiment Plan & Objective

TL2

TL1
Boreholes A1-A12 in BT

A total of 21 boreholes were drilled before the excavation of Blasting Tunnel, used for baseline parameters measurement and sensors installation.
1) **Before excavation:**
   ultrasonic velocity, BTV;

2) **During excavation:**
   Micro-seismic and acoustic emission (AE) monitoring

3) **After excavation:**
   GPR survey in blasted tunnel, core logging, BTV, ultrasonic velocity
Outline

1. EDZ Roles & definition
2. Overview of EDZ studies in URLs
3. In situ experiment Plan & Objective
4. Implementation & data interpretation
5. Discussion and Conclusion
Velocity measurement

Boreholes corresponding to this round

Boreholes corresponding to the previous round, to study the cumulative effect

No measurement in this round

Diagram of ultrasonic probe

Diagram of velocity CT

Velocity measurement along borehole

Velocity tomography
P-wave Velocity of the surrounding rock mass is 3500-5500m/s
velocities within 0.2 m from the excavation surface decreased more than 10%, and from 0.2m to 0.5m the velocity also decreased compared to original rock.
Similar to the results from velocity measurement, results of velocity tomography also shows obvious velocity reduction within 0.4-0.5 m from the wall.
BTV images help to interpret velocity data.

Sensitive to fractures with wide aperture
Sensitive to hole

Velocity is sensitive to heterogeneity of rock masses, which always brings puzzles in the EDZ interpretation practice. **BTV image is helpful in EDZ delineation using ultrasonic velocity data**
16 AE sensors were used in this test, and an installation device is designed for AE sensors installation in boreholes.
Advantages: Easy to be used, ensure good acoustic coupling, adjustable pressure

The AE sensors array was moving forward as the round advanced
Evolution of AE hits

At the firing moment, the number of AE hits suddenly increased to a peak. Then followed by a rapid decrease, but still hold high rate for about 1 h with a negative exponential decay. At last, the AE hits rate maintained low stable state.
Damage stages identification based on AE

The evolution of AE hits after blasting can be divided into three stages: **Blasting Damage stage (BD)**, **Progressive Damage stage (PD)** and **Noise/ stable stage**.
Damage stages identification based on AE

Evolution of AE hits after blasting shows that damage process can be divided into different stages, controlled by distinct mechanisms.
Damage stages identification based on AE

<table>
<thead>
<tr>
<th>Rounds</th>
<th>BD (D1, min)</th>
<th>PD (D2, min)</th>
<th>Noise (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BL1</td>
<td>0-1.36</td>
<td>1.36-55.95</td>
<td>55.95-</td>
</tr>
<tr>
<td>BL2</td>
<td>0-5.5</td>
<td>5.5-125.6</td>
<td>125.6-</td>
</tr>
<tr>
<td>BL3</td>
<td>0-1.36</td>
<td>1.36-61.54</td>
<td>61.54-</td>
</tr>
<tr>
<td>BL4</td>
<td>0-2.04</td>
<td>2.04-91.8</td>
<td>91.8-</td>
</tr>
<tr>
<td>BL5</td>
<td>0-12.29</td>
<td>12.29-322</td>
<td>322-</td>
</tr>
</tbody>
</table>

Good correlation between the duration (BD, PD) and the number of AE hits, an indicator of damage extent, demonstrate the reliability of the stage divisions.
Significant difference of the distribution of AE parameters (Rise time/ amplitude, RA, and average frequency, AF) in BD and PD. Which show that:

**Blasting damage stage**: High R/A value with low AF, shear mechanism

**Progressive damage stage**: Low R/A value with high AF, tensile mechanism
The localization accuracy testing was conducted by knocking on the wall. And results show that the error is 0.3 m.


Temporal and spatial distribution of AE source

AE locations were dispersed in a wide area, suggesting that cracks induced by blasting were widely distributed, up to about 6 m away from the excavation surface.

AE locations were clustering in the range of 0.6 m from the tunnel surface, indicating that the blasting induced damage is within about 0.6 m from the excavation surface.

Note: Re-localized and scaled based on relative location method and newly proposed method by Chen (2016)
AE sources were mainly localized over the range of the current blast round, which indicates that damage induced by blasting was mainly contributed to current round, and the cumulative effect was slight.
**Radar Survey**

**Radar systems:** (a) GSSI SIR-20 with **1.5 GHz** air-coupled antenna; (b) GSSI SIR-20 with **100 MHz borehole radar antenna**; (c) SSI pulse EKKO PRO with **200 MHz** antenna; (d) SSI pulse EKKO PRO with **100 MHz cross-hole radar antenna**; (e) Survey lines of GPR in BT.
Borehole radar system were applied to detect discontinuities in rock mass.

Cross-borehole radar was used to measure the velocity of radar wave in rock mass.
The strong reflection, colored red and blue are observed in the range of 0.10 to 0.25 m from the tunnel surface, indicating significant change in electric conductivity and dielectric value in this zone.
Summery of GPR detecting

Average thickness of EDZ for each blast round

<table>
<thead>
<tr>
<th>Blast round</th>
<th>Average Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BL 1</td>
<td>0.17</td>
</tr>
<tr>
<td>BL 2</td>
<td>0.23</td>
</tr>
<tr>
<td>BL 3</td>
<td>0.215</td>
</tr>
<tr>
<td>BL 4</td>
<td>0.22</td>
</tr>
<tr>
<td>BL 5</td>
<td>0.24</td>
</tr>
</tbody>
</table>

Note: The crushed rock layer filters the GPR signal so it is difficult to detect EDZ reflections under the floor, and data with bold font in the table is of low reliability.

Average thickness of each blasting rounds was calculated and the thickness of each round was correlated well with AE monitoring data.

\[ y = 0.6306x + 17.237 \]

\[ R^2 = 0.70 \]
EDZ shape along Tunnel

Typical EDZ shape for a blast round

EDZ shape for each blast round was delineated by high frequency GPR.
Adjacent boreholes and large discontinuities can be identified by borehole radar.

Unlike the evolution of ultrasonic wave velocity, only a slight increase of radar wave velocity was found in the near field of BT.
Borehole TV and core logging

BTV measurement

Core logging

Core logging

0-2.65m
RQD:51

2.65-5.34m
RQD:71

5.34-7.76m
RQD:64

7.76-10.36m
RQD:80

10.36-13.13m
RQD:77

13.13-15.30m
RQD:63
Boreholes images of good quality were obtained and cracks opened a little induced by excavation.

The average RQD in 0 to 1 m from the tunnel surface is decreased by more than 10% compared to the average RQD more than 1 m from the tunnel surface.
AE Monitoring

- AE monitoring system provided abundant information to analyze the damage process.
- Results from AE monitoring show that damage process can be divided into two stages, viz., blasting damage stage and progressive damage stage.
- For AE localization, AE sensors array should be smaller to provide more precise AE localization, since micro-cracks are limited within a few cm (60 cm) from excavation surface.
However, a thinner damage zone, 0.1 to 0.2 m, determined by radar investigation is defined as inner damage zone with higher damage. GPR is demonstrated as a very promising technique in EDZ study for its excellent capability in delineation of EDZ.

A clear reduction is observed in the range from the wall face to 0.2-0.5 m from the wall, defined as EDZ.
Correlation of AE and GPR results

<table>
<thead>
<tr>
<th>Blast round</th>
<th>Average Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BL 1</td>
<td>17.55</td>
</tr>
<tr>
<td>BL 2</td>
<td>23.02</td>
</tr>
<tr>
<td>BL 3</td>
<td>21.55</td>
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<tr>
<td>BL 4</td>
<td>22.20</td>
</tr>
<tr>
<td>BL 5</td>
<td>23.94</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Blast round</th>
<th>Total AE number ($10^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BL 1</td>
<td>2.63</td>
</tr>
<tr>
<td>BL 2</td>
<td>9.18</td>
</tr>
<tr>
<td>BL 3</td>
<td>4.19</td>
</tr>
<tr>
<td>BL 4</td>
<td>6.74</td>
</tr>
<tr>
<td>BL 5</td>
<td>11.28</td>
</tr>
</tbody>
</table>

The EDZ depth of five blast rounds is compared with the total AE number of each blast round.

Good correlation between AE number and EDZ depth is found.

The correlation of AE and GPR results is shown in the plot. The equation of the line is $y = 0.6306x + 17.237$, with $R^2 = 0.70$. 

![Plot showing correlation between AE hits and EDZ depth](image)
- Visible images were obtained by BTV, which is helpful when ultrasonic velocity data was used to analyze EDZ.
- RQD in 0 to 1 m from the wall is decreased by more than 10% compared to the average RQD more than 1 m from the tunnel surface.

![Graph showing changes in velocity and RQD before and after excavation](image)
Thank you!
Mineralogical investigations of large scale deposition tests

Stephan Kaufhold

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Email: Stephan.Kaufhold@bgr.de

Abstract: Different concepts exist for encapsulation of the worldwide growing amount of high level radioactive waste. Many concepts favor storing the waste deep in crystalline rocks. These rocks are rarely tight with respect to circulating groundwater and hence an additional barrier to isolate the metal canister containing the waste from the formation water is planned to be used. In this respect, bentonite, a natural swelling clay, is worldwide considered as most promising material because it is already used to protect the environment against contaminants from waste dumps or tailings. The performance of bentonite in these systems was investigated in long term experiments in underground rock laboratories. In a repository for high level radioactive waste, however, bentonite will be exposed to a temperature plume in the early phase. Safety assessment require an understanding of the barrier function for up to 1 M years. The performance of bentonite, therefore, is extensively investigated both in laboratory experiments as well as in large scale deposition tests.

In Germany different concepts and different host rocks are currently compared. To date no underground rock laboratory exists in which experiments can be conducted to test the bentonite performance in crystalline host rocks under realistic repository conditions. BGR, therefore, participates in different SKB projects (e.g. prototype repository, PTR; long term test, LOT; alternative buffer material test, ABM; task force on engineered barriers) and joined the last project phase of the FEBEX experiment, which is currently the longest demonstration experiment (18 years).

The different tests proved that dissolution/precipitation processes can occur which are not restricted to (partly) soluble minerals such as carbonates and sulfates. In some instances cristobalite and zeolite also dissolved. In addition cation exchange was observed which was interpreted as reequilibration of the interlayer with the surrounding groundwater. The cation exchange was slower in case of experiments conducted at up to 100°C (PTR, FEBEX) and was almost complete after the first year in the ABM-I test (120-140°C). In all these heater tests an increase of the Mg-content was found at the metal/bentonite interface. In some instances an increasing amount of exchangeable Mg2+ was also observed but this was not necessarily the case. Structural investigations using XRD and IR revealed the formation of trioctahedral domains at the interface. Results obtained from the FEBEX experiment prove that this reaction mechanism is not related to corrosion and does not depend on the type of metal used (Cu or Fe). The mechanism behind this reaction, however, is still to be discovered. Corrosion was observed in all tests. In the case of Cu and MX80 bentonite (PTR, LOT) covellite, probably containing some structural Fe, was observed as corrosion product which formed at the expense of pyrite being present as minor component in the MX80 clay. In the FEBEX project significant oxic corrosion was observed which is characterized by the formation of magnetite on the surface and goethite further away in the clay. The significant oxic corrosion can be explained by the large amount of air which was in the gap between heater and liner. In the frame of the FEBEX experiment a bentonite/cement interface was investigated using electron microscopy. A transition zone with some mineral alteration was identified which, however, was restricted to about 1 mm. The ABM test is conducted to be able to compare the performance of different bentonites. No final conclusion could be drawn in this respect, yet, probably because of the fact that all materials were in contact with each other.
Mineralogical investigations of large scale deposition tests

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Mineralogical investigations of large scale deposition tests

BGR research in 2 granite URLs (underground rock laboratories)
Mineralogical investigations of large scale deposition tests

What did we learn so far from large scale deposition tests?
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Äspö – Prototype repository test (PTR)

6 real scale canisters with heaters and sensors in 2 sections
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PTR – project details – section II

85°C heater/bentonite, 60°C bentonite/rock

Section 2 was terminated after 8 years and bentonite blocks retrieved

Bentonite: MX80
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PTR - sampling

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**PTR – analysis (chemical composition)**

- **CaO** increases at contact
- **MgO** increases at contact
- **Al$_2$O$_3$** decreases at contact
- **SiO$_2$** decreases at contact

All changes were restricted to the very contact, Si/Al ratio constant

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PTR - analysis (chemical composition)

Cu corrosion

Cu an Zn+Mo increased at the contact

Lubricant used to insert the canisters

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PTR – corrosion

SEM

bentonite/Cu interface

Cu sulphides formed

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Long term test – up-scale test with different T (LOT)

Cu heater (10 cm) with MX80 blocks (30 cm), 4 m long, different T

<table>
<thead>
<tr>
<th>type</th>
<th>No</th>
<th>Type</th>
<th>T, °C</th>
<th>Pc</th>
<th>time, y</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>1</td>
<td>standard</td>
<td>90</td>
<td>T</td>
<td>1</td>
<td>Finalized</td>
</tr>
<tr>
<td>S</td>
<td>2</td>
<td>standard</td>
<td>90</td>
<td>T</td>
<td>~ 5</td>
<td>Ongoing</td>
</tr>
<tr>
<td>S</td>
<td>3</td>
<td>standard</td>
<td>90</td>
<td>T</td>
<td>~ 20</td>
<td>Ongoing</td>
</tr>
<tr>
<td>A</td>
<td>0</td>
<td>adverse</td>
<td>120&lt;150</td>
<td>T, ([K^+], Am, pH)</td>
<td>1</td>
<td>Finalized</td>
</tr>
<tr>
<td>A</td>
<td>1</td>
<td>adverse</td>
<td>120&lt;150</td>
<td>T, ([K^+], Am, pH)</td>
<td>1</td>
<td>Finalized</td>
</tr>
<tr>
<td>A</td>
<td>2</td>
<td>adverse</td>
<td>120&lt;150</td>
<td>T, ([K^+], Am, pH)</td>
<td>~ 5</td>
<td>Analyzing</td>
</tr>
<tr>
<td>A</td>
<td>3</td>
<td>high T</td>
<td>120&lt;150</td>
<td>T</td>
<td>~ 5</td>
<td>Ongoing</td>
</tr>
</tbody>
</table>

S = standard conditions  
Pc = controlled parameter  
Ma = mineralogical alteration  
Pc = cementation  
Am = accessory minerals  

Kaufhold, S. and Dohrmann, R. (2009) Mineralogical and geochemical alteration of the MX80 bentonite from the LOT experiment Characterization of the A2 parcel. TR-09-29, ISSN 1404-0344
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LOT A2 (5 years > 120°C)
LOT

Cu increase up to 1 cm into bentonite

Covellite

Cu(Fe)Sx

Kaufhold, S. and Dohrmann, R. (2009) Mineralogical and geochemical alteration of the MX80 bentonite from the LOT experiment Characterization of the A2 parcel. TR-09-29, ISSN 1404-0344
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LOT

Gypsum redistribution

Kaufhold, S. and Dohrmann, R. (2009) Mineralogical and geochemical alteration of the MX80 bentonite from the LOT experiment Characterization of the A2 parcel. TR-09-29, ISSN 1404-0344
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LOT

A small MgO increase was found at the contact to the heater
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Alternative buffer material test – ABM (up-scale test)

Aim: Comparison of different bentonites and clays

Problem: They are all in contact with each other (many more interfaces than common)

Fe-Heater, T about 120°C, different times
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ABM-I: one block of each type of material

ABM-II: all blocks sampled (except for broken pieces)
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ABM-I / ABM-II  cation exchange

Na exchanged bentonites took up Ca and Ca
saturated bentonites took up some Na – all cation populations became more similar (not equal!)

On average Na was desorbed, Ca taken up and some Mg was desorbed

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ABM-I / ABM-II  cation exchange

The Na/Mg ratio was larger in the upper part – reason was boiling and the resulting NaCl precipitation

BOILING observed !!!
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ABM-II model explaining boiling
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FEBEX (full scale = real scale)

Fe heater, diameter ≈ 1 m, 3 rows of blocks (Almeria bent./unprocessed), 18 Years, ≈ 100 °C
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FEBEX (full scale = real scale)

Kaufhold, S., Dohrmann, R., Ufer, K. (in prep.) Mineralogical changes of the bentonite in the frame of the FEBEX experiment at Grimsel, Switzerland, Project report; AITEMIN Full dismantling plan FEBEXe, 2015
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FEBEX (full scale = real scale)

Corrosion     Oxic corrosion between tube and liner

Smectite + goethite

Magnetite + native Fe

E2: brown  E4: grey  E3: black
E5: brown (red)  E6: black
E7: white  E8: white

anhydrite
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FEBEX (full scale = real scale)

BM-S-54-5B

5.5 % +MgO
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FEBEX (full scale = real scale)

Formation of brucite and/or trioctahedral domains (d060,…)

Kaufhold, S., Dohrmann, R., Ufer, K. (in prep.) Mineralogical changes of the bentonite in the frame of the FEBEX experiment at Grimsel, Switzerland, Project report.
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FEBEX (full scale = real scale)

Water saturation was not achieved despite 18 years!!

Kaufhold, S., Dohrmann, R., Ufer, K. (in prep.) Mineralogical changes of the bentonite in the frame of the FEBEX experiment at Grimsel, Switzerland, Project report.
Mineralogical investigations of large scale deposition tests

What did we learn from large scale tests?

Sulphide containing bentonite interacts with Cu surface – covellite formation

Cation exchange takes place easily at $T > 100^\circ C$ (only small amount in PTR) and incomplete in FEBEX

(partly) soluble phases can dissolve and precipitate elsewhere

Something happens to the smectite at the heater interface:
- CEC drops (not always)
- MgO increases
- trioctahedral domains form

  dissolution/precipitation? Or solid state reaction?

This reaction does not depend on corrosion (FEBEX)
Thanks for listening
Mineralogical investigations of large scale deposition tests

References


Mineralogical investigations of large scale deposition tests

Which tests are still running?

Perspective

LOT: S2/S3 running since 2000 (standard-T = 90°C)

ABM3 (running since 2006 + 3 new ones in 2012)

Prototype: 4 real scale canisters left, running since 2003, T = 90°C
The redox potential of Beishan groundwater and its impact on U(VI) reduction by Beishan granite

Mingliang Kang\textsuperscript{a}, Ping Chen\textsuperscript{a}, Yang Song\textsuperscript{a}, Fengqi Xu\textsuperscript{a}, Chengming Shang\textsuperscript{a}, Ju Wang\textsuperscript{b}

\textsuperscript{a} Chinese-French Institute of Nuclear Engineering and Technology, Sun Yat-sen University, Zhuhai 519082, China
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E-mail: kangml3@mail.sysu.edu.cn

Abstract: A major concern for the disposal of high-level radioactive waste (HLW) is the eventual corrosion of the waste canister due to a long-term storage. UO\textsubscript{2} is the matrix material of spent fuel, and its oxidation can also cause the leaching of long-lived fission products and transuranium actinides. The mobility of many redox-sensitive radionuclides (e.g., \textsuperscript{99}Tc, \textsuperscript{79}Se, and other actinides) contained in HLW is largely controlled by the oxidation state, which in turn depends on the redox conditions of the surrounding environment. These radionuclides generally have lower solubility and mobility at lower oxidation states. Consequently, the redox potential is one of the key parameters that can influence the long-term safety of the repository, and understanding the redox behavior of redox-sensitive radionuclides is essential for the safety assessment of the repository.

In this study, the redox potential of Beishan groundwater-rock system was evaluated based on the Fe\textsuperscript{2+}/Fe\textsuperscript{3+} ratio contained in the host rock. Accordingly, its impact on the solubility and mobility of redox-sensitive radionuclides was investigated. The results indicated that the solubility is expected to be relatively high (\approx 10\textsuperscript{-5}-10\textsuperscript{-4} mol/L) for U and Tc, whereas relatively low for Se (\approx 10\textsuperscript{-8} mol/L) and fairly low for Np (\approx 10\textsuperscript{-18} mol/L). On the other hand, because of the abundance of Fe\textsuperscript{2+} in the host rock (mainly exist as F-rich annite), our laboratory experiments indicated that Beishan granite has a considerable reducing capacity toward U(VI), and the reaction kinetics increased with decreasing pH. XPS analysis confirmed the formation a mixed U(IV) and U(VI) product (e.g., U\textsubscript{3}O\textsubscript{8}/U\textsubscript{4}O\textsubscript{9}/U\textsubscript{3}O\textsubscript{7}). A reaction mechanism involved in the dissolution of the bulk Fe\textsuperscript{2+} and subsequent adsorption by the granite-water interface was proposed for the U(VI) reduction. These results demonstrated that Beishan site is in favor of the immobilization of redox-sensitive radionuclides like U. To give a more comprehensive evaluation of the reducing capacity of Beishan granite, further experiments pertinent to other radionuclides are needed.
The redox potential of Beishan groundwater and its impact on U(VI) reduction by Beishan granite

Mingliang Kang\textsuperscript{1}, Ping Chen\textsuperscript{1}, Yang Song\textsuperscript{1}, Fengqi Xu\textsuperscript{1}, Chengming Shang\textsuperscript{1}, Ju Wang\textsuperscript{2}

\textsuperscript{1}. Sino-French Institute of Nuclear Engineering and Technology, Sun Yat-sen University, China
\textsuperscript{2}. Beijing Research Institute of Uranium Geology, Beijing 100029, China

E-mail: kangml3@mail.sysu.edu.cn

3\textsuperscript{rd} Sino-German Workshop on Radioactive Waste Disposal, Jiayuguan, China, 16-19 May, 2017
I. Background

II. Estimation of the redox potential of Beishan groundwater

III. The redox behavior of uranium on Beishan granite

IV. Kinetics of spent fuel (UO$_2$) oxidation by Fe$^{3+}$

V. Conclusions and prospects
Spent Nuclear Fuel of PWR

- 95% $^{238}\text{U}$
- 3% Minor actinide (MA)
- 1% Fission products (FPs)
- 1% $^{235}\text{U}$

lower $^{235}\text{U}$ (~0.3%) in SNF of CANDU reactor (Qinshan nuclear power plant)

disposed directly
Multi-barriers concept

➢ The most potential site for HLW in China: Beishan

The diagram illustrates the concept of a multi-barrier system for high-level waste (HLW) disposal. The system includes a host rock (granite), a waste canister, backfill material, and an underground water layer. The biosphere is also shown, highlighting the complexity of the repository failure and radionuclides migration risk. The diagram references a map of Beishan and a link to a news article on the topic. 

For more information, visit: [http://www.guancha.cn/Science/2014_06_19_239185.shtml](http://www.guancha.cn/Science/2014_06_19_239185.shtml)
UO₂(s) is the matrix material of SNF, its oxidation will cause the leaching of fission products (⁷⁹Se, ⁹⁹Tc, etc) and transuranium actinides. Oxidation will change the solubility of uranium. Redox potential is one of the key parameters that influence the safety of the repository.

- **⁷⁹Se:**
  - Se(IV) & Se(VI): highly soluble and mobile (HSeO₃⁻, SeO₃²⁻, SeO₄²⁻, etc.)
  - Se(0, -I, -II): non-soluble solids (Se⁰, FeSe, FeSe₂, etc.)

- **⁹⁹Tc:**
  - Tc(VII): exist as TcO₄⁻, highly soluble and mobile
  - Tc(IV): non-soluble solids
Estimation of the redox potential of Beishan groundwater

Influencing factors on Eh measurement: effects of solution temperature and pH, irreversible reactions, slow electrode kinetics, non-equilibrium, presence of multiple redox couples, electrode poisoning, small exchange currents and inert redox couples.
Considerable Fe, mainly exist as fluorannite & Magnesiohornblende

BS03-400m granite: 2.12 wt% Fe (as Fe$_2$O$_3$) and 96.86% as Fe(II)
Chemical composition of the groundwater taken from BS-3 at 400 m deep

<table>
<thead>
<tr>
<th>Composition</th>
<th>Na⁺</th>
<th>NH₄⁺</th>
<th>Ca²⁺</th>
<th>K⁺</th>
<th>Mg²⁺</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>C / mg·L⁻¹</td>
<td>1036</td>
<td>0.12</td>
<td>183</td>
<td>15.95</td>
<td>50.4</td>
<td>0.033</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Composition</th>
<th>Cu²⁺</th>
<th>Mn²⁺</th>
<th>Li⁺</th>
<th>Sr²⁺</th>
<th>Al³⁺</th>
<th>HCO₃⁻</th>
</tr>
</thead>
<tbody>
<tr>
<td>C / mg·L⁻¹</td>
<td>0.0001</td>
<td>0.022</td>
<td>0.0112</td>
<td>0.715</td>
<td>0.06</td>
<td>130.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Composition</th>
<th>SO₄²⁻</th>
<th>F⁻</th>
<th>Br⁻</th>
<th>NO₃⁻</th>
<th>Cl⁻</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>C / mg·L⁻¹</td>
<td>941.1</td>
<td>2.2</td>
<td>0.0001</td>
<td>32.6</td>
<td>1193</td>
<td>7.56</td>
</tr>
</tbody>
</table>

Fe²⁺/Fe₄tot ratio is 96.86% in granite, \( a_{\text{Fe}^{2+}} \) and \( a_{\text{Fe}^{3+}} \) are \( 1.473 \times 10^{-7} \) and \( 3.603 \times 10^{-19} \) (PHREEQC calculation), respectively. \( \text{Eh} = 83.2 \text{ mV} \)

BS28-670m groundwater: pH 7.64, Fe 0.078 mg·L⁻¹, …. \( \text{Eh} = 49.9 \text{ mV} \)
Eh is controlled by oxygen partial pressure

\[ \text{O}_2(g) + 4\text{H}^+ + 4e^- = 2\text{H}_2\text{O} \]

\[ E = E_{\text{O}_2/\text{H}_2\text{O}}^\theta + \frac{0.0591}{4} \log \left( \frac{P_{\text{O}_2}}{P^\theta} a_{H^+}^4 \right) = 1.229 + \frac{0.0591}{4} \log \frac{P_{\text{O}_2}}{P^\theta} - 0.0591pH \]

Assume \( P_{\text{O}_2} \) is invariable

\[ \text{pH} = 7.56, \text{Eh} = 83.2 \text{ mV} \]

\[ \text{Eh} = 0.530 - 0.0591pH \]

PHREEQC Calculations
Predominant species

Ca₂UO₂(CO₃)₃
CaUO₂(CO₃)₃²⁻
UO₂(CO₃)₃⁴⁺
MgUO₂(CO₃)₃²⁻

Solubility (mol/L)

\[ \text{pH} = 7.56 \sim 10^{-4} \text{ M} \]

\[ \text{pH} = 7.56 \sim 10^{-5} \text{ M} \]

\[ \text{pH} = 7.56 \sim 10^{-8} \text{ M} \]

\[ \text{pH} = 7.56 \sim 10^{-18} \text{ M} \]
The redox behavior of U(VI) on Beishan granite
Mineral components

BS2-486m granite

Fe$_{tot}$: 5.61 wt% (as Fe$_2$O$_3$)
Fe$^{2+}$: 93.41%

BS28-670m granite

Fe$_{tot}$: 4.22 wt% (as Fe$_2$O$_3$)
Fe$^{2+}$: 95.57%
**Point of zero charge (pzc)**

In absence of specific adsorption, the pH at which the surface is neutral is called pzc.

\[
\text{pH} > \text{pzc}, \text{ negatively charged surface:} \\
\text{SOH}^{(\text{surf})} + \text{OH}^-^{(\text{aq})} = \text{SO}^-^{(\text{surf})} + \text{H}_2\text{O}(l)
\]

\[
\text{pH} < \text{pzc}, \text{ positively charged surface:} \\
\text{SOH}^{(\text{surf})} + \text{H}^+^{(\text{aq})} = \text{SOH}_2^+^{(\text{surf})}
\]
pzc of BsG

-0.040
-0.035
-0.030
-0.025
-0.020
-0.015
-0.010
-0.005
0.000
0.005

Ground to fine powder

anoxic glovebox (O₂ < 1 ppm)

BS02-486m
Sorption experiments of U(VI) on BsG

BS2-486m: in the presence of carbonate & 0.01 M NaCl
BS28-670m: in presence of pristine Beishan groundwater

Aqueous U(VI) decreased at

- pH 4.96 for BS2-486m granite
- pH 4.55-6.60 for BS28-670m granite
Fitted XPS spectra Fe(2p) (left) and U(4f) (right)

BS2-pH4.96

BS28-pH4.55

BS28-pH5.29

BS28-pH6.60
Aqueous U(VI) was partially reduced to U (IV) at an initial pH of 4.96 and 4.55-6.60 with NaCl and native Beishan groundwater as background electrolyte, respectively.

Possible products: U₃O₈, U₃O₇, or U₄O₉.
The oxidation $\text{UO}_2$ by Fe(III) can account for the incomplete reduction of U(VI) by Beishan granite.
Heterogeneous reduction of aqueous U(VI) by Fe$^{2+}$ adsorbed on solid phase (e.g., clay mineral) has widely been reported.

Kinetics of spent fuel (UO$_2$) oxidation by Fe$^{3+}$
Hydrazine hydrate ($\text{N}_2\text{H}_4\cdot\text{H}_2\text{O}$)

➢ XRD patterns of products

UN: uranyl nitrate
UA: uranyl acetate

1: UN(0.05 M) + N$_2$H$_4$(0.5 M)
2: UN(0.05 M) + N$_2$H$_4$(1.0 M)
3: UN(0.05 M) + N$_2$H$_4$(1.5 M)
4: UN(0.05 M) + N$_2$H$_4$(3.0 M)
5: UN(0.05 M) + N$_2$H$_4$(4.0 M)
6: UN(0.05 M) + N$_2$H$_4$(5.0 M)
7: UN(0.01 M) + N$_2$H$_4$(0.025 M)
8: UN(0.01 M) + N$_2$H$_4$(0.04 M)
9: UN(0.01 M) + N$_2$H$_4$(0.04 M)
10: UA(0.01 M) + N$_2$H$_4$(0.025 M)
11: UA(0.01 M) + N$_2$H$_4$(0.04 M)
12: UA(0.05 M) + N$_2$H$_4$(3.0 M)

- UA(0.01) + N$_2$H$_4$(0.025) heated for 18h
- UN(0.05) + EDA(10.0) heated for 48h
- UA(0.025) + EDA(7.50) heated for 48h
- UA(0.01) + N$_2$H$_4$(0.04) heated for 18h
<table>
<thead>
<tr>
<th>Chemical equations</th>
<th>$\Delta_r G^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4\text{UO}_2(\text{cr}) + 2\text{Fe}^{3+} + \text{H}_2\text{O} = \text{U}_4\text{O}_9 + 2\text{H}^+ + 2\text{Fe}^{2+}$</td>
<td>-60.846 kJ/mol</td>
</tr>
<tr>
<td>$3\text{UO}_2(\text{cr}) + 2\text{Fe}^{3+} + \text{H}_2\text{O} = \text{U}_3\text{O}_7(\beta) + 2\text{H}^+ + 2\text{Fe}^{2+}$</td>
<td>-55.063 kJ/mol</td>
</tr>
<tr>
<td>$3\text{UO}_2(\text{cr}) + 4\text{Fe}^{3+} + 2\text{H}_2\text{O} = \text{U}_3\text{O}_8(\text{cr}) + 4\text{H}^+ + 4\text{Fe}^{2+}$</td>
<td>-97.664 kJ/mol</td>
</tr>
</tbody>
</table>
### Experimental conditions

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH&lt;sub&gt;initial&lt;/sub&gt;</td>
<td>1.5</td>
<td>1.8</td>
<td>2.2</td>
<td>2.4</td>
</tr>
<tr>
<td>M&lt;sub&gt;UO2(g)&lt;/sub&gt;</td>
<td>0.05</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[Fe&lt;sup&gt;3+&lt;/sup&gt;]&lt;sub&gt;initial&lt;/sub&gt; ($\times 10^{-5}$M)</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V(mL)</td>
<td>90</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Experimental results

The reaction kinetics increased with increasing pH

- **pH 1.5**:
  - Reaction type: zero order rate low
  - Equation: $y = 4.62(\pm0.9) \times 10^{-5}t + 19.88(\pm1.7)$
  - Correlation coefficient: $R^2 = 0.9960$

- **pH 1.8**:
  - Reaction type: zero order rate low
  - Equation: $y = 10.44(\pm0.26) \times 10^{-5}t + 20.41(\pm0.26)$
  - Correlation coefficient: $R^2 = 0.9947$

- **pH 2.1**:
  - Reaction type: first order rate low
  - Equation: $y = -1.95(\pm0.08) \times 10^{-1}t + 2.91(\pm0.05)$
  - Correlation coefficient: $R^2 = 0.9833$

- **pH 2.4**:
  - Reaction type: first order rate low
  - Equation: $y = -3.11(\pm0.08) \times 10^{-1}t + 2.97(\pm0.03)$
  - Correlation coefficient: $R^2 = 0.9933$

**Low pH**: diffusion of $\text{Fe}^{3+}$ to the surface

**High pH**: remove the oxidation product

Rate determining step
Conclusions

➢ Beishan granite has relatively strong reducing capacity → it is in favor of immobilization of uranium in the long run.

➢ Aqueous U(VI) was partially reduced to U (IV) by Beishan granite in the laboratory time scale at acidic conditions.

➢ Fe$^{3+}$ can oxidize UO$_2$ rapidly, and the reaction kinetics increased with increasing pH. The reaction mechanism is different at different pH.

➢ A method based on the Fe$^{2+}$/Fe$^{3+}$ ratio in Beishan granite was used to estimate the redox potential of groundwater.
Ongoing and future works

➢ the physico-chemical behavior of $^{79}$Se and $^{99}$Tc on BsG
➢ interaction of U(VI) with UO$_2$ and corrosion products
➢ transportation of radionuclides in the groundwater-rock system (in collaboration with colleagues at IFCEN and SUBATECH, France)

• Provide fundamental data for site-selection and safety assessment
• Contribute to China’s HLW disposal project
Thank you for your attention!
GRS’ on-site demonstration work in the Mont Terri underground rock laboratory

Oliver Czaikowski1, Klaus Wieczorek

*Gesellschaft für Anlagen- und Reaktorsicherheit (GRS)*

Email: oliver.czaikowski@grs.de

**Abstract:** For constructing a nuclear waste repository and for ensuring the safety requirements are met over very long time periods, thorough knowledge about the safety-relevant processes occurring in the coupled system of waste containers, engineered barriers, and the host rock is indispensable. Experiments on host rock behaviour and on the coupled system at the real or near-real scale help to make sure the safety-relevant processes are identified and understood and to show that laboratory-scale findings can be extrapolated to repository scale.

For respectively targeted research work, the Mont Terri rock laboratory is a unique facility where repository research is performed in a clay rock environment. It is run by an international consortium which GRS is a member of, with the motivation of

- Gaining profound understanding of the safety-relevant coupled thermal-hydraulic-mechanical (THM) processes running in a repository in clay rock,
- Developing appropriate process models which are needed for long-term prediction of the system evolution, by comparison of simulation results with representative laboratory and in-situ experiments,
- Obtaining reliable data for qualification of process models (including development and improvement of measuring techniques),
- Gaining knowledge by international co-operation.

Some of the work which GRS as one of the Mont Terri partners is involved in is presented on the 3rd Chinese-German Workshop on Radioactive Waste Disposal. The focus is on thermal, hydraulic and mechanical behaviour of host rock and/or engineered barriers.
On-site demonstration work on buffer and backfill materials

Oliver Czaikowski, Klaus Wieczorek, Chun-Liang Zhang
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS), Germany
HLW disposal in clay formations

Clay-based buffer/backfill/seal:
- Re-saturation by water from rock
- Swelling pressure resisting EDZ
- Very low hydraulic conductivity

Swiss disposal concept (nagra)

Clay host rock:
- Very low hydraulic conductivity
- Self-sealing of EDZ
- Sorption of radionuclides

500 - 1000 m
Functions of bentonite-based buffer and sealing materials

**Buffer** providing long-term containment and retardation of radionuclides by

- Limitation of advective transport of water with **low hydraulic conductivity**
- Support of the surrounding rock to reduce EDZ with **certain swelling pressure**
- Stabilisation of HLW canisters in positions with **sufficient stiffness/strength**
- Conduction of heat to avoid excessive temperature with certain **thermal conductivity**
- Reduction of microbial activity and related corrosion with **high density**
- Sorption of radionuclides
- Resistance of mineral transformation and maintain required properties

Similar requirements are suitable for **seal elements** in boreholes, tunnels and shafts.
Experiments at Mont Terri

For ensuring **safe containment** of nuclear waste, it is necessary to characterize and understand the material behaviour of each **EBS component** (waste containers, buffer/backfill/seal) and the host rock.

This can be achieved by R&D
- Theoretical work
- Laboratory experiments
- **In-situ testing**

Recent large-scale experiments
- **HE-E heater experiment**
- **EB engineered barrier**
- **SB borehole seal**
HE-E heater experiment: Objectives and characteristics

- **Objectives:**
  - Gain insight in the early non-isothermal re-saturation process and its impact on the THM behaviour of buffer
  - Provide a data-base for calibration and validation of existing models for simulation of THM processes during the early re-saturation 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 (micro-tunnel; D=1.3m / L=10m)
  - Backfill: granular bentonite (nagra) and sand-bentonite mixture (GRS)
  - Natural re-saturation from clay host rock
  - Heater surface temperature: 140°C
  - Start-up June 2011, ongoing
HE-E: Construction

<table>
<thead>
<tr>
<th></th>
<th>Bentonite Blocks</th>
<th>Granular Bentonite</th>
<th>Sand/Bentonite(65/35)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water content (%)</td>
<td>10.3</td>
<td>5.4</td>
<td>4.1</td>
</tr>
<tr>
<td>Bulk Density (kg/m³)</td>
<td>1.99</td>
<td>1.56</td>
<td>1.44</td>
</tr>
<tr>
<td>Offsite Measurement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry Density (kg/m³)</td>
<td>1.80</td>
<td>1.51</td>
<td>1.38</td>
</tr>
<tr>
<td>Offsite Measurement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk Density Onsite (kg/m³)</td>
<td>1.54</td>
<td></td>
<td>1.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
HE-E: Monitoring results

- Temperature: 45°C, 85°C, 140°C
- Date range: 28.02.2011 to 18.09.2016
- Buffer emplacement
- Relative Humidity [%]
- Heating phase 1 + 2
- D = 1.3 m
EB engineered barrier experiment: Objectives and characteristics

- Objectives: Investigation of buffer performance during re-saturation in the later closure phase after thermal transient period
  - Manufacture of bentonite pellets and blocks at semi-industrial scale
  - Characterisation of HM properties of the materials
  - Demonstration of the emplacement and backfilling techniques
  - Assessment of the quality of the buffer after emplacement
  - Characterisation of EDZ and its effects
  - Monitoring HM processes
  - HM modelling of the complete system

- Characteristics
  - Full-scale experiment
  - Calcium bentonite buffer
  - Artificial re-saturation started in 2002
  - Dismantling and analysis in 2012/13
EB: Monitoring results
EB: Dismantling and evaluation (10.2012 – 01.2013)

- On-site and laboratory analyses of
  - dry density, water content
  - pore size distribution
  - thermal conductivity
  - hydraulic and gas conductivity
  - swelling strain and swelling pressure
  - microbial analyses

- Results
  - Water content lower and dry density higher in the upper part of granular buffer
  - Average saturation degree > 95-98 %
  - Large density contrast between blocks and granular buffer vanished
  - Hydraulic conductivity in the range of 10^{-12} m/s
**SB borehole seal experiment: Objective and approach**

- **Objective:** Optimization of **sand/bentonite mixture** for sealing boreholes with
  - **Low water permeability** for limiting advective transport of water and radionuclides
  - **Low gas entry pressure** for discharge of gases produced in repository to avoid gas-fracturing the host rock
  - **Certain swelling pressure** against EDZ development

- **Approach**
  - Optimisation of SB mixture
  - Mock-up experiment
  - In-situ experiment
  - HM modelling
  - Dismantling & post-analysis

*Mock-up experiment (2x D=0.3m; H=1m)*

*In-situ test layout (4x D=0.3m / H=1m)*
SB: In-situ experiment (2003–2012)

- Four boreholes
  - SB1, SB2: sand/bentonite (65/35)
  - SB15: sand/bentonite (50/50)
  - SB13: pure granular bentonite

- Test procedure
  - Instrumentation & seal installation
  - Determination of initial density
  - Re-saturation by water injection from the bottom
  - Determination of water permeability after full saturation
  - Gas testing to determine gas entry pressure and permeability after break-through
  - Determination of final water content and density by post-testing
SB: Results

- Saturation time was considerably longer than expected from design modelling.

- Significant amounts of water bypassed the seal section via the EDZ around some boreholes, slowing saturation of seal.

- Final properties of SB seal (65/35):
  - bulk density = 1.91 kg/m³
  - water content = 16-20 %
  - water permeability = $4 \cdot 10^{-18}$ m²
  - gas entry pressure = 0.45 MPa

Fulfilling the designed requirements.
Conclusions and perspective

- **Considerable difficulties** in installation, conduction, monitoring and evaluation of the buffer/seal experiments **were overcome**

- **Buffer and seal elements** can be constructed in a way to meet the required conditions

- **Important insight** into the performance of the buffer/seal systems was gained

- **Reliable data-base and numerical modelling** are necessary for the design, understanding, prediction and assessment of the performance of the buffer/seal systems

- In-situ testing of bentonite-based materials for backfilling/sealing repositories is going on…
  - Buffer: Full-scale emplacement experiment (FE) g
  - Borehole/shaft seal: Sandwich-seal experiment to start in next year
Thank you for your attention!

感谢您的关注！
Adsorption of some radionuclides on Beishan granite
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Email: guozhj@lzu.edu.cn

Abstract: Beishan granitic formation is considered as the preliminary selection for host rock of a high-level radioactive waste repository in China\(^1\). Therefore, a thorough understanding of radionuclide behavior in Beishan granite has become a pressing need for the corresponding safety assessment. In this context, we studied the adsorption of Eu(III)/Am(III), Co(II)/Ni(II), U(VI), Se(IV) and Se(VI) on crushed Beishan granite as a function of many in-situ factors, such as temperature, background electrolyte and the presence of fulvic acid at different concentrations.

Granite is an igneous rock consisting of a number of minerals, which makes adsorption modeling still a challenge. Two approaches have been proposed for such modeling: component additivity approach, in which the adsorption model and the effective surface area of each dominant mineral have to be available, and generalized composite (GC) approach, in which granite is integrally considered and surface reactions are assumed to take place on a type of “general” surface sites. The GC approach ignores protonation and deprotonation reactions as well as electrostatic effect, which makes GC model the simplest one with the least adjustable parameters. Therefore, relatively simple GC model may benefit integral modeling and was applied in our study.

Based on GC approach, surface complexation models were constructed to quantitatively describe the adsorption of Eu(III)/Am(III), Co(II)/Ni(II) and U(VI) on crushed Beishan granite. It was found that different site capacities have to be considered for different elements\(^2-3\), that the model for Eu(III) could be extended to describe Am(III) adsorption\(^4\), and that the model for U(VI) could describe literature data for granites from different regions\(^5\).

References:
\(^4\) Jin Qiang et al., 2014. The adsorption of Eu(III) and Am(III) on Beishan granite: XPS, EPMA, batch and modeling study. Applied Geochemistry, 47: 17-24.
Adsorption of some radionuclides on Beishan granite: Experimental and modeling

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School of Nuclear Science and Technology, Lanzhou University

3rd Sino-German Workshop on Radioactive Waste Disposal, Jiayuguan, China, 16-19 May, 2017
Contents

1. Introduction

2. Eu(III) and Am(III) adsorption on BS03 granite

3. Co(II) and Ni(II) adsorption on BS03 granite

4. U(VI) adsorption on BS10-2 granite

5. Se(IV) adsorption on BS03, 04 and 10-1 granite

6. Conclusions
1. Introduction

1.1 Why Beishan granite?

In the case radionuclide releases from canister and bentonite barrier...

The conceptual model for China’s HLW repository in granite.

Schematic of radionuclide migration in Multi-barriers system

1. Introduction

1.2 Why chemical models?

The Advection-Reaction-Dispersion (ARD) equation:

$$\frac{\partial c}{\partial t} = -\nu \frac{\partial c}{\partial x} + \frac{\partial q}{\partial t} + D_L \frac{\partial^2 c}{\partial x^2}$$

- **Advection** $\rightarrow$ flow rate
- **Reaction** $\rightarrow$ Adsorption
- **Dispersion** $\rightarrow$ Diffusion

Adsorption is controlled by a number of factors.

$$K_d = f(Surface, c, pH, I, T, L,...)$$

Surface, c, pH, I, T, L varies spatially and temporally

- Chemical models are the method of choice to quantitatively describe radionuclide adsorption in Beishan granite
- Adsorption data covering all important factors are the basis for chemical modeling
1. Introduction

1.3 Why GC approach?

➢ Component Additivity (CA) approach

- The rock is ideally considered as a mixture of independent mineral components.
- Models for dominant minerals have to be available.

➢ Generalized Composite (GC) approach

- The rock is integrally considered by assuming that surface reactions take place on a type of "general" surface sites.
- The capacity of general sites is estimated by fitting isotherm with Langmuir equation.

Disadvantages of CA approach:

- The models for each individual components are not always available.
- CA requires much more parameters than GC.
- In granite, each minerals are coated with each other, so that the effective surface area of each mineral cannot be reasonably evaluated.
1. Introduction

1.4 Objectives

1. Collect adsorption data of important radionuclides (Ni$^{2+}$, Co$^{2+}$, Eu$^{3+}$, Am$^{3+}$, UO$_2^{2+}$ and SeO$_4^{2-}$) on granite samples from different borehole.

2. Construct corresponding models with GC approach.
Contents

1. Introduction
2. Eu(III) and Am(III) adsorption on BS03 granite
3. Co(II) and Ni(II) adsorption on BS03 granite
4. U(VI) adsorption on BS10-2 granite
5. Se(IV) adsorption on BS03, 04 and 10-1 granite
6. Conclusions
2. Eu(III)/Am(III) adsorption on BS03 granite

Experimental and modeling:

- **Beishan Granite**: boreholes BS03 BS04 and BS10; treated with HCl and conditioned with NaCl;

- Cation exchange capacity (CEC) was determined by Ni-en method (Bradbury M H, Baeyens B., PSI Bericht Nr. 02-10, ISSN 1019-0643, P31.).

- $^{152,154}$Eu, $^{241}$Am and $^{79}$Se radiotracers; UO$_2$(NO$_3$)$_2$·6H$_2$O; Liquid scintillation counter; U(VI) and Arsenazo-III complex;

- Distribution coefficient ($K_d$) and loading ($q$):

  $$K_d = \frac{(A_o - A_{eq}) V}{A_{eq} m}$$

  $$q = \frac{A_o - A_{eq}}{A_o} \cdot \frac{C_o V}{m}$$

- Code: PHREEQC; NEA database; Nagra/PSI
2. Eu(III)/Am(III) adsorption on BS03 granite

Characterization of Beishan granite:

<table>
<thead>
<tr>
<th>Granite</th>
<th>Quartz</th>
<th>Biotite</th>
<th>Plagioclase</th>
<th>Albite</th>
<th>Anorthite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt %</td>
<td>16.3</td>
<td>1.7</td>
<td>27.3</td>
<td>47.9</td>
<td>6.8</td>
</tr>
</tbody>
</table>

Mineralogical composition of the BS03 granite

<table>
<thead>
<tr>
<th>Samples</th>
<th>BSO3</th>
<th>BS10-1</th>
<th>BS10-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{N}_2 \text{ BET (m}^2/\text{g)} )</td>
<td>2.3</td>
<td>3.2</td>
<td>4.1</td>
</tr>
<tr>
<td>CEC (meq/kg)</td>
<td>93±2</td>
<td>65±2</td>
<td>57±2</td>
</tr>
</tbody>
</table>

Specific surface area and cation exchange capacity

SEM images of the BS03 granite
2. Eu(III)/Am(III) adsorption on BS03 granite

2.1 Electron probe micro (EPMA) analysis

Backscattered-electron images (a and b), secondary-electron image (c) and X-ray mapping results for Eu (d). Number 1–7 in (a) denote orthoclase, quartz, biotite, oligoclase, apatite, chlorite, and sphene.

Eu(III) adsorption can take place on each major constituents, and adsorption on biotite was higher than others.

GC approach is the method choice.
2. Eu(III)/Am(III) adsorption on BS03 granite

2.2 The estimation of site capacity for Eu(III)

Generalized Composite approach

<table>
<thead>
<tr>
<th>Sites</th>
<th>Site densities</th>
</tr>
</thead>
<tbody>
<tr>
<td>≡SOH (by Langmuir equation)</td>
<td>$7.35 \times 10^{-6}$ mol/m$^2$</td>
</tr>
<tr>
<td>$X^-$ (CEC measurement)</td>
<td>$4.04 \times 10^{-5}$ mol/m$^2$</td>
</tr>
</tbody>
</table>

$pH = 6.5 \pm 0.1$, $I = 0.10$ mol/L NaCl, $m/V = 1$ g/L

$C_{Eu(II)} = 6.74 \times 10^{-8}$ mol/L, $I = 0.10$ mol/L
2. Eu(III)/Am(III) adsorption on BS03 granite

\[
C_{\text{Eu(II)}} = 6.74 \times 10^{-8} \text{ mol/L}, \ m/V = 1 \text{ g/L}
\]

\[
C_{\text{Eu(III)}} = 6.74 \times 10^{-8} \text{ mol/L}, \ I = 0.1 \text{ mol/L NaCl}
\]

### Modeling parameters:

<table>
<thead>
<tr>
<th>Sites</th>
<th>Site densities</th>
</tr>
</thead>
<tbody>
<tr>
<td>X^-</td>
<td>4.04 \times 10^{-5} \text{ mol/m}^2</td>
</tr>
<tr>
<td>=SOH</td>
<td>7.35 \times 10^{-6} \text{ mol/m}^2</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Reactions</th>
<th>logK</th>
</tr>
</thead>
<tbody>
<tr>
<td>3XNa + Eu^{3+} ⇄ X_3Eu + 3Na^+</td>
<td>2.2 ± 0.3</td>
</tr>
<tr>
<td>=SOH + Eu^{3+} ⇄ =SOEu^{2+} + H^+</td>
<td>-0.6 ± 0.2</td>
</tr>
<tr>
<td>=SOH + Eu^{3+} + 2H_2O ⇄ =SOEu(OH)_2 + 3H^+</td>
<td>-17.2 ± 0.2</td>
</tr>
</tbody>
</table>

2. Eu(III)/Am(III) adsorption on BS03 granite

2.3 Eu(III) adsorption in CaCl₂ solution

\[
XNa + 0.5Ca^{2+} \rightleftharpoons XCa_{0.5} + Na^+ \quad \log K = 0.3 \pm 0.1
\]

To describe the effect of Ca²⁺, an additional cation exchange reaction is required:

\[
C_{Eu(III)} = 6.74 \times 10^{-8} \text{ mol/L}, \quad m/V = 1 \text{ g/L}, \quad I = 0.1 \text{ mol/L CaCl}_2
\]

\[
m/V = 1 \text{ g/L}, \quad I = 0.10 \text{ mol/L CaCl}_2
\]
2. Eu(III)/Am(III) adsorption on BS03 granite

2.4 Am(III) adsorption in NaCl and CaCl$_2$ solution

Eu(III) and Am(III) aqueous thermodynamic data in NEA database

<table>
<thead>
<tr>
<th>$\text{M}^{3+}$ complexes and solids</th>
<th>logK</th>
<th>Eu$^{3+}$</th>
<th>Am$^{3+}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{M}^{3+} + \text{Cl}^- \leftrightarrow \text{MCl}^2^+$</td>
<td>1.1</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>$\text{M}^{3+} + 2\text{Cl}^- \leftrightarrow \text{MCl}_2^+$</td>
<td>1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{M}^{3+} + \text{H}_2\text{O} \leftrightarrow \text{MOH}^2^+ + \text{H}^+$</td>
<td>-7.6</td>
<td>-7.3</td>
<td></td>
</tr>
<tr>
<td>$\text{M}^{3+} + 2\text{H}_2\text{O} \leftrightarrow \text{M(OH)}_2^+ + 2\text{H}^+$</td>
<td>-15.1</td>
<td>-15.2</td>
<td></td>
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<tr>
<td>$\text{M}^{3+} + 3\text{H}_2\text{O} \leftrightarrow \text{M(OH)}_3^{\text{(aq)}} + 3\text{H}^+$</td>
<td>-23.7</td>
<td>-25.7</td>
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</tr>
<tr>
<td>$\text{M}^{3+} + 4\text{H}_2\text{O} \leftrightarrow \text{M(OH)}_4^{\text{2+}} + 4\text{H}^+$</td>
<td>-36.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$C_{\text{Eu(III)}} = 6.74 \times 10^{-8} \text{ mol/L}, \ C_{\text{Am(III)}} = 6.05 \times 10^{-10} \text{ mol/L}, \ I = 0.10 \text{ mol/L NaCl}$
2. Eu(III)/Am(III) adsorption on BS03 granite

2.4 Am(III) adsorption in NaCl and CaCl\(_2\) solution

![Adsorption edge and Isotherm charts]

- **Sites**
  - \(X^-\) 4.04×10\(^{-5}\) mol/m\(^2\)
  - \(\equiv\text{SOH}\) 7.35×10\(^{-6}\) mol/m\(^2\)

<table>
<thead>
<tr>
<th>Reactions</th>
<th>(\log K)</th>
<th>(\text{Eu}^{3+})</th>
<th>(\text{Am}^{3+})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(X\text{Na} + 0.5\text{Ca}^{2+} \rightleftharpoons X\text{Ca}_{0.5} + \text{Na}^+)</td>
<td>0.3±0.1</td>
<td>0.3±0.1</td>
<td></td>
</tr>
<tr>
<td>(3X\text{Na} + M^{3+} \rightleftharpoons 3X \text{M} + 3\text{Na}^+)</td>
<td>2.2±0.3</td>
<td>2.2±0.3</td>
<td></td>
</tr>
<tr>
<td>(\equiv\text{SOH} + M^{3+} \rightleftharpoons \equiv\text{SOM}^{2+} + \text{H}^+)</td>
<td>-0.6±0.2</td>
<td>-0.1±0.2</td>
<td></td>
</tr>
<tr>
<td>(\equiv\text{SOH} + M^{3+} + 2\text{H}_2\text{O} \rightleftharpoons \equiv\text{SOM(OH)}_2 + \text{H}^+)</td>
<td>-17.2±0.2</td>
<td>-18.2±0.2</td>
<td></td>
</tr>
</tbody>
</table>

\(V = 1\) g/L, \(I = 0.10\) mol/L NaCl

Modeling parameters for Am(III) and Eu(III)

### 3. Co(II) and Ni(II) adsorption on BS03 granite

#### 3.1 The estimation of site capacity for Co(II) and Ni(II)

Speciation of Co(II), Ni(II) and Cu(II) in atmosphere

**Adsorption isotherms of Ni(II), Co(II) and Cu(II),
$I = 0.1$ mol/L NaCl**

Parameters estimated by Langmuir equation

<table>
<thead>
<tr>
<th>Element</th>
<th>pH</th>
<th>$10^4 S_{max}$/ (mol/g)</th>
<th>$K_L$/(L/mol)</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni</td>
<td>7.6</td>
<td>1.61</td>
<td>1238.5</td>
<td>0.980</td>
</tr>
<tr>
<td>Cu</td>
<td>6.3</td>
<td>4.19</td>
<td>69504.4</td>
<td>0.878</td>
</tr>
<tr>
<td>Co</td>
<td>6.7</td>
<td>1.23</td>
<td>276.1</td>
<td>0.985</td>
</tr>
</tbody>
</table>
3. Co(II) and Ni(II) adsorption on BS03 granite

3.2 Linear Free Energy Relationship

<table>
<thead>
<tr>
<th>Surface species</th>
<th>$\log K_{x-1}$</th>
<th>Aqueous species</th>
<th>$\log \text{OH}K_x$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$≡\text{SO}\text{Ni}^{2+}$</td>
<td>-7.6&lt;sup&gt;MC&lt;/sup&gt;</td>
<td>NiOH&lt;sup&gt;+&lt;/sup&gt;</td>
<td>-9.86</td>
</tr>
<tr>
<td>$≡\text{SO}\text{NiOH}$</td>
<td>-16&lt;sup&gt;MC&lt;/sup&gt;</td>
<td>Ni(OH)&lt;sub&gt;2&lt;/sub&gt;</td>
<td>-18.99</td>
</tr>
<tr>
<td>$≡\text{SO}\text{Co}^{2+}$</td>
<td>-7.4&lt;sup&gt;MC&lt;/sup&gt;</td>
<td>CoOH&lt;sup&gt;+&lt;/sup&gt;</td>
<td>-9.23</td>
</tr>
<tr>
<td>$≡\text{SO}\text{CoOH}$</td>
<td>-15.5&lt;sup&gt;MC&lt;/sup&gt;</td>
<td>Co(OH)&lt;sub&gt;2&lt;/sub&gt;</td>
<td>-18.6</td>
</tr>
<tr>
<td>$≡\text{SO}\text{Pb}^{2+}$</td>
<td>-5.77&lt;sup&gt;L&lt;/sup&gt;</td>
<td>PbOH&lt;sup&gt;+&lt;/sup&gt;</td>
<td>-7.60</td>
</tr>
<tr>
<td>$≡\text{SO}\text{PbOH}$</td>
<td>-14.23&lt;sup&gt;L&lt;/sup&gt;</td>
<td>Pb(OH)&lt;sub&gt;2&lt;/sub&gt;</td>
<td>-17.09</td>
</tr>
<tr>
<td>$≡\text{SO}\text{Cu}^{2+}$</td>
<td>-5.68&lt;sup&gt;L&lt;/sup&gt;</td>
<td>CuOH&lt;sup&gt;+&lt;/sup&gt;</td>
<td>-7.50</td>
</tr>
<tr>
<td>$≡\text{SO}\text{CuOH}$</td>
<td>-13.43&lt;sup&gt;L&lt;/sup&gt;</td>
<td>Cu(OH)&lt;sub&gt;2&lt;/sub&gt;</td>
<td>-16.19</td>
</tr>
<tr>
<td>$≡\text{SO}\text{Sr}^{2+}$</td>
<td>-10.74&lt;sup&gt;L&lt;/sup&gt;</td>
<td>SrOH&lt;sup&gt;+&lt;/sup&gt;</td>
<td>-24.5</td>
</tr>
<tr>
<td>$≡\text{SO}\text{SrOH}$</td>
<td>-20.82&lt;sup&gt;L&lt;/sup&gt;</td>
<td>Sr(OH)&lt;sub&gt;2&lt;/sub&gt;</td>
<td>-13.17</td>
</tr>
</tbody>
</table>

$$\log K_{x-1} = 0.8909 \log \text{OH}K_x + 0.9992 \quad (R^2 = 0.999)$$

$K_{x-1}$: surface reaction constant

$\text{OH}K_x$: aqueous hydrolysis stability constant
3. Co(II) and Ni(II) adsorption on BS03 granite

3.3 Predictions for the literature data

A: Co(II) adsorption on Bulguksa granite (Korea)
B: Sr(II) adsorption on Bulguksa granite (Korea)
C: Cu(II) adsorption on BS03 granite (China)

4. U(VI) adsorption on BS10-2 granite

4.1 U(VI) adsorption at ambient/elevated temperature

\[ C_{\text{U(VI)}} = 5.21 \times 10^{-5} \text{ mol/L}, \frac{m}{V} = 10 \text{ g/L}, T = 25 \pm 2 \, ^\circ\text{C} \]

U(VI) adsorption on granite is endothermic

Isotherms

\[ q \text{ (mmol/g)} = k \times C_{\text{eq}} \]

\[ q \text{ (mmol/g)} = k' \times \frac{1}{C_{\text{eq}}} \]

\[ k = 2.4 \times 10^{-6} \text{ L/mol} \]

\[ k' = 2.8 \times 10^{-6} \text{ L/mol} \]

\[ C_{\text{eq}} \text{ (mol/L)} = 5.85 \times 10^{-7} \text{ mol/m}^2 \]

(2.8 \times 10^{-6} \text{ mol/g})
4. U(VI) adsorption on BS10-2 granite

4.2 XPS analysis: to constrain parameters

Only three surface reactions are necessary:

\[ \text{SOH} + \text{UO}_2^{2+} \rightleftharpoons \text{SOUO}_2^+ + \text{H}^+ \]

\[ \text{SOH} + 2\text{UO}_2^{2+} + 2\text{H}_2\text{O} \rightleftharpoons \text{SO(UO}_2)_2(\text{OH})_2^+ + 3\text{H}^+ \]

\[ \text{SOH} + 3\text{UO}_2^{2+} + 5\text{H}_2\text{O} \rightleftharpoons \text{SO(UO}_2)_3(\text{OH})_5 + 6\text{H}^+ \]

\[ \log K \]

\[ -0.1 \]

\[ -5.4 \]

\[ -16.5 \]

C_{\text{U(VI)}} = 5.21 \times 10^{-5} \text{ mol/L, } I = 0.01 \text{ mol/L NaCl}

(A) \( T = 25 ^\circ \text{C} \); (B) \( T = 40 ^\circ \text{C} \); (C) \( T = 60 ^\circ \text{C} \)

XPS spectra of U 4f\text{7/2} on U(VI)-granite samples. (A) pH = 4.5; (B) pH = 5.2; (C) pH = 6.3.
4. U(VI) adsorption on BS10-2 granite

4.3 The enthalpy changes ($\Delta H$) of the surface reactions

Surface reactions and corresponding equilibrium constants

<table>
<thead>
<tr>
<th>U(VI) surface complexation reactions</th>
<th>log$K$</th>
<th>$\Delta H$ (KJ/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{SOH} + UO_2^{2+} \rightleftharpoons \text{SOUO}_2^+ + H^+$</td>
<td>$25 \pm 2 ^\circ C$</td>
<td>$40 \pm 2 ^\circ C$</td>
</tr>
<tr>
<td>$-0.1$</td>
<td>$0.2$</td>
<td>$0.5$</td>
</tr>
<tr>
<td>$\text{SOH} + 2UO_2^{2+} + 2H_2O \rightleftharpoons \text{SO(UO}_2)_2(OH)_2 + 3H^+$</td>
<td>$25 \pm 2 ^\circ C$</td>
<td>$40 \pm 2 ^\circ C$</td>
</tr>
<tr>
<td>$-5.4$</td>
<td>$-4.5$</td>
<td>$-3.4$</td>
</tr>
<tr>
<td>$\text{SOH} + 3UO_2^{2+} + 5H_2O \rightleftharpoons \text{SO(UO}_2)_3(OH)_3 + 6H^+$</td>
<td>$25 \pm 2 ^\circ C$</td>
<td>$40 \pm 2 ^\circ C$</td>
</tr>
<tr>
<td>$-16.5$</td>
<td>$-15.4$</td>
<td>$-13.8$</td>
</tr>
</tbody>
</table>

Van’t Hoff equation:

$$\log K = \frac{-\Delta H}{2.303RT} + \frac{\Delta S}{2.303R}$$

$C_{U(VI)} = 5.21 \times 10^{-5}$ mol/L, $m/V = 10$ g/L, $I = 0.01$ mol/L NaCl
4. U(VI) adsorption on BS10-2 granite

4.4 Predictions for the literature data

ambient temperature:
A: Gyeonggi-do granite (Korea)
B: BS03 granite (China)
C: Eibenstock granite (Germany)
D: Gray granite (Spain)

elevated temperature:
A: Gyeonggi-do granite granite (Korea)
B: BS03 granite (China)

5. Se(IV) adsorption on BS 03, 04 and 10-1 granite

5.1 Se(IV) on BS03 granite

\[
\begin{align*}
I &= 0.1 \text{ mol/L NaCl.} \\
[\text{Se(IV)}] &= 1.46 \times 10^{-5} \text{ mol/L.}
\end{align*}
\]

\[
\begin{align*}
\equiv\text{SOH} + \text{HSeO}_3^- &\rightleftharpoons \equiv\text{SSeO}_3^- + \text{H}_2\text{O} \quad \log K = 4.3 \\
\equiv\text{SOH} + \text{HSeO}_3^- &\rightleftharpoons \equiv\text{SHSeO}_3 + \text{OH}^- \quad \log K = -6.3
\end{align*}
\]

5. Se(IV) adsorption on BS 03, 04 and 10-1 granite

5.2 Comparison of Se(IV) adsorption in the absence/presence of Eu(III)

(a) Se(IV) adsorption envelop in the absence and presence of Eu(III)
(b) Eu(III) adsorption edge in the absence and presence of Se(IV)

Se(IV) adsorption and Eu(III) adsorption do not affect each other

\[ \equiv \text{SOH (mol/m}^2\text{)} : \]

\[ \text{Se(IV)} \ 2.17 \times 10^{-7} \ << \text{Eu(III)} \ 7.35 \times 10^{-6} \]

Adsorption sites for Eu(III) and Se(IV) may be different
5. Se(IV) adsorption on BS 03, 04 and 10-1 granite

5.3 Comparison of adsorption on BS04 and 10-1 granite

![Graph showing adsorption vs pH]

\[ K_d (\text{mL/m}^2) \]

\[ C_{\text{Se(IV)}} = 5.18 \times 10^{-6} \text{ mol/L}, \quad m/V = 20.0 \text{ g/L}, \]
\[ I = 0.1 \text{ mol/L NaCl}, \quad T = 25 \pm 2 \text{ °C} \]

XRF analysis

<table>
<thead>
<tr>
<th>Sample</th>
<th>Fe_2O_3</th>
<th>Na_2O</th>
<th>MgO</th>
<th>Al_2O_3</th>
<th>SiO_2</th>
<th>P_2O_5</th>
<th>K_2O</th>
<th>CaO</th>
<th>TiO_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS 10-1</td>
<td>0.96</td>
<td>8.87</td>
<td>0.76</td>
<td>16.83</td>
<td>67.90</td>
<td>0.04</td>
<td>3.68</td>
<td>0.61</td>
<td>0.13</td>
</tr>
<tr>
<td>BS 04</td>
<td>1.87</td>
<td>5.95</td>
<td>1.38</td>
<td>16.99</td>
<td>69.10</td>
<td>0.13</td>
<td>3.78</td>
<td>0.19</td>
<td>0.27</td>
</tr>
</tbody>
</table>

N\textsubscript{2} BET specific surface area

BS10-1: 3.2 m\textsuperscript{2}/g
BS04: 12.8 m\textsuperscript{2}/g
1. Introduction

2. Eu(III) and Am(III) adsorption on BS03 granite

3. Co(II) and Ni(II) adsorption on BS03 granite

4. U(VI) adsorption on BS10-2 granite

5. Se(IV) adsorption on BS03, 04 and 10-1 granite

6. Conclusions
6. Conclusions

1. Different site capacities have to be considered for different elements.
2. The model for Eu(III) could be extended to describe Am(III) adsorption.
3. The model for U(VI) could describe the literature data of granite from different regions.

In general, GC approach is a promising methodology for quantitatively describing radionuclides adsorption on Beishan granite.
Acknowledgement

• 国家自然科学基金委员会
  National Natural Science Foundation of China (NSFC)

• 国家国防科技工业局
  State Administration of Science, Technology and Industry for National Defence, PRC
Adsorption of some radionuclides on Beishan granite: Experimental and modeling

Thank you for your kind attention

Questions?

Zongyuan CHEN
Application of seismic and electro-magnetic reflection methods for underground investigation in a salt mine

Patrick Musmann & Volker Gundelach

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Email: Patrick.Musmann@bgr.de

Topic: Site selection/site investigation methods and technologies (geophysical)

Keywords: seismic, shear-wave, EMR, salt

Abstract: For many years, various geophysical methods have routinely been used for the exploration of salt structures in the subsurface. At the surface, the reflection seismic method is the preferred method to reveal structural information of the subsurface. Borehole measurements link surface information to downhole structures. However, exploration from the surface is often not sufficient to determine the internal structure of a salt body, so that further exploration from within the mine is necessary. In addition to the information received from boreholes, especially the electro-magnetic reflection (EMR) method is the method of choice to image the internal structure of a saliniferous formation at high resolution. In any case, the presence of highly conductive structures, e.g., moisture and clay-containing structures, can severely limit the penetration depth of the EMR method. Seismic methods are usually able to “look” behind such structures. In addition, the combination of several geophysical parameters gains additional value and results in more reliable interpretations. Yet, subsurface seismic measurements are not standard in exploration and suffer from innate problems. In particular, the full space and the limitation of profiles to open drifts cause special challenges for the underground seismic method.

In order to evaluate the possibilities and limitations of conventional reflection seismic measurements and data processing to underground application, we acquired and processed a conventional compressional- and shear-wave reflection seismic 2d-profile in a drift of a salt mine. EMR measurements with high-performance shielded antennas were also carried out along the same profile. The results of both measurements on the one hand show a good agreement in the reflection pattern of the internal structure of the salt body in full space around the profile, on the other hand, clear differences in resolving power and directional sensitivity exist.
Application of seismic and electro-magnetic reflection methods for underground investigation in a salt mine

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

► Motivation & Survey site

► Material & Methods
  ► Electro-magnetic reflection measurements
  ► Seismic reflection measurements

► Results & Comparison

► Conclusions & Outlook
Motivation

► Context: Underground geophysical/ structural exploration in salt mines

► Electro-Magnetic Reflection (EMR/ Geo-Radar/ GPR): Routinely used to image the internal structure of saliniferous formations at high resolution

► Reflection seismic: Standard method of petroleum industry to reveal structural information of the subsurface – application usually at the surface

► Objectives of our seismic test-measurements:
  ► Can seismic reflection method complement EMR method?
  ► Comparison of seismic and EMR structural images
  ► Evaluate possibilities and limitations of conventional reflection seismic measurements and data processing to underground application
Survey site: salt mine @ approx. 350 m below surface

Location of survey site in Germany.
Overview

- Motivation & Survey site

- Material & Methods
  - Electro-magnetic reflection measurements
  - Seismic reflection measurements

- Results & Comparison

- Conclusions & Outlook
EMR measurements

Acquisition
► Antenna: 70 MHz (shielded)
► Record length: 6 \( \mu \text{s} \)
► Sampling interval: 1 ns
► Station interval: 0.75 m

Processing
(1) Time-zero correction
(2) Amplitude normalization
  (2.1) Spherical divergence correction
  (2.2) Attenuation correction
(3) Bandpass filter
(4) Reflector picking and reflector migration
EMR measurements: Reflector picking

Section at roof of gallery:
- Reflection profile

Cross-sections through gallery:
- Approx. azimuths of reflection events

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EMR measurements: Results

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Overview

- Motivation & Survey site

- Material & Methods
  - Electro-magnetic reflection measurements
  - Seismic reflection measurements

- Results & Comparison

- Conclusions & Outlook
Seismic measurements

Acquisition

- Sources: Small P- & SH-wave vibrator ‘ELVIS III’
  - Sweep: 20 – 160 Hz, 10 s, linear, 2x
- Receivers:
  - SM-4 vertical (P-wave) geophone, 10 Hz
  - SM-6/9 horizontal (SH-wave) geophones, 10 Hz
- Source/Receiver spacing: 3 m (on the floor)
- Recording: Geometrics/Geode, 72 channels
- Profile length: ≈ 315 m (P-wave) & ≈ 265 m (SH-wave)

CMP-Processing

1. Elevation statics
2. Top mute
3. Automatic gain control (200 ms)
4. Spectral whitening
5. Bandpass filter
6. Constant velocity stack ($v_s \approx 2600$ m/s)
7. Dip scan stack (to enhance coherent seismic events)
8. Reflector picking
Seismic measurements: Stacked sections

**Vertical (P-wave) profile:**
- Imaging by SV-waves !
- Imaging sideward up and down

**Horizontal (SH-wave) profile:**
- Imaging by SH-waves
- Imaging vertically up and down
Overview

► Motivation & Survey site

► Material & Methods
  ► Electro-magnetic reflection measurements
  ► Seismic reflection measurements

► Results & Comparison

► Conclusions & Outlook
## Results & Comparison

### Horizontal (SH-wave) seismic profile & EMR section at roof

<table>
<thead>
<tr>
<th>Distance [m]</th>
<th>0</th>
<th>25.3</th>
<th>55</th>
<th>84.8</th>
<th>114.5</th>
<th>144.2</th>
<th>174</th>
<th>203.7</th>
<th>233.5</th>
<th>263.2</th>
<th>293</th>
<th>315.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMP</td>
<td>3</td>
<td>20</td>
<td>40</td>
<td>60</td>
<td>80</td>
<td>100</td>
<td>120</td>
<td>140</td>
<td>160</td>
<td>180</td>
<td>200</td>
<td>215</td>
</tr>
</tbody>
</table>

**Graphical Data**

- **Distance [m]**: 0, 25.3, 55, 84.8, 114.5, 144.2, 174, 203.7, 233.5, 263.2, 293, 315.3
- **Depth [m]**: 0, 50, 100, 150, 200, 250, 300, 350, 400
- **Time [ms]**: 0.0, 806.5, 1612.9, 2419.4, 3225.8, 4032.3

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**Note:** The graph shows seismic profile data with distances and depths, along with time measurements in milliseconds. The data is used for comparison and analysis in the field of geosciences.
Results & Comparison

Horizontal (SH-wave) seismic profile & EMR section at roof

**Estimated resolution**

<table>
<thead>
<tr>
<th></th>
<th>seismic</th>
<th>radar</th>
</tr>
</thead>
<tbody>
<tr>
<td>dominant frequency</td>
<td>( \approx 90 \text{ Hz} )</td>
<td>( \approx 50 \text{ MHz} )</td>
</tr>
<tr>
<td>average velocity</td>
<td>2.6 km/s</td>
<td>124 m/( \mu \text{s} )</td>
</tr>
<tr>
<td>exemplary depth</td>
<td>100 m</td>
<td>100 m</td>
</tr>
<tr>
<td>half wave length</td>
<td>( \approx 14 \text{ m} )</td>
<td>( \approx 1.2 \text{ m} )</td>
</tr>
<tr>
<td>radius 1st Fresnel zone</td>
<td>( \approx 38 \text{ m} )</td>
<td>( \approx 11.1 \text{ m} )</td>
</tr>
</tbody>
</table>
Overview

► Motivation & Survey site

► Material & Methods
  ► Electro-magnetic reflection measurements
  ► Seismic reflection measurements

► Results & Comparison

► Conclusions & Outlook

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Conclusions & Outlook

► Conclusions
  ► Both seismic and EMR image the structures within saliniferous formation
  ► Both methods image different physical properties
  ► Each method has different pros and cons, e.g., technical & processing effort, resolution, sensitivity, penetration depth
  ► Seismic reflection method can complement EMR method, depending on the size (and strike) of structure

► Outlook (seismic only!)
  ► Increase resolution, i.e., higher frequency source/receivers
  ► Limit directivity of reflection events, e.g., use 3-component geophones
  ► Migration of data (more closely represents a geological cross-section)
Thank You for Your Attention

Danke für Ihre Aufmerksamkeit
The latest progress of radio-nuclides migration research at CIAE (2012-2017)

Duo Zhou, Hao-qi Long, Tao Jiang, Bo Wang, Liang-jin Bao, Xi Chen

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Email: zd-ciae@163.com

Abstract: The core task for deep geological disposal research of high level radioactive waste is to retard migration of radionuclides as much as possible with the help of multi-barrier system. Long term safety research for nuclear waste disposal at CIAE deals mainly with geochemical contribution to the safety case, involving aquatic chemistry of radionuclides in the geochemical environment of a repository. The recent work on radionuclides (RNs) migration at CIAE focused on solubility experiment of neptunium and plutonium in Beishan groundwater, sorption experiment of neptunium in GMZ bentonite, dispersion experiment of Tc in Beishan granite and research of colloidal behavior for americium in Beishan groundwater.

Oversaturation experiment was performed to determine solubilities of neptunium and plutonium in Beishan groundwater with batch method. The effects of different temperatures on the adsorption behavior of neptunium in Beishan groundwater on bentonite was studied with batch method, the results show that: adsorption Kd value of neptunium on bentonite increases with increasing temperature, indicating that the adsorption of neptunium on bentonite is an endothermic reaction. Dispersion coefficients of 99Tc in Beishan granite were measured under different temperature and different pressure with the method of pulse source and the dispersity of Beishan granite was calculated. Colloidal behavior research of americium was performed, efforts are focused on influences of pH and ionic strength on americium colloid in Beishan groundwater.

Based on this progress and development, next work plan is put forward.

Keywords: solubility; adsorption; dispersion coefficient; colloidal behavior
The latest Progress of Radionuclide Migration Research at CIAE(2012-2017)

Zhou Duo, Long Haoqi, Jiang Tao
Outline

- The current studies on radionuclides (RNs) migration at CIAE
- Results and discussions
  - Solubility of Np and Pu in Beishan groundwater
  - Sorption of Np on bentonite
  - Dispersion of Tc in Beishan granite
  - Colloidal behavior of Am
- Next plan
Introduction

Concept of Nuclide Release Pathway

The core task for deep geological disposal of HLW is to retard the migration of radio-nuclides as much as possible with the help of multi-barrier system.
Introduction

The Current Studies on RNs Migration at CIAE

- Solubility experiment of Np and Pu in Beishan groundwater with oversaturation method
- Sorption experiment of Np for GMZ bentonite with batch method to obtain partition coefficients (Kd)
- Dispersion experiment of Tc in granite
- Research of colloidal behavior for Am
### Results and Discussions

#### Solubility of Tetra-valent Neptunium

##### Solubility Calculated with Phreeqc

<table>
<thead>
<tr>
<th>controlling steady-state solid</th>
<th>Calculated result in deionized water (mol/L)</th>
<th>Calculated result in Beishan groundwater (mol/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Np(OH)$_4$ (am)</td>
<td>$1.48 \times 10^{-9}$</td>
<td>$2.83 \times 10^{-9}$</td>
</tr>
<tr>
<td>NpO$_2$ (cr)</td>
<td>$3.38 \times 10^{-18}$</td>
<td>$3.38 \times 10^{-18}$</td>
</tr>
</tbody>
</table>

Calculated results with phreeqc show that:

Concentration of Np(OH)$_4$ (aq) and Np(CO$_3$)$_2$(OH)$_2$$_2$ in Beishan groundwater are $1.48 \times 10^{-9}$ mol/L and $1.35 \times 10^{-9}$ mol/L respectively, which are in the same order of magnitude.

Experimental results show that:

Solubilities of Np(IV) in deionized water and Beishan groundwater are $(4.59 \pm 0.53) \times 10^{-9}$ mol/L and $(1.12 \pm 0.16) \times 10^{-8}$ mol/L respectively, which are six orders of magnitude more than concentration of other complex of Np(IV) calculated with phreeqc.
When pH ranges from 1 to 6, solubility decreases with increasing pH.

When pH ranges from 6 to 12, there is no change for solubility.

When pH is between 6 and 12, Np(OH)$_4$ (aq) becomes the main speciation in deionized water, the solubility of the Np(IV) does not change along with the change of pH.

Figure 1 Phreeqc simulation results compared with the experimental results

■ calculated solubility of Np (IV) in deionized water with Phreeqc

▲ Experimental solubility of Np (IV) in deionized water
Results and Discussions

Analysis of Controlling Steady-state Solid for Solubility of Plutonium

- Solubilities of Pu in Beishan groundwater were calculated with PHREEQC respectively for PuO$_2$ (cr) and Pu(OH)$_4$(am) as controlling solid phases.

- Experimental solubility of Pu is more closer to calculated solubilities of Pu(OH)$_4$(am) than that of PuO$_2$(cr).

Figure 2 experimental results are compared with calculated results.
Results and Discussions

**Effect of pH on Solubility of Plutonium**

<table>
<thead>
<tr>
<th>pH</th>
<th>The experimental results (mol/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5</td>
<td>((8.35 \pm 0.72) \times 10^{-10})</td>
</tr>
<tr>
<td>6.3</td>
<td>((9.63 \pm 0.91) \times 10^{-10})</td>
</tr>
<tr>
<td>7.1</td>
<td>((1.28 \pm 0.17) \times 10^{-9})</td>
</tr>
<tr>
<td>8.3</td>
<td>((1.57 \pm 0.14) \times 10^{-9})</td>
</tr>
<tr>
<td>9.2</td>
<td>((1.45 \pm 0.12) \times 10^{-9})</td>
</tr>
<tr>
<td>10.0</td>
<td>((1.87 \pm 0.12) \times 10^{-9})</td>
</tr>
</tbody>
</table>

Solubility of Pu has no obvious change when pH ranges from 5.5 to 10.

Figure 3  effects of pH on plutonium solubility
Results and Discussions

Effects of pH and Ionic Strength on Adsorption of Np on Bentonite

- When pH ranges from 1 to 5, there is little impact on adsorption.
- When pH ranges from 5 to 9, the percentage of adsorbed Np on bentonite increases with increasing pH.
- When pH ranges from 9 to 10, the percentage of adsorbed Np on bentonite decreases with increasing pH.

- There is little effect on adsorption when ionic strength ranges from 0.1 to 1 M.
- Electrostatic adsorption is the main mechanism when pH ranges from 1 to 7.
- Surface complex is the main mechanism when pH ranges from 7 to 9.

Figure 4 Effects of pH and ionic strength on adsorption of Np in bentonite
Results and Discussions

Influence of Temperature on Adsorption Behavior of Np on Bentonite

- Kd increases with rising temperature.
- Several important thermodynamic data can be calculated through the relationship between temperature and Kd.
- The results show that the Gibbs free energy ($\Delta G$) of adsorption reaction of Np(V) on bentonite is less than zero, which indicates that the reaction can occur spontaneously.

### Table 1: Thermodynamic Data at Different Temperatures

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>$\Delta H$ (KJ·mol$^{-1}$)</th>
<th>$\Delta S$ (J·mol$^{-1}$·K$^{-1}$)</th>
<th>$\Delta G$ (KJ·mol$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>19.30</td>
<td>91.45</td>
<td>$-8.66$</td>
</tr>
<tr>
<td>45</td>
<td>19.30</td>
<td>91.45</td>
<td>$-9.59$</td>
</tr>
<tr>
<td>60</td>
<td>19.30</td>
<td>91.45</td>
<td>$-10.18$</td>
</tr>
<tr>
<td>80</td>
<td>19.30</td>
<td>91.45</td>
<td>$-11.48$</td>
</tr>
</tbody>
</table>

Figure 5 the influence of temperature on the adsorption behavior
Results and Discussions

Effect of Additives on Adsorption of Penta-valent Neptunium on Bentonite

- Order of additives from the strong adsorption to the weak adsorption: FeO > Fe$_2$O$_3$ > Fe$_3$O$_4$ > FeS$_2$ > stibnite.
- Adding 3% of FeO can make the adsorption percentage of Np increase from 44% to more than 90%.
- It's obvious that very small amounts of FeO can greatly improve adsorption ability of bentonite for Np(V).

Figure 6 effect of the additives on adsorption of Np on bentonite
Results and Discussions

Migration Distance of Penta-valent Neptunium in Bentonite

Migration distance can be calculated based on the Kd value (30 ml/g) and the diffusion coefficient ($8.2 \times 10^{-12}$ m$^2$/s) of Np(V) in bentonite.

Simulation result shows that the migration distance of Np(V) is no longer than 0.2 meters after 300,000 years, which would ensure safety of disposal repository.
Results and Discussions

Dispersion Experiments of Technetium and Tritium in Granite

Figure 8 granite dispersion device

Figure 10 dispersion outflow curve of technetium and tritium in 3 # granite column under the condition of 6.9 MPa / 45 ℃

Figure 9 Dispersion outflow curve of technetium and tritium in 2 # granite column under the condition of 4.9 MPa/80 ℃

Figure 11 dispersion outflow curve of technetium and tritium in 3 # granite column under the condition of 6.9 MPa / 80 ℃
### Results and Discussions

**Dispersion Coefficients of Technetium and Tritium in Granite**

<table>
<thead>
<tr>
<th>S (cm²)</th>
<th>L (cm)</th>
<th>T°C</th>
<th>P (MPa)</th>
<th>V (cm/s)</th>
<th>D (cm²/s)</th>
<th>α (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1#</td>
<td>4.682</td>
<td>4.898</td>
<td>80</td>
<td>3.0</td>
<td>2.6 × 10⁻⁴</td>
<td>1.1 × 10⁻⁴</td>
</tr>
<tr>
<td>2#</td>
<td>4.675</td>
<td>4.850</td>
<td>80</td>
<td>4.9</td>
<td>6.0 × 10⁻⁴</td>
<td>2.9 × 10⁻⁴</td>
</tr>
<tr>
<td>2#</td>
<td>4.675</td>
<td>4.850</td>
<td>80</td>
<td>6.9</td>
<td>6.2 × 10⁻⁴</td>
<td>3.2 × 10⁻⁴</td>
</tr>
<tr>
<td>3#</td>
<td>4.678</td>
<td>4.477</td>
<td>25</td>
<td>6.9</td>
<td>1.2 × 10⁻³</td>
<td>5.7 × 10⁻⁴</td>
</tr>
<tr>
<td>3#</td>
<td>4.678</td>
<td>4.477</td>
<td>45</td>
<td>6.9</td>
<td>1.4 × 10⁻³</td>
<td>6.4 × 10⁻⁴</td>
</tr>
<tr>
<td>3#</td>
<td>4.678</td>
<td>4.477</td>
<td>80</td>
<td>6.9</td>
<td>1.6 × 10⁻³</td>
<td>7.4 × 10⁻⁴</td>
</tr>
</tbody>
</table>

Dispersion coefficients increase with increasing temperature and velocity of groundwater flow, while dispersity is relatively stable.
Results and Discussions

Research of Colloidal Behavior for Am

Geometric radius of colloid and number of particles per milliliter can be measured with AF4-MALLS-rEX.

Hydrodynamic radius and Zeta potential of colloid can be measured with Particle Size and Zeta Potential Particle Analyzer.
Results and Discussions

Behavior of Bentonite Colloid in Beishan Groundwater

Results Fitting

<table>
<thead>
<tr>
<th>geometric radius Rn (nm)</th>
<th>Peak 1</th>
<th>Peak 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>66.5 (±29.5%)</td>
<td>66.4 (±12.5%)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>geometric radius R_{avg} (nm)</th>
<th>Peak 1</th>
<th>Peak 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>73.1 (±3.2%)</td>
<td>79.6 (±0.5%)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number of particles/mL</th>
<th>Peak 1</th>
<th>Peak 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.46 × 10^6 (±16.28%)</td>
<td>6.14 × 10^6 (±4.54%)</td>
<td></td>
</tr>
</tbody>
</table>
Results and Discussions

Influence of pH on Colloidal Behavior of Americium-bentonite in Beishan Groundwater

- Zeta potential and hydrodynamic radius decrease with increasing pH. There is no obvious change for geometry radius.

- Adsorption ratio of Am decreases with increasing pH, while number of particles per milliliter increases with increasing pH.
Results and Discussions

Influence of Ionic Strength on Colloidal Behavior of Americium-bentonite in Beishan Groundwater

- Zeta potential and hydrodynamic radius increase with increasing ionic strength, geometry radius increases weakly with increasing ionic strength.
- Adsorption ratio of Am increases with increasing ionic strength while number of particles per milliliter decreases with increasing ionic strength.
Behavior of Potash Feldspar Colloid in Beishan Groundwater

<table>
<thead>
<tr>
<th></th>
<th>Peak 1</th>
<th>Peak 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry radius $R_n$ (nm)</td>
<td>$53.8 \pm 1.5%$</td>
<td>$42.8 \pm 1.4%$</td>
</tr>
<tr>
<td>Geometry radius $R_{avg}$ (nm)</td>
<td>$52.8 \pm 0.2%$</td>
<td>$55.9 \pm 0.0%$</td>
</tr>
<tr>
<td>Number of particles/mL</td>
<td>$4.60 \times 10^8 \pm 1.33%$</td>
<td>$1.40 \times 10^{10} \pm 0.61%$</td>
</tr>
</tbody>
</table>
Zeta potential and hydrodynamic radius decrease with increasing pH. There is no obvious change for geometry radius of potash feldspar colloid.

Adsorption ratio of Am on potash feldspar colloid decreases with increasing pH while number of particles per milliliter decreases weakly with increasing pH.
Results and Discussions

Influence of Ionic Strength on Colloidal Behavior of Americium-Potash Feldspar in Beishan Groundwater

- Zeta potential, geometry radius and hydrodynamic radius increase with increasing ionic strength.

- Adsorption ratio of Am on potash feldspar and number of particles per milliliter decrease strongly with increasing ionic strength.
Next work plan

- Redox reaction of Uranium, Neptunium, Technetium, Selenium on surface of iron
- Effect of bentonite colloid on migration of nuclides in granite
- Modeling of nuclide migration in near field
- Radionuclide retention by sorption
- Through-diffusion tests of nuclides for granite and bentonite
Thanks for your attention
Abstract: As planned by the government, China will start the construction of Underground Research Laboratory (URL) for HLW disposal in recent years. In 2016, the Xinchang site located in Beishan pre-selected area of Gansu province has been selected as the final URL site, and the preliminary design of URL engineering has been proposed. The main structure of URL is designed with an access ramp and three shafts, and will be constructed by different methods. With the advantages of high construction quality, safety and environmental protection, small disturbance and damage to surrounding rock mass, TBM methodology can be the selected as one of the reference excavation methods for URL ramp. However, using TBM in URL project may face several technical issues due to the very good rock condition (UCS of 110~235MPa, and high RQD) and special layout of the ramp (big inclined gradient of 10%, and small turn radius of 400m). In this presentation, the potential technical difficulties that will be induced by the engineering geological conditions and URL layout limitations are briefly introduced. Then the technical feasibility study on the specific issues, i.e., intact rock mass, high rock strength, high abrasiveness, small curve radius, high slope inclination, difficulty of muck transportation are investigated, based on the rock cutting test, cutter wear test, and similary project comparison. The results show that it is feasible to use TBM for excavation the URL ramp. The results can also provide the reference for the design and construction of China HLW repository.
Preliminary research on Technical feasibility of using TBM in URL Engineering

Hongsu Ma, WANG Ju, MAN Ke, CHEN Liang
Beijing Research Institute of Uranium Geology
Outline

➢ Background
➢ Technical difficulties for TBM excavation
➢ Technical Feasibility Analysis
➢ Conclusions
**Background**

- **Excavation methods for URL?**
  - Drill & Blast method
  - Tunnel boring machine (TBM)

**TBM**
- High advance rate
- High construction quality
- Safety and environmental protection
- Small disturbance and damage to surrounding rock mass

- High cost
- Low flexibility
**URLs using TBM**

- **GTS, Granite**
  - Year: 1983~1984
  - Depth: 400m

- **Äspö HRL, Granite**
  - Year: 1994
  - Depth: 420~460m

Can we use the TBM method for China URL construction?
Technical Difficulties

Engineering Conditions & URL layout on TBM tunneling
## Engineering Conditions

<table>
<thead>
<tr>
<th>Geological factors for TBM tunnelling</th>
<th>Xinchang URL site</th>
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<tbody>
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<td>• Fracture /Fault zone</td>
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<td>• In-situ stress</td>
<td>Low in-situ stress (Max. 20MPa)</td>
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<td>Low permeability (fractured rock $1 \times 10^{-8}$m/s~$1 \times 10^{-6}$m/s)</td>
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- **Granodiorite**
- **Monzonitic granite**

**Intact borehole core of BS32**
## Engineering Conditions

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*Monzonitic granite* 
*Granodiorite* 
*Intact borehole core of BS32*
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</tr>
<tr>
<td>• Rock strength</td>
<td><strong>Intact rock mass with high strength</strong></td>
</tr>
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</tr>
</tbody>
</table>

**URL Site**

- Granodiorite
- Monzonitic granite

**Intact borehole cores of BS32**
URL layout

1 Access Ramp + 3 Shafts

Access Ramp
Depth: -560m
Max. Inclination: 1:10
Tunnel Diameter: 7m
Curve Diameter: 400m
Ramp length: 7970m
Technical difficulties of Ramp construction by TBM

Max. Inclination 1:10
Feasibility for TBM operation?
Efficiency of water drainage?

Curve Diameter 400m
Feasibility for TBM operation?
Muck transportation?

Depth -560m, length 7970m
Material transportation?
Technical Difficulties

(1) Intact rock mass with high strength
(2) High abrasiveness
(3) Small curve radius
(4) High inclination
(5) Muck transportation
(6) Water drainage
(7) Material transportation
Technical Feasibility analysis
Technical Feasibility Analysis

- Experts Consulting
- Discussion with TBM manufactures
- Jobsite investigation
- Visit of TBM factories

- Intact rock mass with high strength
- High abrasiveness
- Small curve radius
- High inclination
- Muck transportation
- Water drainage
- Material transportation
Technical Feasibility Analysis

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- Intact rock mass with high strength
- High abrasiveness
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- Water drainage
- Material transportation
Intact rock mass with high strength

Research on Rock Mass Borability & Advance Rate

- Cutting Test
- Theoretical analysis
- Similar project comparison
Rock Mass Borability—"penetration"

- Excavation distance of TBM per boring unit time.
- A parameter indicating the interaction between rock mass and TBM.
- Indicates whether the selection of TBM in a project is suitable or not.

**Influencing factors**
- Rock property (UCS)
- Cutter spacing
- Cutter dimension (size, tip width)
- Thrust-cutter force
Rock Mass Borability—cutting test

- Mechanical rock breakage experimental platform
  Beijing University of Technology
Rock Mass Borability—cutting test

- BS32
  - UCS=200MPa
- BS33
  - UCS=170MPa
Rock Mass Borability—cutting test

- UCS: 170MPa, 200MPa
- 19 inch cutter
- Cutter tip width (CTW): 8mm, 16mm

The penetration can be up to 4mm when using 19 inch cutter with tip width of 16mm.

Cutter dimension has significant influence on the penetration.
Herrenknecht, Continuous Disc Cutter-Test Rig

- 19 inch cutter, Cutter tip width: 13, 16, 19 mm
Specific rock mass boreability index \( BI(1) = 37.06 \cdot UCS^{0.26} \cdot Bi^{-0.10} \cdot (0.84e^{-0.05Jv} + e^{-0.09} \cdot \sin(\alpha+30^\circ)) \)

Relationship of required cutter force and Depth for different penetrations

Max. bearing capacity of 19 inch cutter

- Penetration of 4mm
Norway Ulriken tunnel constructed by TBM

- Tunnel diameter 9.30m
- 19” inch cutter, tip width 16mm
- Cutter spacing 75mm
- Intact rock mass with UCS=180~200MPa
- Penetration: 2.5mm with limited operation
Prediction of TBM advance rate for Xinchang URL

- Max penetration 4mm, average penetration 2mm
- UCS=175MPa
- 19 inch cutter, tip width 16mm
- Cutter spacing 75~80mm
- 6 rotations/minutes, 14 hours/day, 25 day/month

$$\text{Advance rate} = \frac{2 \times 6 \times 60 \times 14 \times 25}{1000} = 252 \text{m/month}$$

✓ TBM (252m/month) VS Drill & blast (150m/month)
Technical Feasibility Analysis

✓ Intact rock mass with high strength
✓ High abrasiveness: optimum design of cutter, wear protection
✓ Small curve radius: possible for TBM operation
✓ High inclination: possible for TBM operation
✓ Muck transportation: special design for muck conveyor belt
✓ Water drainage: multistage pump system
✓ Material transportation: rubber-tyred vehicle
The potential technical difficulties for using TBM in URL engineering are introduced. “Intact rock mass with high strength” is regarded as the most challenging difficulty for this project.

Research on rock mass borability for TBM method by cutting test, theoretical analysis, and similar project comparison has been carried out. The results show that a good advance rate can be obtained for TBM excavation method.

Technical feasibility analysis show it is suitable to use TBM for excavation the URL ramp.
Thanks for attention!
Advance in safety assessment of geological disposal of HLW in China at sitting stage

Honghui Li
China Institute for Radiation Protection, Taiyuan, Shanxi, China
Email: yz202lhh@163.com

Abstract: In China “The Law on Prevention and Control for Radioactive Pollution” issued in 2003 determined that the high-level waste will be disposed in a deep central geological repository. The main work of China Institute for Radiation Protection (CNNC-mandated comprehensive research) about HLW disposal is Safety Assessment. In 2006-2010 the CIRP have done some work about Safety criteria and safety requirements: Public Radiation protection for post-closure of repository: 0.3mSv/a, Time scale: 10,000a. The CIRP also have established SA methodology and routine. Some software about safety assessment such as: AMBER, Ecolegy, Goldsim, Proflow etc can be familiarly used. The main works in 2014-2017 about safety assessment that have been done are the research of safety requirements of the EBS and host rock, the research of safety function of the EBS and host rock, establishing the safety indicators system of the EBS and host rock, establishing the FEPs list and the scenario analysis in the Conceptual and planning stage, the near field temperature simulation based on conceptual design of the Repository, the safety assessment of Beishan Preliminary Repository. Some of the above works details will be introduced in the introducing ppt. The scenario development is the key step in HLW geological disposal. The features, events and processes (FEPs) should be first considered. The FEPs can be sorted and grouped to form scenario. It is very useful and have reference valve for the developing the FEPs of HLW geological disposal in a conceptual and planning stage in China by introducing the FEPs established and sorted methods. The FEPs list have been built in 2016. Some of the works will be researched in 2017. The details of these works will be introduced in the ppt.
Advance in Safety Assessment of geological disposal of HLW in China at sitting stage

Honghui Li, Division Head

Division of Waste Disposal Technology Department of Radioactive Waste Management

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Mobile phone: 13653411859
Content table

1. Current status
2. Predication of temperature field model
3. Source term release model
4. Calculation on nuclide migration in buffer backfilling material
5. Migration of nuclides in EDZ
6. Calculation on nuclide migration in far-field
7. Sensitivity analysis
8. Capability to acquire key parameters
Progress achieved

- Preparation of *Research Report on Safety Assessment Criteria*
- Preparation of *Research Report on Safety Functions and Features of repository*
- Preparation of *Research Report on Predication of Temperature Field Model*
- Preparation of *Research Report on FEPs List*
- Preparation of the *Technical Research Report on Source Term Release Mode, the Report on Nuclide Migration in Buffer Materials, as well as the Report on Nuclide Migration Model in EDZ*
Information management system for safety assessment
Research on feature, event and process (FEPs) lists

- Investigation, generalization, analysis and summary of the FEP lists and the current status on scenario development study in NEA, IAEA, Japan, the USA, Belgium and so on
- Translation into Chinese, and compilation of, the FEP Lists of foreign countries, such as NEA, IAEA, Japan, the USA and Belgium
- Formulation of our FEPs and the principle, technique, and classification methods scenario development
- Recommendation to develop our FEPs from perspectives of disposal system and barrier
Screening method

Bottom-up approach, covering FEP list collection, repository-specific characteristics analysis:

- Compliance with national law and regulations
- Site-specific characteristics
- Scenario probability and consequence severity
- Importance of impact on disposal repository
- Judgment from experts

Top-down approach

- Breakdown of safety function based on each component of every barrier, together with time-correlation property
- Analysis of potential factors likely to influence safety function
## Screening list

<table>
<thead>
<tr>
<th>Small earthquake occurrence</th>
<th>Very likely</th>
<th>Likely</th>
<th>Less likely</th>
<th>Unlikely</th>
</tr>
</thead>
</table>

- **Very likely**
- **Likely**
- **Less likely**
- **Unlikely**

![Diagram showing screening list](image)

- **Glass Solidification**
- **Earthquake Checklist**
- **CIRP China Institute for Radiation Protection**
Scenario development

- Scenario of normal evolution, with probability of nearly 1
- Scenario of relative small probability, about greatly less than 1
  - Damage to waste canister
  - Full release of nuclides after dissolution of vitrified form
  - Human intrusion
- Postulated scenario, with probability of far less than , for analysis of the role of a single barrier played in the entire shielding system
Research on temperature field model

- Investigation completed of temperature field modes made in several other countries. Modeling established for HLW repository temperature field.
  - Followings completed by aid of Ansys platform:
    - Assessment of lab-based simulated disposal unit temperature field.
    - On HLW repository near-field temperature distribution:
      - Single waste package in a single drill hole.
      - Multiple packages in a single drill hole.
      - Single disposal tunnel and so on.
Analysis of near-field temperature simulated for geological repository

- Simplified model
- Selection of model parameters
- Model analysis
  - Pattern of temperature evolution
  - Model comparison
  - Analysis of disposal arrangement
  - Clearance analysis
  - Analysis of near-field temperature on a scale
Selection of model parameters

Contents in model

- vitrified forms
- waste containers
- Disposal container
- Buffer
- Host rock

Dimension
- thermal parameter
Schematic of disposal arrangement
Pattern of temperature evolution
Analysis of disposal arrangement

- A single package in a single drill hole
  - Tunnel interval
    - 5–20m
  - Drill hole interval
    - 5–20m
Analysis of disposal arrangement

- Multiple packages in a single drill
  - Package: 2-3
  - Interval: 2–5 m
- Tunnel interval: 5–20 m
- Drill hole interval: 5–20 m
Interval analysis

Radiogenic heat conductivity fraction in interval relative to both side material emission rate
Analysis of near-field temperature on a scale

Single tunnel, drill-hole interval 3 m
Analysis of near-field temperature on a scale

Single tunnel, drill-hole interval 5 m
Analysis of near-field temperature on a scale

Single tunnel, single drill-hole, with double packages
Analysis of near-field temperature on a scale

Multiple tunnels
Temperature field distribution 50 and 100 years after closure of repository
Study on source terms for nuclide release

- Investigation and summary of current dissolution and leaching study of vitrified HLW forms
- Analysis of dissolution and leaching process of vitrified HLW forms
- Study and analysis of nuclide migration in vitrified HLW forms
- Investigation and summary of ongoing dissolution model study of vitrified HLW forms
- Development of models for vitrified form dissolution and nuclide migration
- Calculation of source terms for key nuclides migration
Study on source terms for nuclide release

Comparison of radionuclide release rates varying with time (left T=60°C, pH=6; right T=120°C, pH=8.5)
Study on source terms for nuclide release

Comparison of radionuclide release rates varying with time (left $T=60^\circ$C, pH=6; right $T=120^\circ$C, pH=8.5)
Study on source terms for nuclide release
Calculation was made for migration of $^{135}$Cs, $^{239}$Pu, $^{237}$Np, $^{241}$Am and $^{238}$U using kinetic model under assumption of full and part release of nuclides. Results indicate that mass release rate is $10^{-10}$–$10^{-3}$ g/year.

From perspective of solubility, most nuclides has the release rate of relative low order of magnitude. Cs is completely soluble in groundwater, with rate of about $10^{-5}$–$10^{-4}$ g/year.
Nuclide migration in buffer backfilling material

Engineering barrier acts as maintenance of stable structure and buffering pressure on waste container from host rock

Hydraulic barrier severs as confinement of host fracture or pore water prevents and retards groundwater or solution from arriving onto container surface

Chemical barrier is to block nuclide migration to host rock when HLW vitrified forms release nuclides due to groundwater erosion
Nuclide migration in buffer backfilling material

After tens of thousands of years, nuclide leaching from HLW vitrified forms would become inevitable when waste form would have been corroded due to groundwater erosion; if then, to what extent can buffer block nuclide migration?

This model is intended to make quantitative analysis and predication of nuclide migration process.
Nuclide migration in buffer backfilling material

- Nuclide migration mechanism in buffer is under influence of so many physico-chemical factors as seepage of solution containing nuclides in buffer, as well as reaction, adsorption and diffusion of nuclide in buffer.
- Mathematical models were established.
- Sensitivity analysis was made with $^{135}\text{Cs}$ as case study.
Establishing mathematical models

\[
\frac{\partial U}{\partial t} = -\nabla \cdot \vec{N}_h + \sum_i R_i
\]

\[
-\nabla \cdot \vec{N}_h = D_e \left( \frac{\partial^2 c_i}{\partial r^2} + \frac{1}{r} \frac{\partial c_i}{\partial r} \right) - \frac{\partial (qc_i)}{\partial r}
\]

\[
\eta \frac{\partial c_i}{\partial t} = D_e \left( \frac{\partial^2 c_i}{\partial r^2} + \frac{1}{r} \frac{\partial c_i}{\partial r} \right) - \frac{\partial (qc_i)}{\partial r} - \eta \lambda_i c_i - \rho_s \frac{\partial c_i^s}{\partial t} - \rho_s \lambda_i^s c_i^s
\]
Initial results of model-based calculation

![Graphs showing initial results](image_url)
Conclusions on calculation

Buffer has significant retardation on nuclide migration in groundwater. Radioactivity of nuclide passing through buffer will decrease by 2-3 orders of magnitude; as calculated, activity peak at buffer exit varies significantly with different nuclides; for example, $^{135}$Cs activity peak might appear twenty or thirty of thousands of years after migration; whereas seventy of thousands of years will be needed for $^{238}$U to peak.

A first increase and then decrease trend is shown in $^{135}$Cs activity concentration between 5000 and million years; peak appears at the inside entrance of buffer 2-3 tens of thousands after closure.
Conclusions on calculation

- The same trend is also shown at the inside exit about $^{135}\text{Cs}$, with a peak of 700 Bq/m$^3$ appearing early, about 3 tens of thousands years, afterwards activity begin to decrease, reaching at 250 Bq/m$^3$ at one million years.

- Nuclide distribution in buffer is manly governed by effective diffusion coefficient, absorbed distribution coefficient and seepage coefficient and waterhead. The first two has significant influence on nuclide migration, whereas the last two are minor.
Nuclide migration in EDZ

Two kinds of models are used in tackling with hydraulic coupling: equivalent continuous media and discrete fracture network model. The former assumes the media to be continuous and homogenous.
Nuclide migration in EDZ
Nuclide migration in EDZ
Nuclide migration in EDZ
Equivalent compartment model and network model are used for EDZ assessment. Calculation indicates that nuclide-specific difference exists in near-field release rate obtained by using both, but nearly at the same order of magnitude for different nuclides. The values obtained by discrete media method and geometric equivalent method vary to some extent.

The next step is to acquire, based on EDZ field and lab experiments, seepage coefficient in different disturbed zones and key migration and diffusion coefficients, with an aim to develop models for three different disturbed zones.
Development and assessment of nuclide migration model in far-field host rock

Assessment and calculation in terms of granite and clay rock based
Beishan site-based trial-assessment (reference scenario)

- Data on flow and field is acquired from Geological Institute
- Some site-specific data
- Release rate from host rock
- Release rate to biosphere
Beishan site-based trail-assessment (early damage to waste container)

- Data on flow and field is acquired from Geological Institute
- Some site-specific data
- Release rate from host rock
- Release rate to biosphere
Beishan site-based pre-assessment (full release of nuclides from vitrified form)

- Data on flow and field is acquired from Geological Institute
- Some site-specific data
- Release rate from host rock
- Release rate to biosphere
Beishan site-based pre-assessment (postulated scenario: buffer loss)

- Data on flow and field is acquired from Geological Institute
- Some site-specific data
- Release rate from host rock
- Release rate to biosphere
Biosphere nuclide migration and dose assessment are conducted largely in three steps:

1. Analyze the migration process of nuclides in biosphere media
2. Define main exposure pathways
3. Annual average effective dose 0.002–0.005 μSv after closure of repository
Assessment of preselected clay rock zone
Sensitivity analysis

Single parameter variational method is one of sensitivity analysis methods by which a parameter is changed within a reasonable range standard value while fixing other parameters, so as to quantify impact of a parameter on model prediction.

MC random sampling and statistical analysis is among multi-parameters variational methods, one of common probability safety analysis methods; this is to carry out multiple calculations (generally 1000-10000)
Sensitivity analysis

Major factors influencing nuclide migration in bentonite are effective diffusion coefficient, absorbed distribution coefficient, buffer seepage coefficient and water head.

The reference values of these parameters are shown below, with $^{135}\text{Cs}$ for sensitivity analysis and maximum activity at buffer exit as dependent variable; to decrease by 25%, 50% and increase by 25%, 50% based on standard value can examine the variation in maximum activity at buffer exit due to these parameter change.
Sensitivity analysis

Maximum Radioactivity concentration (Bq/m$^3$)

- $D$ (m/s)
- $k_d$ (m$^3$/Kg)
- $K$ (m/s)
- $H$ (m)

Graphs showing the relationship between maximum radioactivity concentration and each of the parameters $D$, $k_d$, $K$, and $H$. The graphs indicate how changes in each parameter affect the maximum radioactivity concentration.
MC-based stochastic sampling and analysis

Order of Cs release rate sensitivity to parameters:
- Water flow around disturbed zone
- Effective diffusion coefficient (buffer)
- Distribution coefficient (buffer)
- Time for disposal container failure
- Decreased dissolution rate of vitrified forms
Capability
to acquire key assessment parameters
Capability to acquire key assessment parameters
Capability
to acquire key assessment parameters
Capability
to acquire key assessment parameters
Effect of Irradiation-solubility

Solubility of Si⁴⁺ increases with increase of cumulative irradiation dose
Swelling pressure decreases with increase of cumulative irradiation dose.
Effect of heating-solubility

Solubility of Si$^{4+}$ increases with increase of aging temperature and aging time.
Effect of heating-swelling pressure

When ≤170℃, it decreases with increase of aging Tem. and lower than reference sample’s;
When ≥190℃, it higher than reference sample’s.
Effect of irradiation and heat - solubility

Solubility of Si\(^{4+}\) increases with increase of aging temperature and aging time.
Effect of irradiation and heat – swelling pressure

When $\leq 170^\circ C$, it increases with increase of aging Tem. and lower than reference sample’s;

When $\geq 190^\circ C$, it higher than reference sample’s.
Thanks
Safety case approaches in Germany

Jens Wilhelm Wolf

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Abstract: During the last decade the concept of the Safety Case has been internationally established. The Safety Case is a compilation of evidence, analyses and arguments that quantify and substantiate a claim that a repository will be safe. The Safety Case evolves stepwise from a preliminary stage into a more and more comprehensive stage. In Germany the idea of the Safety Case for the disposal of HLW has been discussed and developed in the context of R&D projects. Typical questions of Safety Case R&D are high-level analyses such as: How to achieve safety? How to demonstrate safety? How to manage uncertainties? How to communicate safety?

Since 2013, the Repository Site Selection Act (StandAG) governs the process for a science-based and transparent search and the selection of a site for a facility for HLW disposal in Germany. According to this act possible host rocks are clay rocks, salt rock, and crystalline rocks. Starting from the general German regulatory requirements for the disposal of HLW, a methodological approach has been developed in several R&D projects that allows the derivation of a safety concept for a repository for the considered host rock types. The safety concept is based on the safe containment of radioactive waste in a containment-providing rock zone (CRZ). On the basis of a few guiding principles, specific objectives were devised, which were used to identify strategic measures. These measures provide the basis for the detailed design and layout of the repository. A scenario development methodology was developed, which is an important tool for the management of uncertainties and forms the basis for the safety assessment. Each scenario is described in detail by FEP and their characteristics. Key elements of the safety assessment are the integrity proofs for the geological and geotechnical barriers. The potential releases of radionuclides from the CRZ in the derived scenarios were evaluated against radiological safety indicators.

On the basis of these general concepts, Safety Case approaches have been developed for all three candidate host rocks in Germany. This contribution will give an overview on the general aspects of these approaches.
Safety Case Approaches in Germany

Jens Wolf, Head of Safety Analyses Department
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS)

3rd Chinese-German Workshop on Radioactive Waste Disposal,
Jiayuguan, May 15-19, 2017
Safety Case

The safety case is the collection of scientific, technical, administrative and managerial arguments and evidence in support of the safety of a disposal facility, covering the suitability of the site and the design, construction and operation of the facility, the assessment of radiation risks and assurance of the adequacy and quality of all of the safety related work associated with the disposal facility.

(...)

The safety case and supporting safety assessment provide the basis for demonstration of safety and for licensing. They will evolve with the development of the disposal facility, and will assist and guide decisions on siting, design and operations.

Source: IAEA SSG-23
Safety Case: Nature and Purpose

Source: NEA No. 3679, 2004

Source: NEA No. 78121, 2013
Elements of the Safety Case

Safety Case Context → Safety Strategy

- System description
- Safety assessment
- Limits, controls and conditions
- Integration of safety arguments

Iteration and design optimization

Management of uncertainty

Source: IAEA SSG-23
Safety Case R&D

German Safety Case Approach has been developed in R&D projects dealing with the following questions:

How to achieve safety?  → Safety strategy (OS/PCS)
How to demonstrate safety?  → Safety assessment
How to manage uncertainties?  → Management of uncertainties
How to communicate safety?  → Integration of safety arguments

Basis: Generic geological model / disposal concept
Elements of Safety Case R&D
R&D in Germany

- Safety Case Context
- Safety Strategy
- Generic geological model / Disposal Concept
- Safety assessment
- Limits, controls and conditions
- Integration of safety arguments
- Iteration and design optimization
- Management of uncertainty
Safety Case: R&D in Germany

- clay
- salt
- crystalline

AnSichT
- ISIBEL
  - ISIBEL-II
  - KOSINA
  - CHRISTA
- AnSichT-II
- VSG

2018
- 2015-2018
- III/2017

3rd Chinese-German Workshop on Radioactive Waste Disposal | Safety Case Approaches in Germany
Safety Strategy

How to achieve safety?

Protection Goals
Safety Principles / Functions
Guiding Principles
Design Requirements
(...)
Objectives ↔ Measures

Regulations / Geology / Repository Concept

German safety requirements
understanding of repository processes
site characterisation data

guiding principles

design requirement 1
  specific objective 1
  specific objective 2
  specific objective 3
  specific objective 4
  strategic measure 1
  strategic measure 2
  strategic measure 3
  strategic measure 4
  strategic measure 5

design requirement 2
  specific objective 5
  specific objective 6
  strategic measure 6
  strategic measure 7
  strategic measure 8
  strategic measure 9
  strategic measure 10

design requirement 3
  specific objective 8
  strategic measure 11
  strategic measure 12

safety concept for the project VSG
Containment-providing Rock Zone

- Overburden (OV)
- Host Rock (HR)
- Containment-providing rock zone (CRZ)
- Seal of CRZ
- Disposal Area (REP)
- Rock body with safety-relevant barrier function
- Rock body without safety-relevant barrier function

Geological barrier
Seals
Backfill

10^6 a
Requirements for the CRZ

- The formation of **secondary water pathways** within the CRZ which could lead to the ingress or escape of potentially contaminated aqueous solutions can be excluded, and that

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

  *Source: BMUB, 2010*

Only for clay and salt rock? Can crystalline rock fulfill this requirements?

In 2013, enactment of site selection process:
→ Salt, Clay and Crystalline rock potential host rocks
Research Project CHRISTA

- Under which conditions is crystalline rock a candidate host rock for a DGR in Germany?

- Do we have the tools to build a Safety Case for a DGR in crystalline rock?

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Geology host rock</th>
<th>Situation in Germany</th>
<th>Safety Requirements fulfilled?</th>
<th>Requirements for CRZ?</th>
</tr>
</thead>
<tbody>
<tr>
<td>TYPE A</td>
<td>unfractured</td>
<td>not existent</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>fractured, hydraulically insignificant</td>
<td>low probability</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>fractured</td>
<td>existent</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>TYPE Ba</td>
<td>not existent</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TYPE Bb</td>
<td>fractured, argillaceous overburden combined</td>
<td>existent</td>
<td>evaluate</td>
<td>yes</td>
</tr>
<tr>
<td>Multiple CRZ</td>
<td>evaluate</td>
<td>evaluate</td>
<td>yes</td>
<td></td>
</tr>
</tbody>
</table>
CRZ configuration: TYPE Bb

- not in a formation with a high containment capacity
- repository outside the CRZ
- construction of repository in a very stable formation
CRZ configuration: Multiple CRZ

- technical improvement of CRZ is necessary
Management of Uncertainties

- **Scenario** uncertainties
  - Scenario analysis (FEP, scenario development)

- **Data** and **parameter** uncertainties
  - Uncertainty and sensitivity analysis

- **Model** uncertainties
  - Benchmarking, uncertainty and sensitivity analysis
FEP and Scenarios

Safety concept: Containment

Define probability class

Key factors to affect the system

Scenarios
probable, less probable, (improbable)

Consequence Analysis

FEP
Demonstration concept

How to demonstrate safety?

Safety demonstration concept

Handling of uncertainties:
- data
- model
- scenario

Containment:
- CRZ: dimension
- CRZ: preservation
- Integrity of barriers

Evolution(s) of repository system

Radiological safety indicator

Non-radio- logical protection goals

Operational safety

Assessment
Radiological Indicator

Stage 1
RGI = 0
No contact between solution and waste
No release of RN into the gas phase

Stage 2
0 < RGI ≤ 1
Difussive transport of RN
Advective transport of RN

Stage 3
RGI > 1
Criteria according to Safety Requirements fulfilled

Stage 4
RGI > 1
Criteria according to Safety Requirements not fulfilled

Complete containment
Assessment of safe containment
Assessment by simplified statement

Repository system in this form (layout) not suitable

Criteria according to Safety Requirements fulfilled

Stage 2

3rd Chinese-German Workshop on Radioactive Waste Disposal | Safety Case Approaches in Germany
Radiological consequences

Source: Wolf et al. 2013
RepoTRENDS: Tool for Safety Analysis

- **Near field**
  - mobilsation (rate, solubility)
  - transport through technical barriers
  - decay

- **Far field**
  - 1D transport through geosphere (different media)
  - decay

- **Exposure model**

---

**RepoTRENDS**

- **LOPOS, CLAYPOS** (old Fortran code) modified for a new data exchange format

- **GeoTRENDS-POSA** (C++)
  - contaminant transport through fully SAturated POrous media

- **GeoTRENDS-FRAME** (C++)
  - contaminant transport in FRActured MEdia

- **GeoTRENDS-COFRAME** (C++)
  - COllloid facilitated contaminant transport in FRActured MEdia

- **BioTRENDS** (C++)

- **RepoSTAR** (C++)
  - framework for probabilistic calculations (using SimLab 4)
Application to Crystalline Rock

Region Krasnojarsk
2.4 Mio. km²
2.8 Mio. EW

Radiation Exposure

1.5 \times 10^5 \text{ m}^3/\text{a}

152 \text{ m}^3/\text{a}

Bq/\text{a}

---

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Transport distance 100 m

![Graph showing radiation exposure over time for different isotopes and actinides.](image-url)

- **Radiation Exposure [Sv/a]**
- **Time [a]**

- **Se 79**
- **Cs 135**
- **Actinides**
- **Total**

**Legend:**
- LOPOS (CLAYPOSS old Fortran code) modified for a new data exchange format
- GeoTREND-POSA (C++) contaminant transport through fully Saturated PORous media
- GeoTREND-FRAME (C++) contaminant transport in FActured MEdia
- GeoTREND-COFRAE (C++) COllid facilitated contaminant transport in FRActured MEdia
- BioTREND (C++) framework for probabilistic calculations (using SimLab 4)
Conclusions

- Safety Case is accepted in Germany as basic approach for the post closure safety of a repository (incl. regulation)

- German regulation (2010): main safety function: **containment**
  → concept of CRZ: containment **and** concentration
  → focused on salt and clay rock

- Site Selection Act / Commission: + crystalline rock
  → adjustment of safety regulations

  - Safety concept /Demonstration concept
  - FEP catalogue
  - Scenarios / Management of Uncertainties
  - Additional arguments: Indicators, Natural Analogues

- Due to the open decision for a host rock type in Germany, ongoing basic Safety Case R&D for several years
  → requires a high flexible tool box for performance assessment
Acknowledgement

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on the basis of a decision by the German Bundestag
A preliminary study on in situ tests of disposal process of high-level waste in underground research laboratory in China

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Abstract: Based on the investigation of consummate geological disposal process plans of other countries, which has advanced technology on geological disposal and with investigation and designs of disposal projects are well on-going, combined with the conditions of potential site in China for disposal of HLW geological and hydrogeological conditions of the site, features of source item, technique and intrumental levels in construction and disposal process, the investigative content of tests and experiments which are related to disposal process have been provided. The general plan and targets of different period process of the underground research laboratory in China are also present
Performance of buffer material under coupled THM conditions

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Abstract: The concept model of high-level radioactive waste (HLW) repositories in deep geological media is based on a multi-barrier system. Buffer material is considered as an important artificial engineered barrier between the canister and the surrounding rock. Coupled thermo-hydro-mechanical (THM) phenomenon will occur in the buffer material under conditions of the heat generated by the radioactive decay and of the underground water and geo-stress supplied by the surrounding rock, et al. Therefore, it is considered of fundamental important for the evaluation of long-term behavior that the processes taking place in the near filed for the safety operation of the HLW repository. Following the need for understanding the coupled THM behaviors of bentonite, mock-up test is considered as one of the most effective approach. An experiment at middle scale is proposed as a complementary step for the China-Mock-up test. The middle one is carried out to obtain the bentonite parameters and to identify the processes by simulating the conditions of the China-Mock-up test. The aims intended are to know and understand the long-term behavior of the bentonite submitted to thermal and hydraulic gradients at the opposite direction. The characteristic of the bentonite related to swelling pressure, relative humidity and temperature are presented and interpreted. Meanwhile, the water content, dry density, chemical composition and micro-structure of samples are analyzed and compared after dismantling. The results can provide design parameter and theoretical basis for HLW repository.
Detecting the redox condition of groundwater environment in Beishan granite using fracture mineral distribution and geochemistry

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Abstract: Oxidizing conditions normally prevail in surface water and near-surface groundwater, but there is usually a change to reducing conditions in groundwater at greater depth. Dissolved O\textsubscript{2} originally present is consumed through biogenic and inorganic reactions along the flow paths. Fracture minerals participate in these reactions and the fracture mineralogy and geochemistry can be used to detect the redox condition. An important task in the safety assessment of a potential repository for the HLW disposal in granite, at an approximate depth of 550m in Beishan, is to demonstrate that reducing conditions can be maintained for a long period of time. Oxygen may damage the canisters that host nuclear waste; additionally, in the event of a canister failure, oxidizing conditions may increase the mobility of some radionuclides. The present study of the redox condition of groundwater environment is based on mineralogical (redox-sensitive minerals), geochemical (redox-sensitive elements) and U-series disequilibrium investigations of mineral coatings along open fractures. The fractures have been sampled along drill cores from closely spaced, 600m deep boreholes, which were drilled during the site investigation work in the Beishan area, North-western China, carried out by the Beijing Research Institute of Uranium Geology (BRIUG). The distribution of the redox-sensitive minerals pyrite and goethite in open fractures shows that the groundwater environment around the URL site switch from mainly oxidizing condition to mainly reducing condition in the fractures at about 500–520m depth. Negative Ce anomalies along nearly every depth suggest reduction of Ce in the process of calcite formation. The U-series radionuclides show sequeilibrium in most of the samples, indicating deposition of U (due to reduction) during the last 1Ma. Individual disequilibrium of U-series radionuclides seems to have been oxidized in fracture zones. The Fe\textsuperscript{3+}/Fe\textsubscript{tot} ratio is higher in the red-stained rock samples (K-feldsparization) adjacent to fractures whereas the Fe\textsuperscript{3+}/Fe\textsubscript{tot} ratio in the other types of alteration is largely similar to the reference samples (unaltered rock). The quantity of red-staining is apparently rare adjacent to fractures in URL site, indicating the increase of reducing capacity (Fe\textsuperscript{2+}) in geological environment of URL site for HLW disposal.
Detecting the redox condition of groundwater environment in Beishan granite using fracture mineral distribution and geochemistry

TIAN Xiao

Beijing Research Institute of Uranium Geology, CNNC
Outline

- Introduction
- Content and Approach
- Results of investigations and experiments
  - Distribution of redox-sensitive minerals
  - Geochemical characteristics
- Conclusions
Introduction

“\textit{The goal of radioactive waste disposal is passive isolation of waste so that it does not result in undue exposure to radiation of humans or the environment, now or in the future.}”

—– \textit{Safety Guide, IAEA, 1994}

To choose a surrounding geological environment that has suitable geochemical characteristics, including

\begin{itemize}
  \item Reducing condition
\end{itemize}

Preliminary conceptual model for China’s HLW repository
Why is it important to demonstrate the reducing condition in geological environment.

- $O_2$ may harm the canisters in which the radioactive waste is contained.
- In case of canister leakage, oxidizing conditions may increase the mobility of several radionuclides in the HLW, especially $U$.

...It is pretty necessary to know the redox condition in geological environment for HLW disposal.
Content and Approach

- **Measurements of Eh in boreholes**
  - Most frequently used
  - Usually unreliable as affected by oxygen

- **Hydrochemical analysis**
  - Causing mixing of groundwater sample
  - Result in redox-sensitive elements contaminated

- **Fracture mineral distribution & geochemistry**
  - Evaluated with better depth control
  - Reflect the geological evolution, but uncertain for modern geo-environment.
Content and Approach

- **Redox-sensitive minerals**: composition & distribution
- **Redox-sensitive elements** (e.g. Ce, Fe, Mn)
- **U-series radionuclides activity**
Results of investigations and experiments

- **Composition of redox-sensitive minerals**

  - **A/E - Pyrite** (open fracture)
  - **B/F - Pyrite** (closed fracture)
  - **C/G - Goethite**
  - **D/H - Hematite**
Results of investigations and experiments

Redox-sensitive elements

\[ \text{Ce/Ce}^* > 1: \text{positive Ce-anomalies} \quad \text{Oxidation} \]
\[ \text{Ce/Ce}^* < 1: \text{negative Ce-anomalies} \quad \text{Reduction} \]

Most of samples show negative Ce-anomalies, indicating reducing condition in mineral formation,

But only two samples from Shazaoyuan fracture zone show slightly positive Ce-anomalies, suggesting weak oxidative condition.
Results of investigations and experiments

Redox-sensitive elements

Fe$^{2+}$$\quad$ Inorganic redox buffer
$\quad$ Be available in the bedrock and along the fractures to provide enough reducing capacity

- Fe$^{3+}$/Fe$^{tot}$-ratio is slightly higher in red-stained rocks than in other altered rocks.
- This enrichment is related to the replacement of magnetite by hematite and biotite by chlorite due to hydrothermal oxidation.
Results of investigations and experiments

- **Redox-sensitive elements**
  - Red-stained altered rock is generally rare in Xinchang (especially in deep), while in common in Shazaoyuan.
  - In a sense, it is better for redox buffering along fractures in URL site.
Results of investigations and experiments

U-series radionuclides activity

- $^{238}\text{U}_{-}^{234}\text{U}_{-}^{230}\text{Th}$ activity ratio
  - Provide time constraint within 1 Ma
  - Disequilibria indicate redistribution (removal or deposition) in either oxidizing or reducing condition.

- Most of samples fall into uranium deposition sector, possibly as a result of reducing condition.
- Only a few samples from Xinchang show secular equilibrium which indicate insignificant water–rock interaction.
## Conclusions

<table>
<thead>
<tr>
<th>Site (deep rock)</th>
<th>Mineralogy</th>
<th>Geochemistry</th>
<th>U-series nuclides</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Xinchang (URL site)</strong></td>
<td>Goethite or hematite is extremely rare (only in fracture zone), Pyrite is found in common.</td>
<td>a) All samples show negative Ce-anomalies; b) The concentration of Fe2+ is relatively higher along fractures.</td>
<td>Most of samples show secular equilibrium or uranium deposition.</td>
</tr>
<tr>
<td><strong>Shazao-yuan</strong></td>
<td>Goethite or hematite is widely distributed, but pyrite is not found</td>
<td>a) Most samples show negative Ce-anomalies, with only two exceptions (slightly positive Ce-anomalies); b) The concentration of Fe2+ is relatively lower along fractures.</td>
<td>All samples show disequilibrium with complex process.</td>
</tr>
</tbody>
</table>

- In comparison, the redox condition at about 530-600m depth in URL site is more suitable.
- This research provided a reference for determination of the depth of main tunnel in URL.
Thank you for your attention!
Welcome to Beishan site!
Effects of GMZ bentonite on the corrosion evolution of NiCu low alloy steel

Xin Wei, Junhua Dong, Wei Ke

Institute of Metal Research, Chinese Academy of Sciences, Shenyang, China

Email: xwei@imr.ac.cn

Abstract: During the long-term disposal of HLW, the metal container will face the threat of corrosion damage as the groundwater soaking through the buffer material (bentonite). The corrosion mode and corrosion rate of the metal container are not only related to the dissolved oxygen, compositions of groundwater in the deep geological disposal environments, but also depend on the properties of the bentonite. However, the influence mechanism of bentonite on the corrosion evolution of the disposal container has not been clear. This research investigated the effects of GMZ Na-bentonite on the corrosion evolution of NiCu low alloy steel in the simulated environments by the electrochemical in-situ monitoring. In addition, XRD, SEM and EDS were used for analyzing the composition and structure of corrosion products. The polarization curves and open circuit potential (OCP) monitoring results indicated that the bentonite had a great influence on the corrosion mode of NiCu steel in the deaerated bicarbonate environments. In 0.05M NaHCO$_3$ solution, NiCu steel tended to be quasi-passivation under the effect of corrosion product with increasing the immersion time. While the corrosion mode of NiCu steel was always active dissolution in 0.05M NaHCO$_3$ solution/bentonite system. The fitting results of EIS showed that the charge transfer resistance Rct of NiCu steel in bentonite was obviously higher than that in the simulated solution, and the corrosion rate reduced an order of magnitude. Moreover, the influence of bentonite deposits on the corrosion evolution of NiCu steel had been investigated in 0.05M NaHCO$_3$+0.1M NaCl+0.1M Na$_2$SO$_4$ solution/bentonite. Under the bentonite, the corrosion rate of NiCu steel was significantly lower than that in the supernatant and localized corrosion was less prone to occur. Besides, the rust layer informed on NiCu steel buried in bentonite was thinner and the corrosion products were mainly composed of GR II, iron oxide hydroxide, ferrous sulfate and chloritoid.
Effects of GMZ bentonite on the corrosion evolution of NiCu low alloy steel

Xin Wei, Junhua Dong, Wei Ke
Institute of Metal Research, Chinese Academy of Sciences

2017. 05. 17 Jiayuguan
Outline

➢ Background

➢ The long-term corrosion evolution of NiCu low alloy steel in bentonite environments

➢ Influence of bentonite deposits on the corrosion behavior of NiCu low alloy steel
The multi-barrier system is composed of solidified glass, metal container and buffer materials.

The disposal container is required to maintain the structural integrity and to prevent the vitrified waste from contacting with groundwater.

Corrosion damage the most important problem of the metal container

The geological disposal concept of HLW
Corrosion environment

Chemical Compositions of Groundwater

Calculated results in Japan

<table>
<thead>
<tr>
<th>chemicals</th>
<th>Concentration [mol l⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCO₃⁻/CO₃²⁻/H₂CO₃</td>
<td>&lt;7.3×10⁻²</td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>&lt;6.1×10⁻²</td>
</tr>
<tr>
<td>HS⁻/H₂S</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>NH₃</td>
<td>&lt;1.6×10⁻⁴</td>
</tr>
<tr>
<td>NH₄⁺</td>
<td>&lt;5.1×10⁻³</td>
</tr>
<tr>
<td>pH</td>
<td>5.9~8.4</td>
</tr>
</tbody>
</table>

Beishan (granite well 3#, 430 meters), BRIUG

<table>
<thead>
<tr>
<th>Cation</th>
<th>mol/L</th>
<th>Anion</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>
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<tr>
<td>NO₃⁻</td>
<td>3.08×10⁻⁴</td>
<td>Ca²⁺</td>
<td>1.54×10⁻³</td>
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<tr>
<td>SO₄²⁻</td>
<td>1.39×10⁻²</td>
<td>Mg²⁺</td>
<td>1.01×10⁻²</td>
</tr>
<tr>
<td>CO₃²⁻</td>
<td>0.84×10⁻⁴</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HCO₃⁻</td>
<td>1.90×10⁻³</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Constituent of GMZ Bentonite

<table>
<thead>
<tr>
<th>Montmorillonite</th>
<th>Quartz</th>
<th>Cristobalite</th>
<th>Feldspar</th>
<th>calcite and kaolinite</th>
</tr>
</thead>
<tbody>
<tr>
<td>75±1%</td>
<td>12±1%</td>
<td>7±1%</td>
<td>4±1%</td>
<td>1±1%</td>
</tr>
</tbody>
</table>
## Materials of Disposal Container

**Materials**
- Carbon steels
  - France
  - Germany
  - Japan, Spain
  - Switzerland, UK
- Low alloy steels
- Cast irons
- Copper
  - Canada
  - Finland
  - Sweden
- Titanium and its alloys
  - Canada
  - Japan
- Stainless alloys
  - Belgium
  - France
  - USA

**Country**

### Material selection is one of the controversial problems

Recent years, low carbon steel, NiCu low alloy steel, copper and titanium were selected as the candidate materials of disposal container in China.
The long-term corrosion evolution of NiCu low alloy steel in bentonite environments
### Material

<table>
<thead>
<tr>
<th>Elements</th>
<th>Ni</th>
<th>Cu</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>S</th>
<th>P</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content</td>
<td>3</td>
<td>0.3</td>
<td>0.21</td>
<td>0.21</td>
<td>0.58</td>
<td>0.0036</td>
<td>0.017</td>
<td>balance</td>
</tr>
</tbody>
</table>

### Simulated environments

**GMZ Na-Bentonite + the simulated solutions**

1. Deionized water/bentonite
2. 0.02M NaHCO$_3$ solution/bentonite
3. 0.05M NaHCO$_3$ solution/bentonite
4. 0.02M NaHCO$_3$ + 0.1M NaCl solution/bentonite
5. 0.02M NaHCO$_3$ + 0.1M Na$_2$SO$_4$ solution/bentonite
6. 0.02M NaHCO$_3$ + 0.1M NaCl + 0.1M Na$_2$SO$_4$ solution/bentonite
Experimental device

A small-cage Titanium alloy electrolytic cell

**WE**: NiCu steel  **RE**: Ag/AgCl  **CE**: Pt

Electrochemical method:  Polarization curves
Open-circuit potential monitoring
Electrochemical impedance spectroscopy
At the initial stage, three anodic curves all present the active dissolution characteristic in bentonite. Anodic and cathodic processes are both suppressed by HCO$_3^-$.

The OCP of NiCu steel decreases with the increase of HCO$_3^-$ concentration. The fluctuation of OCP is mainly related to the formation and migration of the corrosion products.
EIS Results

Initiation (I):
\[ R_e(Q_1R_1)(Q_2R_2)(Q_3R_{ct}) \]

Long-term (II):
\[ R_e(Q_1(R_1(Q_2R_2)(Q_3R_{ct}))) \]

\( R_e \) ----- medium resistance
\( R_1 \) and \( Q_1 \) ----- R and C of the mixing layer of the outer corrosion products /bentonite
\( R_2 \) and \( Q_2 \) ----- R and C of the inner corrosion products
\( Q_3 \) ----- double layer capacitance, \( R_{ct} \) ----- charge transfer resistance

Deionized water/bentonite

\( Z(\Omega \cdot \text{cm}^2) \)

Frequency (Hz)
EIS Results

0.02M NaHCO₃ solution/bentonite

(a) Z(Ω·cm²)
Frequency (Hz)

3 days
7 days
24 days
Fitting lines

(b) Phase of Z(deg)
Frequency (Hz)

4 days
80 days
136 days
244 days
394 days
Fitting lines

0.05M NaHCO₃ solution/bentonite

(a) Z(Ω·cm²)
Frequency (Hz)

52 days
80 days
136 days
244 days
394 days
Fitting lines

(b) Phase of Z(deg)
Frequency (Hz)

4 days
11 days
32 days
Fitting lines
Calculation of Corrosion Rate

Stern-Geary: \[ I_{\text{corr}} = \frac{B}{R_{\text{ct}}} \]

\( I_{\text{corr}} \): corrosion current density, \( B \): Stern-Geary coefficient, 20 mV

\( v = 11.7 \, I_{\text{corr}} \)

Deionized water/bentonite

<table>
<thead>
<tr>
<th>Time (Days)</th>
<th>( R_e ) (Ω·cm²)</th>
<th>( Q_1 ) (F·cm⁻²)</th>
<th>( n_1 )</th>
<th>( R_1 ) (Ω·cm²)</th>
<th>( Q_2 ) (F·cm⁻²)</th>
<th>( n_2 )</th>
<th>( R_2 ) (Ω·cm²)</th>
<th>( Q_3 ) (F·cm⁻²)</th>
<th>( n_3 )</th>
<th>( R_{\text{ct}} ) (Ω·cm²)</th>
<th>( v ) (mm/a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>96.8</td>
<td>1.5×10⁻⁷</td>
<td>0.82</td>
<td>66</td>
<td>4.2×10⁻⁴</td>
<td>0.43</td>
<td>40.7</td>
<td>3.4×10⁻⁴</td>
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<td>3326</td>
<td>0.07</td>
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<tr>
<td>11</td>
<td>103</td>
<td>4.7×10⁻⁶</td>
<td>0.58</td>
<td>89.9</td>
<td>1.0×10⁻³</td>
<td>0.86</td>
<td>2093</td>
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<td>18290</td>
<td>0.013</td>
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<tr>
<td>32</td>
<td>100.6</td>
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<td>2.2×10⁻³</td>
<td>1</td>
<td>11.9</td>
<td>8.2×10⁻⁴</td>
<td>0.92</td>
<td>27400</td>
<td>0.009</td>
</tr>
<tr>
<td>103</td>
<td>114.7</td>
<td>1.8×10⁻⁴</td>
<td>0.36</td>
<td>52.8</td>
<td>2.3×10⁻³</td>
<td>0.84</td>
<td>9.6</td>
<td>1.2×10⁻³</td>
<td>0.91</td>
<td>27500</td>
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<tr>
<td>130</td>
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<td>0.37</td>
<td>43.1</td>
<td>2.2×10⁻³</td>
<td>0.88</td>
<td>8.8</td>
<td>1.4×10⁻³</td>
<td>0.92</td>
<td>31000</td>
<td>0.008</td>
</tr>
<tr>
<td>244</td>
<td>81</td>
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<td>49.8</td>
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<tr>
<td>356</td>
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<td>0.3</td>
<td>122.6</td>
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<td>0.5</td>
<td>9.5</td>
<td>6.7×10⁻³</td>
<td>0.76</td>
<td>31560</td>
<td>0.007</td>
</tr>
</tbody>
</table>
### 0.02M NaHCO$_3$ solution/bentonite

<table>
<thead>
<tr>
<th>Time (Days)</th>
<th>$R_e$ (Ω·cm$^2$)</th>
<th>$Q_1$ (F·cm$^{-2}$)</th>
<th>$n_1$</th>
<th>$R_1$ (Ω·cm$^2$)</th>
<th>$Q_2$ (F·cm$^{-2}$)</th>
<th>$n_2$</th>
<th>$R_2$ (Ω·cm$^2$)</th>
<th>$Q_3$ (F·cm$^{-2}$)</th>
<th>$n_3$</th>
<th>$R_{ct}$ (Ω·cm$^2$)</th>
<th>$v$ (mm/a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>74.7</td>
<td>1.55×10$^{-5}$</td>
<td>0.64</td>
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<td>4×10$^{-3}$</td>
<td>0.83</td>
<td>36280</td>
<td>0.006</td>
</tr>
</tbody>
</table>

### 0.05M NaHCO$_3$ solution/bentonite

<table>
<thead>
<tr>
<th>Time (Days)</th>
<th>$R_e$ (Ω·cm$^2$)</th>
<th>$Q_1$ (F·cm$^{-2}$)</th>
<th>$n_1$</th>
<th>$R_1$ (Ω·cm$^2$)</th>
<th>$Q_2$ (F·cm$^{-2}$)</th>
<th>$n_2$</th>
<th>$R_2$ (Ω·cm$^2$)</th>
<th>$Q_3$ (F·cm$^{-2}$)</th>
<th>$n_3$</th>
<th>$R_{ct}$ (Ω·cm$^2$)</th>
<th>$v$ (mm/a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>88.2</td>
<td>2.5×10$^{-4}$</td>
<td>0.89</td>
<td>61.5</td>
<td>2.4×10$^{-3}$</td>
<td>0.2</td>
<td>60.6</td>
<td>6.2×10$^{-4}$</td>
<td>0.8</td>
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<td>11</td>
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<td>64.4</td>
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<tr>
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<td>30.2</td>
<td>0.01</td>
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<td>2.6×10$^{-3}$</td>
<td>0.93</td>
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</tr>
<tr>
<td>356</td>
<td>106.5</td>
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<td>1.9×10$^{-3}$</td>
<td>0.97</td>
<td>25970</td>
<td>0.009</td>
</tr>
</tbody>
</table>
All curves present the **active dissolution behavior** in bentonite. \( \text{Cl}^- \) and \( \text{SO}_4^{2-} \) both can increase the corrosion current density.

With adding \( \text{Cl}^- \) and \( \text{SO}_4^{2-} \), the corrosion potential increases, which indicates that \( \text{Cl}^- \) and \( \text{SO}_4^{2-} \) could promote the formation of the corrosion products.
EIS Results

0.02M HCO$_3^-$ + 0.1M SO$_4^{2-}$ solution / bentonite  
0.02M HCO$_3^-$ + 0.1M Cl$^-$ solution / bentonite
0.02M HCO$_3^-$ + 0.1M Cl$^-$ + 0.1M SO$_4^{2-}$ solution / bentonite

### Fitting Results

<table>
<thead>
<tr>
<th>Time</th>
<th>$R_e$</th>
<th>$Q_1$</th>
<th>$n_1$</th>
<th>$R_1$</th>
<th>$Q_2$</th>
<th>$n_2$</th>
<th>$R_2$</th>
<th>$Q_3$</th>
<th>$n_3$</th>
<th>$R_{ct}$</th>
<th>$v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Days</td>
<td>Ω⋅cm$^2$</td>
<td>F⋅cm$^{-2}$</td>
<td>Ω⋅cm$^2$</td>
<td>F⋅cm$^{-2}$</td>
<td>Ω⋅cm$^2$</td>
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### 0.02M HCO$_3^-$ + 0.1M Cl$^-$ solution / bentonite

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### 0.02M HCO$_3^-$ + 0.1M Cl$^-$ + 0.1M SO$_4^{2-}$ solution / bentonite

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Corrosion Mechanism

Initial stage

Anodic reaction: \( \text{Fe} \rightarrow \text{Fe}^{2+} + 2\text{e}^- \)

Cathodic reaction: \( \text{O}_2 + 2\text{H}_2\text{O} + 4\text{e}^- \rightarrow 4\text{OH}^- \)

\[ 4\text{Fe(OH)}_2 + \text{O}_2 = 4\alpha\text{-FeOOH} + 2\text{H}_2\text{O} \quad (1) \]

\[ 2\text{Fe}_2\text{(OH)}_2\text{CO}_3 + \text{O}_2 + 2\text{OH}^- = 4\alpha\text{-FeOOH} + 2\text{HCO}_3^- \quad (2) \]

\[ \text{Fe}_6\text{(OH)}_{12}\text{CO}_3 + \text{O}_2 + \text{OH}^- = 6\alpha\text{-FeOOH} + \text{HCO}_3^- + 3\text{H}_2\text{O} \quad (3) \]

\[ \text{Fe(II)} \rightarrow \text{Fe(III)} \]

Oxygen depletion stage

Anodic reaction: \( \text{Fe} \rightarrow \text{Fe}^{2+} + 2\text{e}^- \)

Cathodic reaction: Reduction of corrosion products

\[ 3\alpha\text{-FeOOH} + \text{H}^+ + \text{e} = \text{Fe}_3\text{O}_4 + 2\text{H}_2\text{O} \quad (4) \]

\[ 8\alpha\text{-FeOOH} + \text{Fe}^{2+} + 2\text{e} = 3\text{Fe}_3\text{O}_4 + 4\text{H}_2\text{O} \quad (5) \]

\[ 8\alpha\text{-FeOOH} + \text{Fe}^{3+} + 3\text{e} = 3\text{Fe}_3\text{O}_4 + 4\text{H}_2\text{O} \quad (6) \]
In bentonite environments, the corrosion rate of NiCu steel increases with time, which is higher than that in simulated solutions. The corrosion rate obviously decreased by an order of magnitude.

In deareated 0.05M NaHCO$_3$ solution, NiCu steel tends to be passivated. But NiCu steel tends to be active dissolution in 0.05M NaHCO$_3$ solution/bentonite. The bentonite can change the corrosion mode of NiCu steel. In bentonite environments, $R_{ct}$ of NiCu steel increases with time, which is higher than that in simulated solutions. The corrosion rate obviously decreased by an order of magnitude.
Influence of bentonite deposits on the corrosion behavior of NiCu low alloy steel
Material and Simulated environments

Material

3Ni0.3Cu low alloy steel

Simulated environments

0.05M NaHCO₃+0.1M NaCl+0.1M Na₂SO₄/bentonite

Bentonite : solution = 1:10

Material and Simulated environments

Material

3Ni0.3Cu low alloy steel

Simulated environments

0.05M NaHCO₃+0.1M NaCl+0.1M Na₂SO₄/bentonite

Bentonite : solution = 1:10

Material and Simulated environments

Material

3Ni0.3Cu low alloy steel

Simulated environments

0.05M NaHCO₃+0.1M NaCl+0.1M Na₂SO₄/bentonite

Bentonite : solution = 1:10
In the supernatant, the corrosion potential of NiCu steel is located at the strong polarization region after 52 days. While the OCP of NiCu steel buried in bentonite is situated in the weak polarization region, the corresponding corrosion current density is only 16.7 μA/cm².
In-situ EIS measurement

Initial stage

Fitting circuits of EIS

\[ R_e(Q_{dl}R_{ct}) \]
Long-term EIS results

In the supernatant

Buried in bentonite

Fitting circuits of EIS

\[ R_e(Q_f R_f)(Q_{dl} R_{ct}) \]
Fitting results of EIS

In the supernatant

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Buried in bentonite

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The bentonite layer covered on the electrode could inhabitant the anodic active dissolution of NiCu steel.
Corrosion Products Analysis

In the supernatant, the color is reddish brown, Fe (II) is oxidized to Fe (III). The corrosion products mainly contain iron oxide hydroxide, chloride and sulphate.

Under the bentonite, the color is dark green. The corrosion products include Green rust II, iron oxide hydroxide and ferrous sulfate. Montmorillonite, feldspar and chloritoid are also detected.
Cross-sectional morphology and EDS analysis

Without bentonite deposition, the rust layer is thicker (60μm). The pitting corrosion is induced by the interaction of dissolved oxygen and Cl\(^-\). There is a large amount of Cl\(^-\) accumulated in the pit.
Under the bentonite

The thickness of the rust layer is only about 10 μm. Fe are found in the deposited bentonite layer, which indicates that corrosion products (Fe$^{2+}$/Fe$^{3+}$) could migrate into the bentonite during the corrosion process. The corrosion mode of NiCu steel is dominated by uniform corrosion with bentonite deposition.
Thanks for Your attention!
Discussion on retrievability strategy of radioactive waste disposal in China

Xin Wang
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Abstract: Currently, the issue of “Retrievable” of radioactive waste disposal has caused widespread concern in academe and engineering, but there haven’t carry out any research work in China. "Retrievability" is the ability to remove the waste or waste packages from the repository in various stages, including after final sealing and closure. This paper has conducted a systematic research in connection with the information on retrievable of radioactive waste disposal in France, Sweden, Canada, Germany, Switzerland, etc. And sorted out the general requirements of retrieved laws and regulations, retrieved wastes type, retrieved time and retrieved process in different country. This paper focused on analysis the background and reasons of retrieved policy for each country, and combined with the national conditions of our country, finally given the advices of retrieved laws and regulations, retrieved wastes type, retrieved time in China.
Calculation on nuclide transport for rock cavern disposal by compartment model

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Abstract: Currently, there are three radioactive waste disposal facilities accepting waste in China, all of them are near-surface disposals for Low and Intermediate Level Waste. The rock cavern type disposal has several practices around the world, and in China, the rock cavern disposal has developed to the pre-feasibility study phase.

It is obvious that the calculation of radioactive nuclide transport for rock cavern disposal is different from near-surface disposal, therefore new modelling concept and associated assumptions need to be developed and made. The modelling of nuclide transport is accomplished by compartment model, which is one of numerical calculation methods. The disposal is composed by disposal tunnels, which is further represented by disposal cells; and the near field surrounding disposal cell is divided into a number of compartments, which represent different barrier materials, including grouting and concrete. Nuclide transport in near field is dominated by diffusion, and decay of nuclide is considered. Nuclide transport in excavated disturbed zone and geosphere is dominated by advection and dispersion. The modelling results indicate that the compartment modelling method is a handle tool for calculation of radioactive nuclide transport for rock cavern disposal.

The presentation includes introduction of the compartment modelling method, modelling of the radioactive nuclide transport and corresponding assumptions, as well as modelling results.
Preparation of large-scale compacted block of bentonite-sand mixture as HLW buffer

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Abstract: Mixtures of GMZ001 bentonite and quartz sand have been chosen as one of the alternative buffer materials for geological disposal of high level radioactive waste in China. A sand addition of 30% is considered to be the optimum sand addition according to the results which comes from laboratory tests on compaction properties, swelling characteristics, hydraulic properties and mechanical properties. This work presents a method for preparing large-scale compacted blocks with bentonite-sand mixture into fan-shape, of which 12 blocks can be assembled into a circular ring. The blocks were compacted under 20MPa to achieve dry density of 1.6~1.8g/cm$^3$ using an oil pressure machine under strain controlling mode. The formed blocks were sawed into 64 sub-specimens to measure dry density and water content distribution, degree of water saturation and void ratio of these sub-specimens have been also calculated. The results indicate that the compacted block have a high quality and it is nearly homogeneous. Furthermore, Longitudinal wave velocity in different direction of the blocks, such as radius direction and height direction were measured. Wet blocks after being compacted were exposed in a box with controlled temperature of 40℃ and relative humidity of 85% to verify the degradation process. The exposure test illustrates that degradation process can be limited effectively by controlling the aging environment of the block under an optimum of temperature and humidity correspending to initial condition of the blocks as prepared.
Preparation of large-scale compacted block of bentonite-sand mixture as HLW buffer

Yumeng Sheng, Yu Tan
Lanzhou University, China
Outline

• Background
• Compaction of the blocks
• Tests on blocks’ quality
• Conclusions
Background

Laboratory tests:
small-sized samples

Manufacturing tests:
buffer block

Mould of block type B

Sheng: Preparation of large-scale compacted block of bentonite-sand mixture as HLW buffer
Geometry of the barrier and forms of the blocks

Block type A

Block type B

(Dimension in millimeter)

Sheng: Preparation of large-scale compacted block of bentonite-sand mixture as HLW buffer
### Physical properties of materials

<table>
<thead>
<tr>
<th></th>
<th>GMZ bentonite</th>
<th>Quartz sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle diameter</td>
<td>2.70</td>
<td>Main 0.5-1mm</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>2.70</td>
<td>2.65</td>
</tr>
<tr>
<td>Plastic limit</td>
<td>28%</td>
<td>0%</td>
</tr>
<tr>
<td>Liquid limit</td>
<td>152%</td>
<td>9.56%</td>
</tr>
<tr>
<td>Air-dried moisture content</td>
<td>9.56%</td>
<td>Main 0.5-1mm</td>
</tr>
<tr>
<td>Specific gravity</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Sheng: Preparation of large-scale compacted block of bentonite-sand mixture as HLW buffer**
Block manufacturing test

(1) Mixing of bentonite-sand and water.
\[ m_{\text{bentonite}} : m_{\text{sand}} = 7 : 3 \]

(2) The mixed material is compacted into fan-shape block under 20MPa.

(3) Compacted block is ejected by the bottom piston.

Sheng: Preparation of large-scale compacted block of bentonite-sand mixture as HLW buffer
Cracks are caused by air that was entrapped in the blocks during the compaction.

Damages are caused by friction between the mould and block.

Sheng: Preparation of large-scale compacted block of bentonite-sand mixture as HLW buffer
Surface of the compacted block

Sheng: Preparation of large-scale compacted block of bentonite-sand mixture as HLW buffer
Dry density distribution of the blocks

The different value between $\rho_{dmax}$, $\rho_{dmin}$ and $\rho_{davergae}$ of blocks with different water content.
Dry density distribution of the block

Sheng: Preparation of large-scale compacted block of bentonite-sand mixture as HLW buffer
Void ratio distribution of the blocks

(1) Vertical direction
(2) Radial direction

Sheng: Preparation of large-scale compacted block of bentonite-sand mixture as HLW buffer
Water content distribution of the block

Sheng: Preparation of large-scale compacted block of bentonite-sand mixture as HLW buffer
Degree of saturation distribution of the blocks

(1) Vertical direction

(2) Radial direction

Sheng: Preparation of large-scale compacted block of bentonite-sand mixture as HLW buffer
Conclusions

1. The optimum moisture content is approximately 13% and the maximum dry density is 1.89g/cm³;

2. Relatively homogeneous buffer blocks have been produced.
Thanks for your attention!
Laboratory investigations of joints on self-sealing behavior of compacted bentonite-sand blocks

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Abstract: At present, several foreign countries have commenced the full-scale compaction test for geological disposal of high level radioactive waste. In China, compacted bentonite blocks is suggested as a prototype plan to construct the engineering barrier in HLW too. Considering the native structure property of assembly blocks and shortage of machinery in the real construction site, the joint areas as artificial defects between blocks tend to destroy the integrity of barrier system, and the self-healing performance of joint has become a new concern in engineering design.

In this presentation, two different types of laboratory tests have been carried out: permeameter test and swelling test. The main purpose of the permeameter tests was to investigate the anti-seepage performance of compacted bentonite-sand blocks with a fixed joint which was backfilled with several different materials such as bentonite powder, slurry and pallets. In these test the governing sealing process understudied is hydraulic conductivity and thermal conductivity. we observed a total recovery of the hydraulic properties, the hydraulic conductivity of samples with different joint treatment types varies between $K=2.51-4.94\times10^{-10}$ cm/s with respect to integrity sample and the average thermal conductivities of different joint treatment types are measured at $\lambda=1.43-1.63\,W/(m\cdot K)$. the bentonite pellets with grain size of 0.25-0.5mm in 70% pellet ration showed the best sealing performance.

The other swelling test was to estimate the evolution process of swelling of blocks with joint. The whole test was carried out in a rigid permeameter device and the swelling processes were monitored within joint and block. Test revealed that: with the growth of time, the swelling stress increased gradually and finally tends to be stable. It should be noticed that the swelling stress of joint exhibits an obviously phased property of time. With the further hydration of block, swelling between joint tends to push bentonite material into joint area and makes the joint being healed automatically.

Based on the existed test data, the whole engineering property of compacted bentonite-sand blocks showed good performance and the swelling pressure in the sealing process revealed a reliable self-sealing property which supply a strong guarantee in the deep geological repository construction.
Laboratory investigations of joints on self-sealing behavior of compacted bentonite-sand blocks

Ying Wang, Huyuan Zhang
Lanzhou University, China
Wang: Laboratory investigations of joints on self-sealing behavior of compacted bentonite-sand blocks
Gelogical disposal of HLW

- Engineering barrier: bentonite/bentonite-sand
- Compacted block: prototype in China
- Joints: potential defects during the installation
Research Content

(1) Sealing material of granulated bentonite pellet-powder;

(2) Engineering performance of compacted bentonite-sand blocks with joint;

(3) Analysis of tests
Research process

1. Joint preparation
2. Sealing material preparation
   - Permeameter test
   - Thermal parameter test
   - Swelling test
3. Analysis

Wang: Laboratory investigations of joints on self-sealing behavior of compacted bentonite-sand blocks
Joint and Sealing materials

➢ Compacted block

<table>
<thead>
<tr>
<th>Block</th>
<th>Water content (%)</th>
<th>Sand addition rate (%)</th>
<th>Dry density (g/cm³)</th>
<th>Joint width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>φ102mm × 20mm</td>
<td>10%</td>
<td>30</td>
<td>1.7</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 1. Sample parameter

<table>
<thead>
<tr>
<th>Bentonite</th>
<th>Specific gravity</th>
<th>Water content (%)</th>
<th>montmorillonite content(%)</th>
<th>Plastic limit (%)</th>
<th>Liquid limit (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMZ001</td>
<td>2.70</td>
<td>9.00</td>
<td>63.77-80.92</td>
<td>33.4</td>
<td>228</td>
</tr>
</tbody>
</table>

Table 2. Physical properties of bentonite

Wang: Laboratory investigations of joints on self-sealing behavior of compacted bentonite-sand blocks
Joint and Sealing materials

➢ Sealing material

1. Mixture of bentonite pellet-powder

2. Bentonite slurry

3. Bentonite power

Fig2. polished bentonite pellet

(a) 0.25-0.5mm  (b) 0.5-1mm  (c) 1-2mm

particle rate: 30%, 50%, 70%, 90%
Joint and Sealing materials

Fig 3. Accumulation volume and density vs. Particle rate ($R_g$)

Fig 4. Free expansion rate vs. Particle rate ($R_g$)

- The more effective selection:
  - Particle rate ($R_g$): 70%,
  - Particle size: 0.25-0.5mm

Wang: Laboratory investigations of joints on self-sealing behavior of compacted bentonite-sand blocks
Backfilling of the sealing materials

Joint with bentonite powder

Joint with bentonite slurry

Joint with bentonite pellet-powder
Permeability of joint system

- Range of hydraulic conductivity: \((2.51-4.94) \times 10^{-10}\) cm/s
- \(K_{\text{min}}\): Bentonite pellets-powder, \(R_g = 70\%\);
Thermal conduction of joint system

- Range of thermal conductivity \(1.43-1.63 \text{ W/(m}\cdot\text{k})\)
- \(K_{\text{min}}\): Bentonite pellets-powder, \(R_g = 70\%\)

Wang: Laboratory investigations of joints on self-sealing behavior of compacted bentonite-sand blocks
Swelling of joint system

3. Swelling stress vs. Time monitoring is still going on

Swelling stress was increased with the saturation of water.
Conclusions

1. Optimal sealing material: 70% B-pellete+30% B-powder

2. Engineering performance: block with joint show reliable properties of anti-seepage, thermal conduction as well as swelling.

3. Self-sealing property of joint supply a strong guarantee of barrier.
Thank you for your patience!
Research progress in studying Beishan granite and radioactive waste disposal project

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**Abstract:** Granite is considered to be an ideal rock for geological disposal of high level radioactive waste because of its stability, high strength and low permeability. It is also the main candidate rock of China’s high level radioactive waste disposal project. Therefore, the research on the mechanics characteristics of the surrounding rock is an important prerequisite and basis for the research and development of high-level waste geological disposal engineering technology.

Some tests (axial compression test, triaxial compression test) are performed in laboratory to analyze the mechanics characteristics of Beishan granite. Parameters (Young modulus, Poisson’s ratio, compression strength and etc.) are obtained according to the test results. It can also be concluded that the failure form of rock is closely related to confining pressure. With the increase of confining pressure, the peak compressive strength of granite is obviously improved, the non-linear behavior before the peak is strengthened, the failure form is transformed from brittle failure of single shear plane to ductile failure of multiple fracture surfaces, which has great plastic deformation characteristics in the peak stress stage. In addition, the granite exhibits obvious dilatation characteristics near the stage of failure and post-peak. Beside the tests, a lot of relevant data about the mechanics characteristics of granite of similar projects are also collected and the comparisons of the results are performed.

Numerical simulations for excavation of Beishan deep tunnel were conducted based on different strength criteria including Mohr-Coulomb, Hoek-Brown and Drucker-Prager by different numerical software such as Midas, FLAC3D and 3DEC. By comparing the results of displacement, stress and plastic zone by different software, it is proved that the simulation results by 3DEC is the most reasonable and the Hoek-Brown criterions is the most suitable for the Beishan granite which is under high geo-stress.
Detection technologies of geological safety for disposal laboratory construction

Feng Yang

China University of Mining and Technology (Beijing)

Email: yangf@cumtb.edu.cn

Abstract: For the construction of the Underground Geological Disposal Laboratory for High Radioactive Waste in granite area, the hidden small structure in the stratum threatens the construction safety. And this research on the advanced geological prediction technology for the front of tunnel excavation face and surrounding rock, and to construct the advanced prediction technology system, providing support for the construction safety for the underground disposal laboratory. Ground penetrating radar (GPR) is the main detection technology that used to predict the potential geological disasters of disposal laboratory construction in our system. Customized GPR detecting system with high precision and detection technology for granite advanced prediction with GPR devices will be introduced in this report.

In order to effectively detect the geological risks, the GPR with high precision is exclusively developed to meet the advanced prediction demand of granite area. Three parts of core content are researched for the GPR: The low frequency explosion transmitter with wideband is firstly made to improve the identification ability for deep geological disasters. The low frequency plate-style antenna is secondly developed to improve detection depth. The combined low-frequency antenna and impedance matching is finally designed to improve the transmission efficiency of the antenna. Two kinds of low-frequency shielded antennas are developed whose main frequency 50MHz and 80MHz respectively.

Detection technology for granite advanced prediction can detect the potential disasters in the process of tunnel excavation. Using GPR devices with different main frequency, the detection depth and effects are obviously different. Therefore, all kinds of GPR devices are combined and periodically used in this research, so that rich geological information including deep and shallow parts can be got from the detection results and comprehensive advanced prediction can be more accurate and more reliable. 200-400MHz antenna can be used to identify the 0.02M fracture distribution, whose detection distance range is 0-8m. The above low-frequency GPR (50-80MHz) can detect risks in medium range distance (10-30m), e.g. fissure zone and water area.

Many application cases of our GPR including detection of mine and road disaster sources are introduced, especially the detection case in the construction process of “Beishan Exploration Tunnel”. Although the advanced geological prediction technology based on GPR made great progress and the detection effect is better than others advanced detection methods, some difficulties still exist to get ideal results.
Study on the relationship between mineral composition and engineering intensity of the upper mudstone at the Bayinggebi group in the Tamusu preselected site of clay rock as the host rock for HLW repository

Pinghui Liu
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Abstract: The engineering strength of the rock is an important research direction in the evaluation of the surrounding rock of the repository. In order to evaluate the engineering and construction conditions of clay rock, the mechanical properties of the upper mudstone at the Bayinggebi Group in the Tamusu Preselected Site of clay rock were studied. By studying its mineral composition, and its chemical composition, physical and chemical characteristics and engineering strength between the factors to study, obtained the following main conclusions and understanding

(1) The average content of dolomite and clay minerals in the mineral composition of Tamusu clay rock is 70% ~ 80%; the chemical content of SiO$_2$ is the highest, with an average of 40%. The carbonate content in the rock is between 12.51% and 17.2%, and the carbonate content is comparable to the content of the dolomite in the mineral composition. The natural clay content of Tamusu clay rock is between 1.11% and 2.52%, the natural bulk density is between 2.25 and 2.65 g/cm$^3$, the particle density is between 2.41 and 2.72 g/cm$^3$, and the porosity is between 2.58 and 6.64 %. Indicating that the clay structure of the region is dense.

(2) The tensile strength of Tamusu clay rock is 10MPa, the point load intensity is 4.47MPa in the vertical bedding direction, 2.73MPa in the horizontal bedding direction, and the point anisotropy index is 1.64. The point load intensity is mainly controlled by the rock itself; The uniaxial compressive strength is 94.9MPa, and the macroscopic characteristics are uniform in particle size, small in particle size and uniform in distribution. It is found that the mechanical strength and deformation of the deep rock in the Tarim region increase with the increase of the confining pressure, and the peak stress decreases rapidly after the failure, accompanied by the rapid expansion of the volume, and the strain softens Characteristics, the cracks in the rock are unstable rupture propagation, deformation is brittle damage characteristics; In addition, due to the influence of the temperature of the clay minerals, the mechanical strength of the rock decreases with the increase of the temperature, and exhibits obvious plastic deformation under the condition of 90°C and 30MPa confining pressure.

(3) The material parameters of FLAC 3D on the experimental results of numerical simulation analysis, simulation of constitutive equation of selected Moore in Kulun model, by comparing the simulation curves recorded in the material loading test curves and real tests, found that the change trend of simulation material on the central axis of the stress and the actual test record is similar, compared with the actual macro the failure characteristics of rock in uniaxial compression test, the partial match.

(4) Comprehensive comparison of Swiss Mont Terri on physical and mechanical properties of
waste disposal underground laboratory Opalinus clay rocks and French HLW repository Meuse/Haunt Marn site Callovo-Oxfordian clay rock, clay rocks in Tamusu area have higher compressive strength, tensile strength, elastic modulus, large angle of internal friction and low cohesion. The high strength tower clay rock is beneficial to the construction and operation of the underground reservoir, especially in the environment of high stress, the damage strength of the tower is much larger than that of the foreign clay rock.
Study on Mineral Composition and Engineering Intensity of the Upper Claystone at Bayingebi Formation in Tamusu Preselected Site as Host Rock for HLW Repository

Pinghui Liu, Gengwei Rao, Long Xiang

East China University of Technology

E-mail: pinghui_liu@126.com

3rd Chinese-German Workshop on Radioactive Waste Disposal
May, 2017, Jiayuguan, China
1. Study area of Tamusu
2. Mineral composition of claystone in Tamusu area
3. Engineering intensity of claystone in Tamusu area
4. Conclusions
Introduction•Location of Tamusu area

Fig. 1 Traffic map around Tamusu area
### Tab. 1 Characteristic of sedimentary cover in Tamusu area

<table>
<thead>
<tr>
<th>Earthen</th>
<th>System</th>
<th>Series</th>
<th>Formation</th>
<th>Member</th>
<th>Thickness (m)</th>
</tr>
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<tbody>
<tr>
<td>Kz</td>
<td>Q</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>K₂</td>
<td>K₂W</td>
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<td>&gt;200</td>
</tr>
<tr>
<td>Mz</td>
<td>K</td>
<td>K₁</td>
<td>K₁b</td>
<td>K₁b²</td>
<td>&gt;911</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>K₁b¹</td>
<td>1418</td>
</tr>
<tr>
<td>J</td>
<td>J₁-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Introduction**

*target bed*
Introduction: the claystone

Deep lacustrine facies

Braided delta

Fig. 2 Profile of exploration line H16 in Tamusu area
### Preliminary results of mineral composition

Tab.2 Mineral type and content in claystone of Tamusu area

<table>
<thead>
<tr>
<th>Samples</th>
<th>% Argillaceous</th>
<th>Dolomite</th>
<th>Calcite</th>
<th>Quartz</th>
<th>Muscovite</th>
<th>Feldspar</th>
<th>Pyrite</th>
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</thead>
<tbody>
<tr>
<td>ZKH88-7-1</td>
<td>%</td>
<td>42</td>
<td>52</td>
<td>2</td>
<td>2-3</td>
<td>1</td>
<td>few</td>
</tr>
<tr>
<td>ZKH88-7-2</td>
<td>%</td>
<td>30</td>
<td>63</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>1</td>
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<tr>
<td>ZKH88-7-3</td>
<td>%</td>
<td>35</td>
<td>55</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>ZKH88-7-4</td>
<td>%</td>
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<td>59</td>
<td>1</td>
<td>5</td>
<td>•</td>
<td>1</td>
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<td>%</td>
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<td>65</td>
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<td>1-2</td>
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<tr>
<td>ZKH88-7-6</td>
<td>%</td>
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<td>58</td>
<td>4</td>
<td>2-3</td>
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<td>65</td>
<td>3</td>
<td>3</td>
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<tr>
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<td>6</td>
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<tr>
<td>ZKH36-16</td>
<td>%</td>
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<td>41</td>
<td>8</td>
<td>1</td>
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<td>ZKH8-14</td>
<td>%</td>
<td>50</td>
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<td>1</td>
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<tr>
<td>ZKH36-41</td>
<td>%</td>
<td>25</td>
<td>60</td>
<td>10</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>ZKH32-19</td>
<td>%</td>
<td>50</td>
<td>23</td>
<td>25</td>
<td>2</td>
<td></td>
<td></td>
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<tr>
<td>ZKH88-4</td>
<td>%</td>
<td>15</td>
<td>78</td>
<td>5</td>
<td>1-2</td>
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</tbody>
</table>

Method: Leitz polarizing microscope

Total contents of argillaceous and dolomite is up to 80% ~ 90%.
<table>
<thead>
<tr>
<th>No.</th>
<th>SiO₂</th>
<th>TiO₂</th>
<th>Al₂O₃</th>
<th>TFe₂O₃</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na₂O</th>
<th>K₂O</th>
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<th>LOS</th>
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<tbody>
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<td>0.12</td>
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<td>3</td>
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<td>15.22</td>
<td>7.95</td>
<td>0.16</td>
<td>5.2</td>
<td>6.9</td>
<td>5.38</td>
<td>3.34</td>
<td>0.22</td>
<td>13.32</td>
<td>99.98</td>
</tr>
<tr>
<td>4</td>
<td>40.82</td>
<td>0.81</td>
<td>14.38</td>
<td>5.77</td>
<td>0.11</td>
<td>5.37</td>
<td>8.5</td>
<td>5.15</td>
<td>3.12</td>
<td>0.12</td>
<td>15.84</td>
<td>99.99</td>
</tr>
<tr>
<td>5</td>
<td>36.02</td>
<td>0.5</td>
<td>8.81</td>
<td>2.92</td>
<td>0.12</td>
<td>9.81</td>
<td>13.51</td>
<td>3.65</td>
<td>1.42</td>
<td>0.13</td>
<td>23.22</td>
<td>100.11</td>
</tr>
</tbody>
</table>
## Preliminary results of physical properties

### Tab.4 Physical properties of claystone in Tamusu area

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>Range of values</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water content</td>
<td>1.11%~2.52%</td>
<td>1.11%~2.52%</td>
</tr>
<tr>
<td>Bulk density</td>
<td>2.25~2.65 g/cm³</td>
<td>2.41 g/cm³</td>
</tr>
<tr>
<td>Particle density</td>
<td>2.41~2.72 g/cm³</td>
<td>2.62 g/cm³</td>
</tr>
<tr>
<td>Porosity</td>
<td>2.58~6.64%</td>
<td>4.89%</td>
</tr>
</tbody>
</table>

Inner dense structure
Engineering intensity of claystone in $K_1b^2$

- Engineering intensity
  - Tensile strength test ➔ BRAZI test
  - Compressive strength test ➔ Point-load test
  - Uniaxial & Triaxial test of shallow claystone
  - Uniaxial & Triaxial test of deep claystone
The tensile strength ranges from 6.59 to 17.69 MPa with the average value of 10 MPa.
### Tab.6 Point-load test results of claystone

<table>
<thead>
<tr>
<th>Samples</th>
<th>Sampling depth (m)</th>
<th>Loading direction</th>
<th>Point load strength (MPa)</th>
<th>Mean (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZKH8-14</td>
<td>649</td>
<td>perpendicular to the bedding</td>
<td>4.68</td>
<td>4.467</td>
</tr>
<tr>
<td>ZKH8-14</td>
<td>628</td>
<td></td>
<td>4.18</td>
<td></td>
</tr>
<tr>
<td>ZKH8-14</td>
<td>617</td>
<td></td>
<td>3.52</td>
<td></td>
</tr>
<tr>
<td>ZKH36-16</td>
<td>644.64</td>
<td></td>
<td>4.09</td>
<td></td>
</tr>
<tr>
<td>ZKH32-19</td>
<td>550.5</td>
<td></td>
<td>3.21</td>
<td></td>
</tr>
<tr>
<td>ZKH32-19</td>
<td>566.0</td>
<td></td>
<td>2.61</td>
<td></td>
</tr>
<tr>
<td>ZKH32-19</td>
<td>566.9</td>
<td>parallel to the bedding</td>
<td>2.68</td>
<td>2.726</td>
</tr>
<tr>
<td>ZKH8-14</td>
<td>720</td>
<td></td>
<td>2.85</td>
<td></td>
</tr>
<tr>
<td>ZKH8-14</td>
<td>720</td>
<td></td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>ZKH8-14</td>
<td>667</td>
<td></td>
<td>2.79</td>
<td></td>
</tr>
</tbody>
</table>

Failure of perpendicular to the bedding

Failure of parallel to the bedding
Uniaxial compressive strength test of shallow claystone (room temperature) dominated by elastic deformation.
Triaxial compressive test of shallow claystone (room temperature with 5 MPa) dominated by plastic deformation
<table>
<thead>
<tr>
<th>No.</th>
<th>Samples</th>
<th>Depth (m)</th>
<th>Elastic modulus (GPa)</th>
<th>Deformation modulus (GPa)</th>
<th>Uniaxial compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ZKH0-16-3</td>
<td>650.5</td>
<td>13.331</td>
<td>11.643</td>
<td>73.55</td>
</tr>
<tr>
<td></td>
<td>ZKH0-16-4</td>
<td>650.5</td>
<td>14.133</td>
<td>6.914</td>
<td>59.48</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td></td>
<td>13.732</td>
<td>9.2785</td>
<td>66.515</td>
</tr>
<tr>
<td>2</td>
<td>ZKH8-14-1</td>
<td>605</td>
<td>19.346</td>
<td>13.215</td>
<td>128.64</td>
</tr>
<tr>
<td></td>
<td>ZKH8-14-3</td>
<td>605</td>
<td>18.379</td>
<td>15.617</td>
<td>103.93</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td></td>
<td>18.8625</td>
<td>14.416</td>
<td>116.285</td>
</tr>
<tr>
<td>3</td>
<td>ZKH24-16-2</td>
<td>600</td>
<td>16.205</td>
<td>13.562</td>
<td>98.85</td>
</tr>
<tr>
<td></td>
<td>ZKH24-16-3</td>
<td>600</td>
<td>13.903</td>
<td>8.089</td>
<td>92.72</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td></td>
<td>15.054</td>
<td>10.8255</td>
<td>95.785</td>
</tr>
<tr>
<td>4</td>
<td>ZKH80-17</td>
<td>614</td>
<td>29.024</td>
<td>24.237</td>
<td>112.8</td>
</tr>
<tr>
<td></td>
<td>ZKH80-17-1</td>
<td>622</td>
<td>19.665</td>
<td>16.341</td>
<td>117.59</td>
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<tr>
<td></td>
<td>Mean</td>
<td></td>
<td>24.3445</td>
<td>20.289</td>
<td>115.195</td>
</tr>
</tbody>
</table>

Uniaxial compressive strength ranges from 59.48 to 117.59 MPa with average value of 94.9Mpa.
Tab. 8 Triaxial compressive test results of deep claystone (room temperature)

<table>
<thead>
<tr>
<th>Samples</th>
<th>Depth (m)</th>
<th>Wallrock pressure (MPa)</th>
<th>Elastic modulus (GPa)</th>
<th>Poisson ratio</th>
<th>Triaxial compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZKH16-16-1</td>
<td>650.5</td>
<td>10</td>
<td>16.165</td>
<td>0.29</td>
<td>147.26</td>
</tr>
<tr>
<td>ZKH16-16-2</td>
<td>650.5</td>
<td>10</td>
<td>14.262</td>
<td>0.25</td>
<td>130.9</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td>15.214</td>
<td>0.27</td>
<td>139.08</td>
</tr>
<tr>
<td>ZKH16-16-3</td>
<td>620</td>
<td>20</td>
<td>23.281</td>
<td>0.28</td>
<td>293.94</td>
</tr>
<tr>
<td>ZKH16-16-4</td>
<td>641</td>
<td>20</td>
<td>22.329</td>
<td>0.28</td>
<td>250.01</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td>22.805</td>
<td>0.28</td>
<td>271.98</td>
</tr>
<tr>
<td>ZKH16-16-5</td>
<td>643</td>
<td>30</td>
<td>26.686</td>
<td>0.29</td>
<td>407.84</td>
</tr>
<tr>
<td>ZKH16-16-6</td>
<td>643</td>
<td>30</td>
<td>27.125</td>
<td>0.44</td>
<td>387.58</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td>26.906</td>
<td>0.37</td>
<td>397.71</td>
</tr>
</tbody>
</table>

Relationship between triaxial compressive strength and transverse strain and axial deformation
Relationship between triaxial compressive strength and axial strain with different wallrock pressure and temperature

### Tab.9 Triaxial compressive test results of deep claystone (different temperature)

<table>
<thead>
<tr>
<th>Samples</th>
<th>Depth (m)</th>
<th>Test temperature (℃)</th>
<th>Wallrock pressure (MPa)</th>
<th>Compressive strength (MPa)</th>
<th>Elastic modulus (GPa)</th>
<th>Poisson ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZKH32-19-1</td>
<td>550.5</td>
<td>60</td>
<td>10</td>
<td>154.72</td>
<td>20.04</td>
<td>0.2</td>
</tr>
<tr>
<td>ZKH32-19-2</td>
<td>556.9</td>
<td>60</td>
<td>20</td>
<td>202.33</td>
<td>28.72</td>
<td>0.44</td>
</tr>
<tr>
<td>ZKH36-32</td>
<td>634.65</td>
<td>60</td>
<td>30</td>
<td>265.11</td>
<td>28.45</td>
<td>0.33</td>
</tr>
<tr>
<td>ZKH32-19-3</td>
<td>556.9</td>
<td>90</td>
<td>10</td>
<td>50.91</td>
<td>29.76</td>
<td>0.2</td>
</tr>
<tr>
<td>ZKH36-16</td>
<td>644.64</td>
<td>90</td>
<td>20</td>
<td>82.26</td>
<td>14.66</td>
<td>0.26</td>
</tr>
<tr>
<td>ZKH32-19-4</td>
<td>556.4</td>
<td>90</td>
<td>30</td>
<td>100.28</td>
<td>10.43</td>
<td>0.24</td>
</tr>
</tbody>
</table>

Brittle deformation

Plastic deformation

Relationship between triaxial compressive strength and axial strain with different wallrock pressure and temperature
## Conclusions

Tab.10 Parameters comparison of claystone between Tamusu and France and Switzerland

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Tamusu</th>
<th>Opalinus in Switzerland</th>
<th>Callovo-Oxfordian in France</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burial depth (m)</td>
<td>600~770</td>
<td>600~700</td>
<td>420~550</td>
</tr>
<tr>
<td>Thickness of layer (m)</td>
<td>&gt;150</td>
<td>90~100</td>
<td>130</td>
</tr>
<tr>
<td>Water content (%)</td>
<td>1.11~2.52</td>
<td>5.0~8.9</td>
<td>2.8~8.7</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>2.58~6.64</td>
<td>14~24.7</td>
<td>9~18</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.14~0.48</td>
<td>0.16~0.32</td>
<td>0.17~0.4</td>
</tr>
<tr>
<td>Cohesion (MPa)</td>
<td>1.52</td>
<td>3.6</td>
<td>—</td>
</tr>
<tr>
<td>Uniaxial compressive strength (Mpa)</td>
<td>59.48~117.6</td>
<td>23.1~28.1</td>
<td>12~49</td>
</tr>
<tr>
<td>Tensile strength (Mpa)</td>
<td>6.59~17.69</td>
<td>1</td>
<td>0.9~5.4</td>
</tr>
<tr>
<td>Elastic modulus (GPa)</td>
<td>11.98~29.02</td>
<td>10.3~13.5</td>
<td>2.3~11</td>
</tr>
<tr>
<td>Internal friction angle (°)</td>
<td>59</td>
<td>25</td>
<td>—</td>
</tr>
</tbody>
</table>
• (1) **Mineral composition:** total contents of argillaceous and dolomite in claystone of Tamusu area is up to 80% ~ 90%, and content of SiO$_2$ with an average of 40%.

• (2) **Physical properties:** Water content: 1.11%~2.52%; bulk density: 2.25~2.65 g/cm$^3$; particle density: 2.41~2.72 g/cm$^3$; and porosity: 2.58~6.64%.

• (3) **Average tensile strength:** 10MPa; **Point load strength:** 4.47MPa perpendicular to the bedding and 2.73MPa parallel to the bedding.

• (4) The mechanical strength and deformation capacity of claystone in Tamusu area will increase with the increase of wallrock pressure and rapid expansion of volume at the same time. Meanwhile, it is noteworthy that it shift into plastic deformation at 90°C and 30MPa of wallrock pressure.

• (5) Claystone has higher compressive strength, tensile strength, elastic modulus, bigger internal friction angle and lower cohesion when comparing to claystone in France and Switzerland. The high strength claystone in Tamusu area is favorable for construction and operation of underground disposal repository, especially in geological setting with higher crustal stress.
Drill site in Tamusu

Thank you
Field experiment on deformation monitoring of surrounding rock in BET

Erbing Li

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Email: lebingest@126.com

**Abstract:** In order to evaluate the deformation and stability of surrounding rock in the process of BET construction, analyze the applicability of different monitoring methods for surrounding rock deformation and provide the basis for establishing the deformation monitoring technology system of surrounding rock during the construction of URL, the in-situ test scheme was established for the deformation monitoring of the surrounding rock, and the field experiment was carried out in BET.

The whole process of dynamic change of internal displacement of surrounding rock before and after blasting excavation in Beishan granite geological condition was captured by advanced multi-point displacement meter and high frequency automatic monitoring method. It is divided into three stages: initial growth, rapid growth and stable convergence, the monitoring results show that the displacement-time curves of the surrounding rocks obtained near the monitoring section show the characteristics of the stepped displacement of the hard rock, and the monitoring section is set 2 meters away from excavation surface, the loss displacement accounts for more than 50% of the total displacement under the geological conditions of Beishan granite.

A long-term monitoring test was carried out on the supporting structure of fracture zone in BET using the tunnel profile monitoring system (TPMS), which is mainly composed of the measurement unit and the data acquisition system. Each measuring station and the adjacent measuring arm form a measuring unit, in which the sensor body integrates an angle sensor and a displacement sensor. The long-term deformation rate of the surrounding rock is very small, and the maximum occurs at the vault, only 0.0096mm/d, which is much smaller than the engineering stability criterion. However, the stable displacement change shows that the surrounding rock has certain rheological properties in fracture zone. The results show that the TPMS can meet the requirements of high-precision, automatic and real-time measurement of long-term deformation.
Grouting in BET

Qiang Xu

The Fourth Research and Design Engineering Corporation of CNNC, Shijiazhuang 050021

Email: xuq@c-fine.com.cn

Abstract: During the process of diagenesis, geological structural movement and excavation disturbance, the development of rock fracture with different scales will be produced. The existence of these fracture brings a variety of difficulties to the safe and smooth construction of the project, especially for the security levels and long-term stability requirements for the construction of nuclear disposal repository. In our country, the Beishan area is preselected as for the nuclear waste disposal. And the fractures exist in the form of fault, intercalated gouge, dike and joint. The Shiyuejing Well, as well as the most complicated area of the geological tectonic movement in this region, includes micro-fracture, fault and other kinds of joints. Considered the water seepage of nuclear waste disposal in the process of construction and operation, the classification of fracture occurrence form, water quality ion and long-term stability requirements were analyzed. And the grouting material based on inorganic (Superfine) cement was proposed. The optimization test for grouting material was put forward through orthogonal test. The influence of the water-cement ratio, grouting pressure and the geometry of the fracture on the grouting effect is studied with numerical simulation method using UDEC program. Then the preliminary grouting parameters was proposed. In-situ grouting test was carried out in the main Shiyuejing fracture zone and ear-hole micro-fracture development area, which verifies the rationality of the initial grouting slurry, grouting parameters and grouting process. Based on the stability experiments of grouting material, a multi-stage and high-pressure grouting method was proposed to improve the fracturing slurry filling density and ensure the long-term stability.
Research on safety monitoring method of URL

Xiaoheng Duan

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Email: duanxh@c-fine.com.cn

Abstract: The underground research laboratory (URL) is an important research platform for high-level radioactive waste disposal. According to the area spatial structure model of underground laboratory in Beishan pre-selection region of Gansu Province, the risk factors of URL were analyzed. In order to ensure the safety of the URL, the environmental monitoring, personnel positioning, equipment management was studied. Use “wisdom +” integration of communication technology, form the URL management platform achieve real-time safety monitoring system, so that provide a safe place for all the people in it.
Experimental analysis study on direct tensile test of rocks in URL for high-level radioactive waste disposal

Chuancheng Liu
Shandong University
Email: 190648705@qq.com

Abstract: In recent years, in the forefront of the field of engineering, including hydropower, traffic, energy extraction and reserve, and disposal of nuclear waste, geotechnical engineering is developing rapidly. The internal crack propagation and failure of rock caused by the tensile stress is also increasing. For the tension failure of hard rock, tensile strain failure criterion should be considered to judge its destruction. The direct axial tensile test is the only way to test the ultimate tensile strain of rock.

Because of the difficulties about the rock specimen processing, the attaching to testing machine, and the control of eccentric, research on rock tensile test was carried out rarely. At present, indirect test methods such as Brazil splitting test and bending test are commonly used to test rock tensile strength. In the indirect tensile test process, the stress state of rock is very complex, and the test results must exist deviation. Meanwhile, indirect test methods cannot effectively get the tensile stress-strain curves, rock ultimate tensile strain and tensile deformation characteristics.

The rock direct tension test for granite of Beishan was carried out by using the new rock axial direct tensile test device developed independent. The tensile strength, ultimate tensile strain and tensile elastic modulus of the rocks were obtained. The whole process rock tensile stress-strain curves were also obtained. Comparative analysis the test results of the direct tensile test and indirect Brazil splitting test, the results show that: Rock tensile strength tested by direct tensile test is less than Brazil splitting test result. The results of the electron microscope scanning test of the rock fracture show that: The fracture surface of the direct tensile test is clean without rock slag, and there is no cutting or rubbing marks which is different from splitting test. The rock fracture of the direct tensile test belong to typical brittle tensile failure.
Experimental Analysis Study On Direct Tensile Test of Rocks in URL for High Level Radioactive Waste Disposal

Chuancheng Liu
Shandong University
May 17, 2017
Outline

1. Research Background of Direct Tensile Test
2. Positioning Device of Direct Tensile Test
3. Direct Tensile Test for Rocks of BS28
4. SEM Test and Micro-Mechanism Analysis of Rock Fracture
Research Background of Direct Tensile Test
The engineering rock mass can easily appear tensile failure or tensile shear failure in tensile stress zone or tensile shear stress zone.

It is unreasonable to judge the failure of rock by the yield criterion of compression shear type.

It is critical to determine the ultimate tensile strain of rock accurately in the tensile strain failure criterion.
Axial tensile test has many difficulties in rock specimen processing, connection with test machine and centering control eccentricity.

At present, indirect tests such as Brazil splitting test and bend test are usually used to test rock tensile strength.

The tensile strength measured must have errors. The complete stress-strain curve of rock under tensile stress cannot be effectively obtained.

It is difficult to process specimens in bending test. The tensile strength of rock is higher than that of split test and axial tensile test.
In spite of many difficulties, scholars have made valuable exploration on the method of rock direct tension test. 

The specimen which needs special shape is difficult to be machined and the test is difficult to carry out; there is eccentricity in the test process, especially the eccentricity between the sample and the device.
Positioning Device of Direct Tensile Test
In We have developed a centering device for the axial tensile test of rock, which includes a centering device and a centering device.

- Bonding centering device
- Stretching centering device
Positioning Device of Direct Tensile Test

1. Cylinder
2. Column
3. Upper pull head
4. Upper pull head locating sleeve
5. Wedge clamping valve
6. Test piece clamping sleeve
7. Below pull head
8. Fine tuning knob

The specimen clamping sleeve and clamping wedge valve fixed specimens, guarantee the specimen drop during adhesion and coaxial head on.

Specimen clamping effect diagram
Positioning Device of Direct Tensile Test

1. Fit Locating sleeve of lower pull head
2. Insert specimen
3. Clamping specimen
4. Splice lower pull head
5. Splice upper pull head
6. Take out the bonded specimen

The main operation steps of the centering device
The device can not only connect the tested rock sample with the universal testing machine, but also eliminate the eccentricity during the test.
Positioning Device of Direct Tensile Test

1. Fit the appropriate collet
2. Install ball hinge
3. Connect the pull head with the T slider
4. Put the T slider in the T chute

The main operation steps of Stretching centering device
It can not only test the tensile strength of rock, but also can test the ultimate tensile strain and tensile stress-strain curve of rock effectively.

Solves the problem of bonding eccentricity of the specimen.

Solves the problem of the eccentricity of rock specimen during tension.
Direct Tensile Test for Rocks of BS28
Preparation of indoor standard specimens
Process of Direct tensile test

Failure form of Direct tensile test
Most of the direct tensile failure surfaces of granite occur in the uniform tensile zone near the central part; There is no shear failure mark in the tensile failure surface of the specimen. It is a typical brittle fracture; The tensile stress-strain curve can be divided into four typical stages.
Tensile strength of rock obtained by Brazil splitting test is about 30% higher than that obtained by the direct tensile test; in order to ensure the safety of the project, the tensile strength should be tested by the direct tension test; on the premise that the test piece is not eccentric, the direct tensile test of rock is the only method to obtain the ultimate tensile strain and the complete stress-strain curve of rock.
SEM Test and Micro-Mechanism Analysis of Rock Fracture
SEM Test and Micro-Mechanism Analysis of Rock Fracture

observation samples

Vacuum plating palladium

Observation sample after gilding

Scanning electron microscopy

Process of SEM Test and EDS test
The tensile failure of rock is mainly characterized by brittle fracture.

The fracture mainly includes transgranular fracture and intergranular fracture.
The is relatively broken, the fracture edges and corners of the crystal have been polished, which has obvious shear marks.

The stress state of Brazil split specimen is very complex, not simply tensile failure.
SEM Test and Micro-Mechanism Analysis of Rock Fracture

Energy spectrum analysis results of intergranular fracture

<table>
<thead>
<tr>
<th>元素</th>
<th>重量百分比</th>
<th>原子百分比</th>
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</thead>
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<tr>
<td>C</td>
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</tr>
<tr>
<td>O</td>
<td>46.32</td>
<td>59.87</td>
</tr>
<tr>
<td>Na</td>
<td>0.37</td>
<td>0.33</td>
</tr>
<tr>
<td>Al</td>
<td>0.66</td>
<td>0.50</td>
</tr>
<tr>
<td>Si</td>
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<td>38.03</td>
</tr>
<tr>
<td>Ca</td>
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<td>0.20</td>
</tr>
<tr>
<td>总量</td>
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</tbody>
</table>

Energy spectrum analysis chart of intergranular fracture
SEM Test and Micro-Mechanism Analysis of Rock Fracture

Energy spectrum analysis results of transgranular fracture

<table>
<thead>
<tr>
<th>元素</th>
<th>重量百分比</th>
<th>原子百分比</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>45.90</td>
<td>63.98</td>
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总差 100

Energy spectrum analysis chart of Transgranular fracture
Thanks!
Introduction of the Beishan Exploration Tunnel (BET)

Liang CHEN, Ju WANG
Beijing Research Institute of Uranium Geology, CNNC
3-stage strategy for HLW disposal

1985 → 2020 → 2050

Site → URL → Repository

China National Nuclear Corporation (CNNC)
R&D Plan before 2020

Project I: Basic theoretic and technologic studies
- Design and construction technologies
- Measurement techniques of key parameters
- Security controlling system
- Long-term stability analysis

Approved in 2014

Program II: Pre-studies of URL
- Site selection
- R&D planning in URL
- Structural layout and design
- Design of security controlling system
- Data acquisition and management system

Project III: URL construction
- Surface facilities
- Shaft and access galleries
- Experimental galleries
- Other subsidiary systems

2014 2015 2017 2020
Beishan Exploration Tunnel

Location of the BET

Shi Yuejing Fault
Objectives of the project

- To provide a platform for the field experiment and validation of the technologies which will be employed in the URL construction.
- To develop the dynamic data management technologies of the URL project.
- To establish the management system of the URL construction and in situ experiment.
Distribution of the in situ tests
Working camp
Thanks!
ANNEX
3rd Chinese-German Workshop on Radioactive Waste Disposal

Jiayuguan City, China
May 15-19, 2017

Venue
Plaza Holiday Inn Jiayuguan
No.1799, S Wenhua Road
735100 Jiayuguan
Gansu Province, China
Monday, May 15
Arrival & Registration

Tuesday, May 16
08:30 Welcome address

Mr Lixin Shen, Deputy Secretary-General, Chinese Nuclear Society (CNS)
Mr Holger Wirth, Federal Ministry for Economic Affairs and Energy (BMWi)
Mr Sen Lin, Director-General, Department of International Cooperation, CNNC

08:45 Keynote: Geological disposal of high-level radioactive waste in China: Update 2017
Ju Wang, Beijing Research Institute of Uranium Geology

Topic 1: Site Selection
Chairs: Feng RONG, Walter STEININGER

09:15 Germany’s new approach for siting a nuclear waste repository
Volkmar Bräuer, Federal Institute for Geosciences and Natural Resources (BGR)

09:35 Research progress on the design of high-level radioactive waste disposal URL in china
Feng Rong, The Fourth Research and Design Engineering Corporation of CNNC

09:55 Underground exploration for mechanical and hydraulic characterization of host rocks
Jürgen Hesser, Federal Institute for Geosciences and Natural Resources (BGR)

10:15 A new rock suitability classification system for geological disposal (Q_{HLW}) and its application in China’s URL site selection
Liang Chen, Beijing Research Institute of Uranium Geology

10:35 Break

10:50 Underground application of non-destructive geophysical methods (seismic, temperature, EMR, ERT) for site investigation
Patrick Musmann, Federal Institute for Geosciences and Natural Resources (BGR)

11:10 Siting of clay formation as the potential host rock for HLW disposal repository in northwest China
Xiaodong Liu, Jiujiang University
Topic 2: Repository Concepts and Technology
Chairs: Yuemiao LIU, Hua SHAO

11:30 Concepts and emplacement technologies for an HLW repository in Germany
Niklas Bertrams, DBE Technology GmbH

11:50 Test of VPC glass in Beishan granite-GMZ bentonite barrier
Zhentao Zhang, China Institute of Atomic Energy

12:10 Disposal without monitoring? Yin without Yang?
Karl-Heinz Lux, Clausthal University of Technology

12:30 Lunch

13:30 Long-term performance of GMZ bentonite as buffer material for HLW repository in China
Yuemiao Liu, Beijing Research Institute of Uranium Geology

13:50 Laboratory investigations of HLRW bentonites
Stephan Kaufhold, Federal Institute for Geosiences and Natural Resources (BGR)

14:10 Advances in investigations into chemo-mechanical coupling effects on the volume change behavior of compacted GMZ01 bentonite
Weimin Ye, Tongji University

14:30 Sealing performance of clay-based materials
Chun-Liang Zhang, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS)

14:50 Corrosion study of low alloy steel based on the effect of trace dissolve oxygen in HLW HLW geological disposal repository
Junhua Dong, Institute of Metal Research, Chinese Academy of Sciences

15:10 Break

Topic 3: Modelling
Chairs: Xiaozhao LI, Olaf KOLDITZ

15:25 Benchmark project for flow and transport in fractured rock and coupled THM processes in bentonite
Hua Shao, Federal Institute for Geosiences and Natural Resources (BGR)

15:45 Analysis of discontinuities based on the integration of measurements, experiments and modeling
Xiaozhao Li, Nanjing University

16:05 d³f++ - Modelling tool for density-driven flow and transport
Hong Zhao, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS)
16:25 3D geological model of URL in Xinchang preselected site  
Hui Luo, Beijing Research Institute of Uranium Geology

16:45 Simulation of density-driven flow in heterogeneous and fractured porous media  
Gabriel Wittum, Goethe University Frankfurt

17:05 Break

17:20 Discrete fracture network modelling of host rock for high-level radioactive waste disposal  
Jian Liu, Beijing Research Institute of Uranium Geology

17:40 Continuous workflows for process analysis in radioactive waste disposals  
Olaf Kolditz, Helmholtz Center for Environmental Research UFZ / TU Dresden

18:00 Hydrogeological characterization of Xinchang site  
Ruili Ji, Beijing Research Institute of Uranium Geology

18:20 ReSUS: A new probabilistic and sensitivity analysis software tool and its test problems  
Xiaoshou Li, Clausthal University of Technology

18:40 Adjourn

19:00 Welcome Dinner

---

Wednesday, May 17

Topic 4: Experiments  
Chairs: Chunhe YANG, Thorsten SCHÄFER

8:30 Coupled processes controlling radionuclide behavior in nuclear waste repository compartments  
Horst Geckeis, Karlsruhe Institute of Technology, Institute for Nuclear Waste Disposal (KIT-INE)

8:50 Research on EDZ characterization system for URL: Field EDZ monitoring experiment at BET  
Chunhe Yang, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences

9:10 Mineralogical investigations of large-scale deposition tests  
Stephan Kaufhold, Federal Institute for Geosciences and Natural Resources (BGR)

9:30 The redox behavior of Beishan groundwater and its impact on U (VI) reduction by Beishan granite  
Mingliang Kang, Sun Yat-sen University

9:50 GRS’ on-site demonstration work on buffer and backfill materials  
Oliver Czaikowski, Gesellschaft für Anlage- und Reaktorsicherheit
10:10 Adsorption of some radionuclides on Beishan granite
Zhijun Guo, Lanzhou University

10:30 Break

10:45 Application of seismic and electro-magnetic reflection methods for underground investigation in a salt mine
Patrick Musmann, Federal Institute for Geosciences and Natural Resources (BGR)

11:05 The latest progress of radionuclide migration in CIAE
Duo Zhou, China Institute of Atomic Energy

11:25 Preliminary research on technical feasibility of using TBM in URL engineering
Hongsu Ma, Beijing Research Institute of Uranium Geology

**Topic 5: Safety Case Aspects**
**Chairs: Xiaodong LIU, Jens WOLF**

11:45 Advance in safety assessment of geological disposal of HLW in China at siting stage
Honghui Li, China Institute for Radiation Protection

12:05 Safety case approaches in Germany
Jens Wolf, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS)

12:25 Lunch

**Afternoon of May 17 (in 2 sessions)**

**Session 1 Repository Concept and Engineered barriers**
**Chairs: Weimin YE, Stephan KAUFHOLD**

14:00 A preliminary study on in situ tests of disposal process of high-level waste in underground research laboratory in China
Wei Hou, China Nuclear Power Engineering Co., Ltd

14:15 Performance of buffer material under coupled THM conditions
Shengfei Chao, Beijing Research Institute of Uranium Geology

14:30 Detecting the redox condition of groundwater environment in Beishan granite using fracture mineral distribution and geochemistry
Xiao Tian, Beijing Research Institute of Uranium Geology

14:45 Effects of GMZ bentonite on the corrosion evolution of NiCu low alloy steel
Xin Wei, Institute of Metal Research, Chinese Academy of Sciences

15:00 Break
15:15 Discussion on retrievability strategy of radioactive waste disposal in China  
   Xin Wang, China Nuclear Power Engineering Co., Ltd

15:30 Calculation on nuclide transport for rock cavern disposal by compartment model  
   Xiangyu Liu, China Nuclear Power Engineering Co., Ltd

15:45 Preparation of large-scale compacted block of bentonite-sand mixture as HLW buffer  
   Yumeng Sheng, Lanzhou University

16:00 Laboratory investigations of joints on self-sealing behaviour of compacted bentonite- 
   sand blocks  
   Ying Wang, Lanzhou University

Session 2 Construction Technologies & Hydrogeology  
Chairs: Liang CHEN, Chun-Liang ZHANG

14:00 Research progress in studying Beishan granite and radioactive waste disposal project  
   Yujie Yang, China Institute of Water Resources and Hydropower Research

14:15 Detection technologies of geological safety for disposal laboratory construction  
   Feng Yang, China University of Mining & Technology, Beijing

14:30 Study on the relationship between mineral composition and engineering intensity of the upper mudstone at the Bayinggebi group in the Tamusu preselected site of clay rock as the host rock for HLW repository  
   Pinghui Liu, East China University of Technology

14:45 Field experiment on deformation monitoring of surrounding rock in BET  
   Erbing Li, PLA University of science and technology

15:00 Break

15:15 Grouting in BET  
   Qiang Xu, The Forth Research and Design Engineering Corporation of CNNC

15:30 Research on safety monitoring method of URL  
   Xiaoheng Duan, The Fourth Research and Design Engineering Corporation of CNNC

15:45 Experimental analysis study on direct tensile test of rocks in URL for high-level radioactive waste disposal  
   Chuancheng Liu, Shandong University

16:00 Break

16:30 Concluding remarks

17:00 Adjourn

18:00 Dinner
Technical Tours

Thursday, May 18

06:20  Breakfast

07:00  Meet at Hotel Parking Lot and Departure for Beishan site & BET by Bus

- Bus No 1: Jiayuguan > Beishan > Dunhuang
- Technical Visit BET at the Beishan Site (overnight in Dunhuang)
- Bus No 2: Jiayuguan > Beishan > Jiayuguan

11:30  Arrival & Visit BET

13:00  Departure for Dunhuang
14:00  Departure for Jiayuguan

Friday, May 19

Group 1: Visit Mogao Caves in Dunhuang City, then go back to Jiayuguan
Group 2: Visit the Great Wall in Jiayuguan

Saturday, May 20

Leave Jiayuguan for home
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