Proceedings of the Workshop "Final Disposal in Deep Boreholes Using Multiple Geological Barriers: Digging Deeper for Safety" Juni 2015, Berlin

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Gesellschaft für Anlagen-
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Proceedings of the Workshop "Final Disposal in Deep Boreholes Using Multiple Geological Barriers: Digging Deeper for Safety" Juni 2015, Berlin

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Inhaltsverzeichnis

1 Introduction

1.1 Im Spannungsfeld…

…zwischen der Überzeugung, dass es bezüglich der Endlagerung radioaktiver Abfälle einen ausgezeichneten Stand von Wissenschaft und Technik gibt und dass eine Standortfindung schwierig ist, entstand bei Einigen der Gedanke eine Alternative zu der bisher betrachteten Option der Endlagerung in einem Bergwerk zu untersuchen.

In vielen, zunächst vorsichtig sondierenden, Gesprächen mit Erfahrungsträgern aus dem Bereich der Tiefbohrtechnik (Öl und Gas), Tiefen Geothermie und Bohrlochmesstechnik näherte man sich der Idee einer genaueren Betrachtung der Option einer Endlagerung von radioaktiven Abfällen in tiefen Bohrlöchern.

Es zeigte sich schnell, dass auch für eine solche Idee eine große Anzahl von technisch grundsätzlich machbaren Varianten betrachtet werden könnte.

Selbstverständlich steht am Anfang diesbezüglicher weiterer Überlegungen ein Konzept, das eine erste Bewertung dieser möglichen Varianten auf Machbarkeit und Sinnfälligkeit ermöglicht. Auf dieser Grundlage kann eine Entscheidung in Bezug auf ein entsprechendes Untersuchungsprogramm für eine vertiefende Bewertung getroffen werden.

Dabei ist insbesondere zu berücksichtigen, dass eine Endlagerung in tiefen Bohrlöchern einer eigenen Langzeitsicherheitskonzeption bedarf, um Vor- und Nachteile einer Endlagerung in tiefen Bohrlöchern fundiert bewerten werden könnten.

Bei den Herausgebern dieser Proceedings besteht ein Konsens mit den Aussagen von Andrew Orrell bei der Anhörung der Arbeitsgruppe 3 der Kommission… am 08. Juni 2015:

„… Jeder Gesteinstyp (Salz, Ton, Kristallin) und jedes Endlagerkonzept (Bergbau oder Tiefes Bohrloch) hat – aus rein technischer Sicht - seine spezifischen Vor- und Nachteile. Man kann schnell Argumente für die Einlagerung bestimmter Abfälle in den verschiedenen geologischen Situationen und Einlagerungsmethoden finden. Jedes Einlagerungskonzept besteht aus einer Kombination von natürlichen und technischen Barrieren. Viele der Konzepte mögen für unterschiedliche Arten von Abfällen anwendbar sein.

Dabei ist es nicht einfach zwischen “besseren” und den “besten“ Konzepten zu entscheiden, da es sich jeweils um komplexe Systeme handelt, die über sehr lange Zeiträume sicher funktionieren müssen.

Deswegen wird eine ausreichende Isolierung der Abfälle vor dem Hintergrund der jeweiligen rechtlichen Anforderungen mit einem großen Vertrauen in die Zuverlässigkeit der Bewertung und die Dauerhaftigkeit des Ergebnisses von allen angestrebt.“

In diesem Sinne…

Der Reiz,

vielleicht den gordischen Knoten der Endlagerung zu durchschlagen,
das Vertrauen der Bevölkerung zu gewinnen,
die Distanz der Radionuklide zu dem Bereich, der unsere Lebensgrundlagen sichert, dem Bereich der für die Trinkwassergewinnung nutzbaren Grundwasserleiter, dem Bereich der für die Lebensmittelgewinnung nutzbaren Böden - zur Biosphäre - deutlich zu erhöhen,
die Chance zu vergrößern, dass die Radionuklide, die möglicherweise dennoch auf diesem Weg gelangen, besser zurückgehalten werden,

trieb die Herausgeber an diese Option ernsthaft zu diskutieren.

Ein Charme

einer Endlagerung in tiefen Bohrlöchern liegt ja auch darin, dass man in den Fällen, in denen sich nach Fertigung des Bohrloches herausstellt, dass ein Standort nicht geeignet ist, dieses Bohrloch aufgeben kann. Diese Möglichkeit ist bei einem Bergwerk – ist es erst einmal aufgefahren – zwar gegeben, ist aber mit einem deutlich höheren Aufwand, deutlich höheren Kosten, verbunden.

Eine Akzeptanz,

das wissen alle Beteiligten, die die Etappen – von manchen als Stationen eines Kreuzwegs empfunden – auf dem Weg zu einem Endlager für radioaktive Abfälle gestalten oder begleiten, ist nur durch breite Kommunikation, größte Offenheit und durch Empathie getragenes Verständnis für die Sorgen der Bevölkerung und das Anbieten von ernsthaften Wahlalternativen zu erreichen.

Vor dem Hintergrund der Haltung „Endlager ja, aber nicht bei uns“ ist man eher bereit negative Einflüsse auf unsere Lebensqualität zu akzeptieren, wenn diese auch viele andere Menschen betreffen („geteiltes Leid ist halbes Leid“). Eine Verteilung von Endlagerstandorten auf mehrere Bundesländer würde dieser Befindlichkeit entgegenkommen.

Kosten

Eine Endlagerung in tiefen Bohrlöchern könnte nach ersten Schätzungen unter denen für die Auffahrung und Betrieb eines Bergwerks liegen.

Es ist Zeit

die Gefahren, die mit einer langfristigen Zwischenlagerung hoch radioaktiver Abfälle verbunden sind, baldmöglichst zu beseitigen. Die Schaffung der expliziten wissenschaftlich-technischen Rahmenbedingungen für zügig durchführbare Endlageroptionen ist daher erstrebenswert.

2 International status and safety requirements

2.1.1 Orrell A.: On the Genesis of the Recent U.S. R&D Concerning the Deep Borehole Disposal Concept

Andrew Orrell, Section Head for Waste and Environmental Safety, Division of Nuclear Safety and Security, International Atomic Energy Agency

Note: Any comments or opinions expressed are those of the author, and do not necessarily represent those of the IAEA unless explicitly stated.

2.1.2 Foreword

This brief paper accompanies the presentation given at the opening of the international expert workshop "Final Disposal in Deep Borehole Using Multiple Geologic Barriers" held June 5 & 6, 2015 near Berlin, Germany. Further, the text herein is adapted from testimony provided by the author on June 8, 2015 to the German Bundestag's Commission on the Storage of Highly Radioactive Materials and the Working Group 3 on societal, technological and scientific decision-making criteria /ORR 15/.

As countries continue to contemplate solutions to the disposal of radioactive waste in deep geologic environments, several are also deliberating the potential alternatives to a traditional mined repository, a solution for which the technical feasibility is less in doubt than the socio-political achievability. As several countries have painfully experienced, the reliance on a single repository model comes with the real risk of having a single point of failure. But with the advancements of drilling technology of the past several decades, driven by the oil & gas and geothermal industries, the deep borehole disposal concept (i.e. up to 5 km deep, large diameter bores in crystalline rock) is now considered by many to be technically feasible while offering a potentially different social-political dynamic to siting and operation. The quality of the workshop discussions, and a visit to the KTB drill site were compelling to these very issues of deep borehole disposal feasibility.

So what led to the more recent interest in the U.S. to pursue the research, development and demonstration of the deep borehole concept? Similar to many national programs, Germany's included, current efforts and directions are a reflection of its past attempts to achieve a deep geologic disposal facility.

2.1.3 Historical Outline

As for the U.S., after many years and considerable expense, the world's first safety case and license application for a deep geologic repository for SNF and HLW, at Yucca Mountain, Nevada, was delivered to the Nuclear Regulatory Commission in June 2008. In about 2009, the new U.S. President Obama effectively cancelled further development of the Yucca Mountain repository with the zeroing of congressional appropriations for the project. One could say this was in recognition that the existing policies for waste management had been troubled for decades, and as the Secretary of Energy put it; "*Yucca Mountain was no longer a viable option*". Subsequently, President Obama directed the formation of a federal advisory commission, which by law are limited to two years, its membership should be fairly balanced in its points of view and represent a cross-section of interests, and the public should be afforded ample opportunity to provide input.

2.1.4 Blue Ribbon Commission

Thus, the Blue Ribbon Commission on America's Nuclear Future (BRC) was formed in January 2010 to conduct a comprehensive review of strategies and programs for managing radioactive waste, including disposal options, and to recommend new strategies. The parallels are obvious between the developments in the U.S. and German programs and their subsequent advisory commissions, the BRC and the Bundestag's Commission on the Storage of Highly Radioactive Materials, respectively. In January 2012, the BRC delivered its final report and was disbanded. A few key points from the BRC final report that are relevant to deep boreholes are noted below.

The BRC noted "*...we [this commission representing this generation] owe it to future generations to avoid foreclosing options wherever possible so that they can make choices... about the management of the nuclear fuel cycle [including waste and disposal]...based on emerging technologies and developments and their own best interests.*"

To this end, the BRC was sensitive to its responsibilities, and to not rush to judgement, for or against, an emerging technology that could be of interest to the next generation, as the one which will undoubtedly inherit the problem of nuclear waste disposal that this generation has struggled to implement. Thus while it may be arguable whether deep borehole disposal technology is emerging or presently available, the caution remains the same to not unreasonably preclude certain technologies and foreclose options to the next generation. This is often said in regard to advanced nuclear fuel cycles, and the same should be said for disposal concepts and options.

As evident in the next excerpt from their report, the BRC thoroughly evaluated the deep borehole disposal concept and technology, and was unequivocal by explicitly including it in their recommendations, stating: "*The advantages have been cited that support further efforts to investigate the deep borehole option. These include the potential to achieve (compared to mined geologic repositories) reduced mobility of radionuclides and greater isolation of waste, greater tolerance for waste heat generation, modularity and flexibility in terms of expanding disposal capacity, and compatibility with a larger number and variety of possible sites.*" … "*Overall, the Commission recommends further RD&D to help resolve some of the current uncertainties about deep borehole disposal and to allow for a more comprehensive (and conclusive) evaluation of the potential practicality of licensing and deploying this approach, particularly as a disposal alternative for certain forms of waste that have essentially no potential for re-use. Likewise, EPA and NRC should begin work on a regulatory framework for borehole disposal, in parallel with their development of a site-independent safety standard for mined geologic repositories, to support the RD&D effort leading to licensed demonstration of the borehole concept.*" … "*DOE should develop an RD&D plan and roadmap for taking the borehole disposal concept to the point of a licensed demonstration.*"

Here the BRC fully recognizes the deep borehole disposal concept is less well understood from a licensing perspective, while recognizing the potential benefits warrant further development by demonstration. After the BRC final report report of January 2012, the Administration issued a response in January 2013, stating: "*In FY 2013, the Department is undertaking disposal-related research and development work in the following areas: an evaluation of whether direct disposal of existing storage containers used at utility sites can be accomplished in various geologic media; an evaluation of various types and design features of back-filled engineered barriers systems and materials; evaluating geologic media for their impacts on waste isolation; evaluating thermal management options for various geologic media; establishing cooperative agreements with international programs; and developing a research and development plan for deep borehole disposal, consistent with BRC recommendations.*"

2.1.5 Administration

Drawing attention on the last two points of the Administration's response; first the federal-level intent to support development of a deep borehole disposal option which will be further discussed in a moment, and second, the intent to establish cooperative agreements with international programs. If Germany opts to similarly develop deep borehole disposal, it is possible that a cooperative agreement could be reached for mutual benefit and accelerating the availability of the deep borehole disposal concept. This would be very similar to the very fruitful U.S. - German collaborations in salt repository science that have now been fostered for more than two decades.

Lastly, it is noted the U.S. government in March of 2015, issued a draft Request for Proposals for a field-test of the deep borehole disposal concept, with the intent in the next four years to

1. site and drill two separate 5 km deep boreholes; a 21.6 cm characterization borehole, and a field test borehole at 43.2 cm at total depth,
2. characterize and test bedrock in-situ conditions,
3. collect relevant geochemical profiles, and,
4. demonstrate the emplacement and retrieval of surrogate canisters.

This demonstration, while not specifically for spent nuclear fuel (perhaps due to unresolved legal issues surrounding Yucca Mountain), does share many of the same design elements and objectives for such a system. Such a demonstration will fulfil a key recommendation of the BRC and a key element of the current Administration's efforts to address the disposal of radioactive waste. Regardless, the commitment of the federal government does not come without considerable review and deliberation on the merits of such an investment. Post-workshop, in January 2016, the U.S. selected one of the several teams which responded to the request for proposals.

The socio-political events are not the only factor, but were instrumental to the most recent decisions and commitments to pursue the development and demonstration of a deep borehole in the U.S. While the concept has been studied academically off and on for many decades, in the last 10 years more detailed engineering, safety case, and performance assessment studies by researchers at e.g. Massachusetts Institute of Technology, Sandia National Laboratories, University of Sheffield, and others, have contributed greatly to the growing sense of feasibility and the value of a large-scale demonstration, with the ultimate goal of developing an additional option for achieving safe disposal.

It is the very notion of 'safe disposal' that contributes to the renewed search for disposal options, in the U.S., Germany, and elsewhere. So what is 'safe disposal' and how might the deep borehole concept contribute to it?

2.1.6 Disposal Safety

Any geologic repository concept, especially for long-lived radioisotopes requiring long-term isolation and containment, must be approached from the perspective of understanding what constitutes safety, how to achieve it, and how to demonstrate compliance with safety performance criteria to a regulator and a generally wary public. One must take into consideration all the various factual data (and its sometimes large uncertainties) from all the various sub-disciplines (i.e. hydrology, geomechanics, radiochemistry, corrosion, engineering, etc.) and evaluate the overall system performance, i.e. safety with respect to the *confidence* one has in the system to *contain and isolate the waste* from the accessible environment.

The basic objective or standard of performance for any geologic disposal of radioactive wastes as articulated by the IAEA is: "to provide sufficient isolation, both from human activity and from dynamic natural processes, that eventual releases of radionuclides will be in such low concentrations that they do not pose a hazard to human health and the natural environment." The key here is the level of confidence one has in the system performance for achieving and maintaining waste isolation, and the defensibility of that assessment before the questioning attitude of a regulator and public.

Every rock type (salt, clay, crystalline) and disposal concept (mined or borehole) have their particular advantages and disadvantages from a strictly technical perspective. It is readily argued that different geologic settings and emplacement methods may be better for particular types of waste. However, as every repository concept has a combination of natural and engineered barriers and some measure of defense in depth (i.e. multiple barriers) many or all of the concepts may ultimately be found to demonstrate acceptable performance for a wide range of wastes. There are no simple measures of "better" or "best" when dealing with complex systems that will evolve over millennia. Thus 'repository scientists and engineers' seek "sufficient isolation", i.e. below regulatory criteria, and with a high confidence in the defensibility of the assessment and the result.

Considering the programmatic aspects of a repository for disposal for long-lived radioactive waste, it is suggested that the operator/licensee, the regulator and the public, all share an interest in achieving a high-confidence in the isolation and containment performance over very long time frames (i.e. the risk to future generations is no greater than the current generation accepts for itself), and doing so at a reasonable cost to the current generation. And since often ‘time is money’, the time for development and operations is also a figure of merit. From a technical aspect, and from experience with developing the safety case for geologic repositories the desirable features and characteristics of a geologic repository such as large diffusive barriers, reducing environments, minimal use of engineered barriers, etc., contribute to a higher confidence in the long-term performance of the repository. It is noted that the intrinsic sense of disposal isolation in a deep borehole is largely shared with salt-based and perhaps clay-based repositories; crystalline rock based repositories, while effective, depend more on the performance of the engineered barriers.

Work to date on analyzing deep borehole disposal concepts supports the position that long-term performance confidence is high:

5. The disposal zone of a deep borehole system approximately 3 - 5 km below the surface is expected to be density stratified, and to have long residence times, reducing conditions, low permeability and lack hydraulic connection to shallow groundwater, where dose criteria would normally be assessed. The multi-kilometer plug and seal zone, in addition to the surrounding host rock, provides a long diffusive barrier and substantial defence in depth by the provision of multiple barrier components in the seal system.

6. From a safety assessment perspective, the multi-kilometer depth of deep borehole disposal more effectively decouples the repository from the biosphere effects and consequences on dose. An element of all mined repositories (those of a few hundred meters below the surface) is their greater potential for interactions between surface phenomena and the underground, complicating the safety case and assessment of performance.

All traditional mined repositories present some unique challenges that are a consequence of their location being only a few hundreds of meters below the surface, meaning consequential interactions with the accessible environment can’t be easily ruled out. Traditional mined repositories are loosely to tightly coupled to the surface biosphere effects, which complicates the process of understanding the effects of the biosphere on the repository and the effects of the repository on the biosphere. Most repository development programmes in mined repositories, spend considerable time and money on those very interactions between the surface and disposal environment (e.g. infiltration, corrosion, transport, etc.) in the effort to assert a confident understanding of their evolution and consequence on the performance of the system (e.g. as determined by dose).

In contrast to most mined repositories, the apparent smaller number of features, events and processes that would require inclusion in a performance assessment (many such phenomena could be screened out based on a lack of consequence) could reduce the time and cost of site characterization and for developing a high-confidence safety case and licensing basis.

Researchers at Sandia National Laboratories published in 2009 a very conservative safety assessment evaluation of a deep borehole disposal concept for spent nuclear fuel. The results were notable for the extremely low, diffusion-limited dose rates. Considering uncertainty and sensitivity, the system was thought robust, that is having few factors that would perturb that performance. And with regard to a hypothetical licensing, there was readily documented high confidence and conservatism in the known or assumed parameters, which tends to make for defensible safety cases and license applications. Beyond performance, cost and schedule were also estimated based on available analogues from the geothermal industry and even when scaled by experience with government-responsible operations, the numbers were again compelling in contrast to what is known about many mined repositories.

2.1.7 Feasibility

So if the concept of deep borehole disposal is compelling, it is feasible? On the issue of feasibility, all evidence would suggest it is possible, with today's technology to develop large diameter boreholes in crystalline rock of depths to 5 km. The German KTB (Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland) and several other similar boreholes around the world provide compelling 'engineering analogues' for the feasibility of developing and implementing the deep boreholes disposal option.

The KTB hole did reach at total depth of 9.1 km in challenging crystalline rock. Perhaps more importantly, in the first 2 years, from 1990 to 1992, the KTB hole was drilled AND cased with 13 3/8 inch (.34 m) casing to a depth of 6 km. This leaves little doubt that continued engineering and innovation could readily achieve a slightly wider diameter to only 5 km. Experienced representatives from several drilling companies, in Germany and at other workshops held in the U.S. echo this conclusion. To the observation that such diameters and depths have not been demonstrated in crystalline rock is explained simply by the lack of a prior commercial need or benefit. The application of all existing technology to new uses is not demonstrated until it is.

So if the concept of deep borehole disposal affords high-confidence waste isolation, and is technically feasible, then the question becomes is it licensable in a regulatory setting? Noting that most national programs call for only one national repository facility, issues of equity in benefit and burden, and the concomitant socio-political tensions arise. If a national waste management program were of a size to only need one mined facility or one borehole, it is not clear if the socio-political issues would be substantially different, with the possible exception of the issues noted above regarding performance confidence, license defensibility, cost profiles, etc. If however, the national strategy or program was such that multiple boreholes were contemplated, perhaps simultaneously in different locations, then a different socio-political dynamic could occur. It is only possible to touch on the technical potential for licensing issues here…the issues of the socio-political aspects of licensing are deferred to another discussion.

To evaluate the strength of a licensing (i.e. the technical defensibility of the safety case) there are a numerous issues such as data quality assurance, repeatability, representativeness, the treatment of epistemic and aleatoric uncertainty, alternative conceptual models, parameter distributions, coupled effects, etc. that must be considered. Beyond the technical parameters affecting dose assessments, there are operational safety issues; package handling and transport, retrievability, etc. that may come into play. The assembly of a defensible licensing safety case, pre- and post-closure, is not a trivial exercise, but every geologic repository concept has this challenge.

To judge whether a particular safety case is defensible and would be compliant with (known or assumed) licensing criteria without a rigorous analytical, documented and reviewed effort should be based more on actual experience and less on conjecture. Based on the experience of numerous professionals that have or had direct involvement in licensing and safety case development, the answer to the defensibility of a deep borehole safety case is a qualified yes.

On a first order, such judgements need at a minimum to know or reasonably assume:

7. a specific site and its characteristics,
8. the waste type and its characteristics,
9. the regulatory framework, criteria, standards, etc. and,
10. a description of the disposal concept, including the engineered barriers, in sufficient detail.

For most any repository concept not formally proposed, one can only make assumptions for much of the content that would be needed. By employing known or reliable analogues, and applying appropriate conservatisms, one can develop a sense of the strengths and weaknesses of a particular hypothetical licensing effort. In the case of evaluating deep borehole disposal in crystalline rock, these principles were applied in the 2009 Sandia report, and continue to be applied in all subsequent work, with the same result of a qualified sense of confidence as to the ability to license. Most uncertain perhaps are the licensing criteria and specifically the issue of retrievability.

The BRC recognized that the same level of retrievability common to mined repositories may not be practical or even necessary in the context of other disposal approaches, such as deep boreholes. The BRC recommended related regulatory requirements and time periods can and should be reassessed as part of a larger evaluation of disposal system performance objectives. The issues of retrievability, whether for mined or borehole systems, can only be adequately addressed when the purpose, intent, criteria and applicable timeframe for retrievability are understood. But from an engineering sense, the same confidence and experience that supports the drilling and emplacement of waste in a deep borehole is the same that supports that assertion that retrievability can be, if necessary, achieved. Only for disposal systems that are designed primarily for retrievability would such operation be more facilitated. Regardless, the IAEA Specific Safety Requirements # SSR-5, Disposal of Radioactive Waste /IAEA 11/, notes: "*No relaxation of safety standards or requirements could be allowed on the grounds that waste retrieval may be possible or may be facilitated by a particular provision. It would have to be ensured that any such provision would not have an unacceptable adverse effect on safety or on the performance of the disposal system.*" In short, the provision for retrievability, in a mined or borehole disposal concept, is not to supplant long-term safety or relax the requirements for the same.

2.1.8 Conclusion

In conclusion, no safety case or license could ever proceed on assertions alone, however expert. It is for these reasons that a large-scale demonstration, whether in the U.S. or elsewhere, is advised, and preferably with the collaboration of international partners sharing an interest in achieving much needed capacity and a manifestation of the disposal of radioactive waste and/or spent nuclear fuel. The hard evidence now available supports the conclusion that the deep borehole disposal concept should provide high confidence in long-term performance for safety, is technically feasible, and could be readily licensed under appropriate regulatory frameworks. Thus the addition of deep borehole disposal capability could provide a much-needed high-level waste disposal capacity and option. This may be especially true for those countries with smaller nuclear programmes that can ill afford the time and cost profile of a traditional mined deep geologic repository facility.

Lastly, it is emphasized that this should not be a question of whether to pursue only mined or only borehole based disposal. The point of this discussion is not suggest that deep borehole disposal is the best or only solution for geologic disposal, but rather to point out that the concept holds such significant promise that it warrants consideration of an effort to accelerate its pilot demonstration, and to vet its true feasibility and viability. Indeed, the intent of this discussion is to encourage the pursuit of both concepts in order to provide a waste management system with needed capability, capacity and the flexibility to perhaps begin to achieve this generation's obligation to safely dispose of the radioactive waste it produced and to avoid leaving it to future generations.

References

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/ORR 15/ Orrell, A.: Statement des Sachverständigen Andrew Orrell, International Atomic Energy Agency. Anhörung „Tiefe Bohrlöcher“ in der 9. Sitzung der Arbeitsgruppe 3 am 8. Juni 2015. Ed.: Kommission Lagerung hoch radioaktiver Abfallstoffe gemäß § 3 Standortauswahlgesetz, K-Drs./AG3-26, 7 pp., 2015, cited on 8 March 2016.

Final Disposal in Deep Boreholes Using Multiple Geologic Barriers: Digging Deeper for Safety

Genesis of the US R&D Program for Deep Borehole Disposal

Andrew Orrell

International Expert-Workshop on June 5 and June 6, 2015

IAEA

International Atomic Energy Agency

Outline

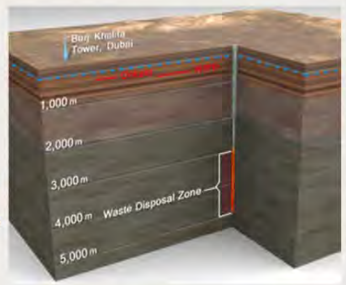
- Objective
- Concept
- History
- Recent U.S. Developments
  - Motivations for a Renewed Consideration
  - 2008-2013
- Final Thoughts

Objective

- To understand the context of what led to the current momentum to develop deep borehole disposal concept
- To accelerate and contribute to your own deliberations on whether to pursue

Deep Borehole Disposal Concept

- Disposal concept consists of drilling a borehole or array of boreholes into crystalline basement rock to about 5,000 m depth to ~45 cm diameter
  - Bottom hole diameter
    - 17 in. for bulk waste forms or SNF/HLW
    - 8.5 in. for smaller DOE-managed waste forms
- Borehole casing or liner assures unrestricted emplacement of waste canisters
- Waste would consist of spent nuclear fuel and/or high-level radioactive waste
- Approximately 400 waste canisters would be emplaced in the lower 2,000 m of the borehole
- Upper borehole would be sealed with compacted bentonite clay, cement plugs, and cemented backfill



4

5 Km Paths

x 13.5 = 5 KM.

Tallest structure in Germany, Berliner Fernsehturm

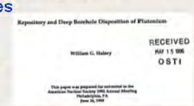
Asserted Benefits of DBH Disposal Concepts

- Crystalline basement rocks are relatively common at depths of 2 km to 5km
- Disposal could occur at multiple locations, reducing waste transportation costs and risks
  - Greater potential for site to site performance comparability, possibly avoiding 'best site' contentions, fostering equity and fairness issues.
- Low permeability and high salinity in the deep crystalline basement suggest extremely limited interaction with shallow groundwater resources; high confidence isolation
- Thermal loading issues are minimized
- Geochemically reducing conditions limit solubility and enhance the sorption of many radionuclides
- Retrievability is difficult, but not impossible
- Compatible with multiple waste forms and types (e.g. CANDU bundles, PWR w/ or w/o rod consolidation)
- The deep borehole disposal concept is modular, with construction and operational costs scaling approximately linearly with waste inventory
- Existing drilling technology permits construction of boreholes at a cost of about $20 million each
  - Low cost facilitates abandonment of emplacement-ready holes that fail to meet minimum criteria, limits 'make it work' perceptions
- Disposal capacity of ~950 boreholes would allow disposal of projected US SNF inventory
  - Dry Rod Consolidation (demonstrated at INL in the 80's and at present in Germany, Sweden) could reduce this by ~1/2, or possibly further reduce costs for smaller hole bottom diameter

Source: Brady, P.V., B.W. Arnold, G.A. Freeze, P.N. Swift, S.J. Bauer, J.L. Kanney, R.P. Rechard, J.S. Stein, 2009, *Deep Borehole Disposal of High-Level Radioactive Waste*, SAND2009-4401, Sandia National Laboratories, Albuquerque, NM, and Technology and Policy Aspects of Deep Borehole Nuclear Waste Disposal, M.J. Driscoll, R.K. Lester, K.G. Jensen (MIT), B.W. Arnold, P.N. Swift, and P.V. Brady (SNL)

History of Deep Borehole Disposal

- Deep borehole disposal of high-level waste (HLW) has been considered in the US since 1950s
- Deep borehole disposal of spent nuclear fuel and HLW has been studied in increasing detail periodically since the 1970s to the present (mostly in paper studies), usually in relation to various pressures
  - **Disposal of surplus weapons Pu**
  - **Disposal of vitrified or cemented wastes**
  - **Disposal of fuel assemblies (with or without rod consolidation)**
  - **Melting of host rock to encapsulate waste**
- Time was not ripe
  - **Technological risks lower with u/g mining**
  - **Technical capability absent**
- What has Changed?
  - **Drilling technology capability has greatly increased**
  - **Experience with mined disposal repositories**
  - **New pressures for disposal**


Repository and Deep Borehole Disposition of Plutonium

William G. Halsey

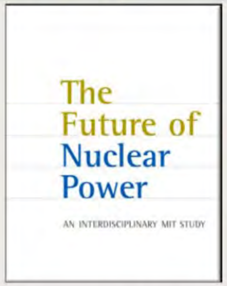
RECEIVED

OSTI

Recent U.S. Developments

MOTIVATIONS FOR A RENEWED CONSIDERATION

Deep Borehole Disposal
MIT July 2003



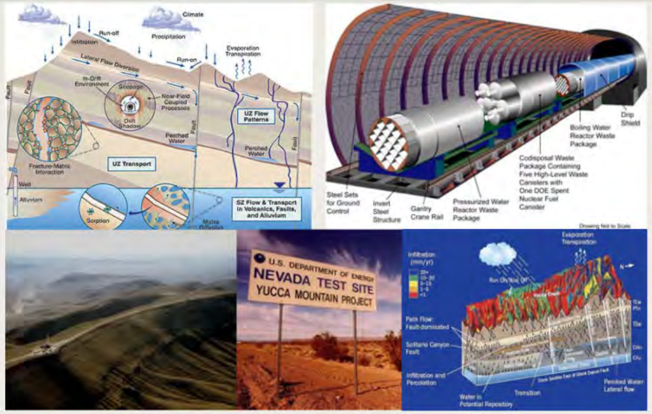
"We further conclude that waste management strategies in the once-through fuel cycle are potentially available that could yield long-term risk reductions at least as great as those claimed for waste partitioning and transmutation, with fewer short-term risks and lower development and deployment costs. *These include both incremental improvements to the current mainstream mined repositories approach and more far-reaching innovations such as deep borehole disposal."*

"More attention needs to be given to the characterization of waste forms and engineered barriers, followed by development and testing of engineered barrier systems. *We believe deep boreholes, as an alternative to mined repositories, should be aggressively pursued.* These issues are inherently of international interest in the growth scenario and should be pursed in such a context.

***"A research program should be launched to determine the viability of geologic disposal in deep boreholes within a decade. "* (Listed as one of the principle recommendations on waste management – July 2003)**

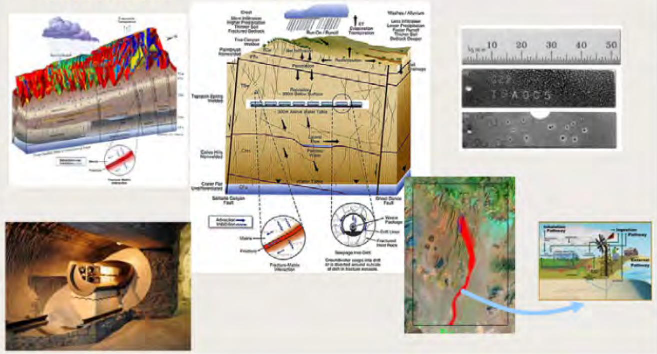
Professors John Deutch and Ernest Moniz Chaired Effort to Identify Barriers and Solutions for Nuclear Option in Reducing Greenhouse Gases

Perspectives from a Mined Repository

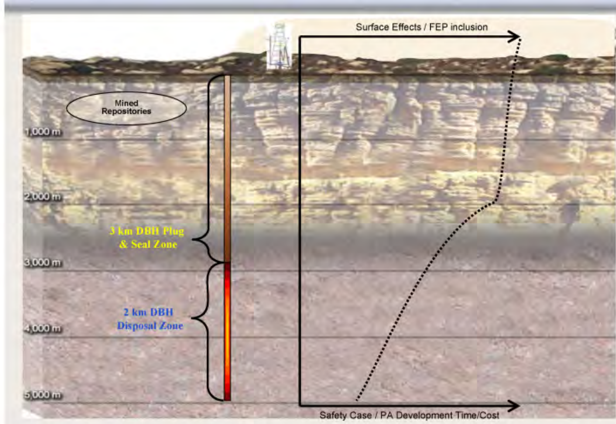


Mined Repositories

- Coupling between the surface and near-field disposal environment



Deep Borehole Disposal Concept
Faster, Cheaper, Better Drivers



Performance Assessment
August 2009

SANDIA REPORT
SAND2009-4401
Unlimited Release
Printed August 2009

Deep Borehole Disposal of High-Level Radioactive Waste

Patrick V. Brady, Bill W. Arnold, Geoff A. Freeze, Peter N. Swift, Stephen J. Bauer, Joseph L. Kanney, Robert P. Rechard, Joshua S. Stein

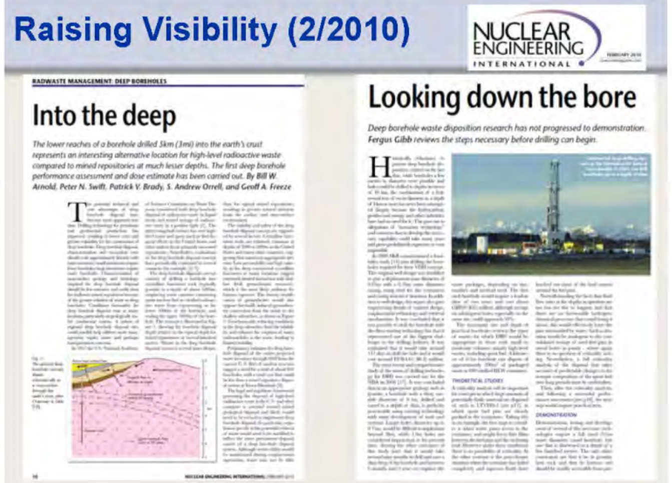
Sandia National Laboratories

Preliminary analysis suggests excellent long-term performance

- Conservative estimate of deep borehole peak dose to a hypothetical human withdrawing groundwater above the disposal hole is
- 1.4 x 10-10 mrem/yr (1.4 x 10-12 mSv/yr)
- YMP standard is 15 mrem/yr (< 10,000 yrs) and 100 mrem/yr (peak dose to 1M yrs)

Source: Brady, P.V., B.W. Arnold, G.A. Freeze, P.N. Swift, S.J. Bauer, J.L. Kanney, R.P. Rechard, J.S. Stein, 2009, *Deep Borehole Disposal of High-Level Radioactive Waste*, SAND2009-4401, Sandia National Laboratories, Albuquerque, NM

Raising Visibility (2/2010)



Blue Ribbon Commission
January 2010- January 2012

- DBH mentioned in first open meeting opening remarks March 2010

The Blue Ribbon Commission on America's Nuclear Future (BRC) was formed by the Secretary of Energy at the request of the President to conduct a comprehensive review of policies for managing the back end of the nuclear fuel cycle and recommend a new strategy. It was co-chaired by Rep. Lee H. Hamilton and Gen. Brent Scowcroft. Other Commissioners are Mr. Mark H. Ayers, the Hon. Vicky A. Bailey, Dr. Albert Carnesale, Sen. Pete Domenici, Ms. Susan Eisenhower, Sen. Chuck Hagel, Mr. Jonathan Lash, Dr. Allison M. Macfarlane, Dr. Richard A. Meserve, Dr. Ernest J. Moniz, Dr. Per Peterson, Mr. John Rowe, and Rep. Phil Sharp.

The Commission and its subcommittees met more than two dozen times between March 2010 and January 2012 to hear testimony from experts and stakeholders, to visit nuclear waste management facilities in the United States and abroad, and to discuss the issues identified in its Charter. Additionally, in September and October 2011, the Commission held five public meetings, in different regions of the country, to hear feedback on its draft

- Note participants subsequent career positions

Nuclear Waste Technical Review Board Meeting
Las Vegas, NV - February 16, 2011

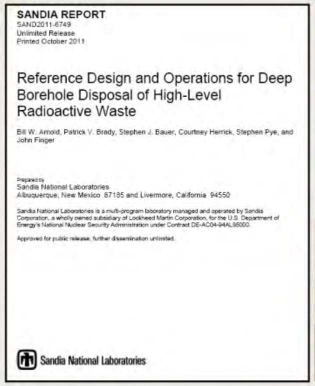
- "The Board certainly agrees with your conclusions on the technical aspects of deep borehole disposal and it appears that it is time to plan to move forward with a common vision for the technology."
- "It is time for detail implementation plans to be developed that include drilling, design of infrastructure and facilities to handle waste, and demonstrations with surrogate material; paper study of this disposal option is relatively complete."

NWTRB Letter to Assistant Secretary for Nuclear Energy, July 2011

- To follow-up on the presentations at the February meeting, the Board would like to know more about the progress being made regarding borehole disposal and other geologic-specific disposal programs that are under consideration. We are planning to make this a central part of the Board meeting we are planning for the spring of 2012 and will be contacting you or your staff regarding this in the near future. In this regard, we are particularly interested in work directed at optimizing the characteristics of the waste forms intended for disposal in specific geologic media.

Sandia Progress

Workshop: Pilot Testing Deep Borehole Disposal of Nuclear Waste, October 2011



SANDIA REPORT
SAND2011-6749
Unlimited Release
Printed October 2011

Reference Design and Operations for Deep Borehole Disposal of High-Level Radioactive Waste

Bill W. Arnold, Patrick V. Brady, Stephen J. Bauer, Courtney Herrick, Stephen Pye, and John Finger

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

Approved for public release; further dissemination unlimited.

Sandia National Laboratories

In October, 2011 Sandia brought together twenty representatives from the fields of radioactive waste disposal and drilling to:

- review the state of deep borehole science and engineering;
- identify the necessary features of a deep borehole pilot demonstration; and,
- consider organizational approaches to implementing a deep borehole pilot.

Blue Ribbon Commission on America's Nuclear Future Report to the Secretary of Energy, January 2012

- "In its deliberations, the Commission focused chiefly on two deep geologic disposal options: disposal in a mined geological formation and disposal in deep boreholes. The former has been the front-running disposal strategy in the United States for more than 50 years; it is also the approach being taken in other countries with spent fuel or HLW disposal programs. By contrast, disposal in deep boreholes may hold promise but this option is less well understood and the development of an appropriate safety standard, along with further RD&D is needed to fully assess its potential advantages and disadvantages.
- A number of possible advantages have been cited that support further efforts to investigate the deep borehole option. These include the potential to achieve (compared to mined geologic repositories) reduced mobility of radionuclides and greater isolation of waste, greater tolerance for waste heat generation, modularity and flexibility in terms of expanding disposal capacity, and compatibility with a larger number and variety of possible sites. On the other hand, deep boreholes may also have some disadvantages in terms of the difficulty and cost of retrieving waste (if retrievability is desired) after a borehole is sealed, relatively high costs per volume of waste capacity, and constraints on the form or packaging of the waste to be emplaced.

Blue Ribbon Commission on America's Nuclear Future
U. S. Department of Energy

Blue Ribbon Commission on America's Nuclear Future Report to the Secretary of Energy, January 2012

- Overall, the Commission recommends further RD&D to help resolve some of the current uncertainties about deep borehole disposal and to allow for a more comprehensive (and conclusive) evaluation of the potential practicality of licensing and deploying this approach, particularly as a disposal alternative for certain forms of waste that have essentially no potential for re-use.
- 9.3 Recommendations for Developing Future Disposal Facility Standards—
  - *7. EPA and NRC should also develop a regulatory framework and standards for deep borehole disposal facilities (p. 105).*
  - The Commission has identified deep boreholes as a potentially promising technology for geologic disposal that could increase the flexibility of the overall waste management system and therefore merits further research, development, and demonstration. While a regulatory framework and safety standards for deep boreholes would have much in common with those for mined geologic repositories, the technologies also have key differences. For this reason the Commission recommends that EPA and NRC develop a regulatory framework and safety standard for deep boreholes as a way to support further RD&D efforts aimed at developing a licensed demonstration project (*though we also note that this effort should not detract in any way from the expeditious development of revised generic regulations for mined geologic repositories*).

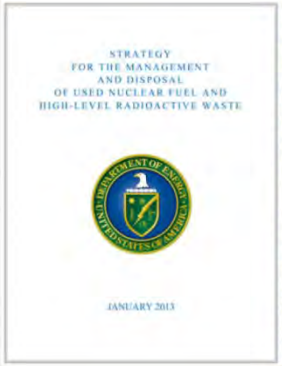
Blue Ribbon Commission on America's Nuclear Future
U. S. Department of Energy

Blue Ribbon Commission on America's Nuclear Future
Report to the Secretary of Energy, January 2012

- 12. Near Term Actions
  - Disposal
    - DOE should develop an RD&D plan and roadmap for taking the borehole disposal concept to the point of a licensed demonstration (p. 134).
  - Regulatory Actions
    - The Administration should identify an agency to take the lead in defining an appropriate process (with opportunity for public input) for developing a generic safety standard for geologic disposal sites. The same lead agency should coordinate the implementation of this standard-setting process with the aim of developing draft regulations for mined repositories and deep borehole facilities (p. 135).

Blue Ribbon Commission on America's Nuclear Future
U. S. Department of Energy

Administration Response to BRC
January 2013



"The ability to retrieve used nuclear fuel and high-level radioactive waste from a geologic repository for safety purposes or future reuse has been a subject of repository design debate for many years. A recently completed technical review by Oak Ridge National Laboratory found that approximately 98 percent of the total current inventory of commercial used nuclear fuel by mass can proceed to permanent disposal without the need to ensure post-closure recovery for reuse based on consideration of the viability of economic recovery of nuclear materials, research and development (R&D) needs, time frames in which recycling might be deployed, the wide diversity of types of used nuclear fuel from past operations, and possible uses to support national security interests. This assessment does not preclude any decision about future fuel cycle options, but does indicate that retrievability it is not necessary for purposes of future reuse."

- this is open recognition of support for direct disposal AND no need for retrievability for reuse

"In FY 2013, the Department is undertaking disposal-related research and development work in the following areas: an evaluation of whether direct disposal of existing storage containers used at utility sites can be accomplished in various geologic media; an evaluation of various types and design features of back-filled engineered barriers systems and materials; evaluating geologic media for their impacts on waste isolation; evaluating thermal management options for various geologic media; establishing cooperative agreements with international programs; and developing a research and development plan for deep borehole disposal, consistent with BRC recommendations."

- explicit recognition of deep borehole development as on the R&D agenda

October 2014

Other countries have also expressed interest (Germany, China, Korea, Ukraine…

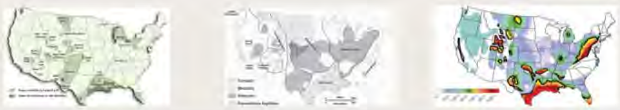
Final Thoughts

CAN DBH BE 'FASTER, CHEAPER, BETTER'?

Potential Repository Host Rocks

Property	Salt	Shale	Granite	Deep boreholes
Thermal conductivity	High	Low	Medium	Medium
Permeability	Practically impermeable	Very low to low	Very low (unfractured) to permeable (fractured)	Very low
Strength	Medium	Low to medium	High	High
Deformation behavior	Visco-plastic (creep)	Plastic to brittle	Brittle	Brittle
Stability of cavities	Self-supporting on decade scale	Artificial reinforcement required	High (unfractured) to low (highly fractured)	Medium at great depth
In situ stress	Isotropic	Anisotropic	Anisotropic	Anisotropic
Dissolution behavior	High	Very low	Very low	Very low
Sorption behavior	Very low	Very high	Medium to high	Medium to high
Chemical	Reducing	Reducing	Reducing	Reducing
Heat resistance	High	Low	High	High
Mining experience	High	Low	High	Low
Available geology*	Wide	Wide	Medium	Wide
Geologic stability	High	High	High	High
Engineered barriers	Minimal	Minimal	Needed	Minimal

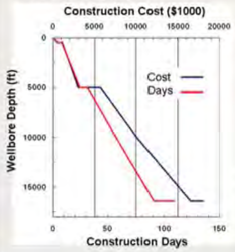
Favorable property   Average   Unfavorable property



Feasibility

Note: All costs are in 2011 $US and approximately for 2011 expenses.	Cost per Borehole
Drilling, Casing, and Borehole Completion	$27,296,587
Waste Canisters and Loading	$7,629,600
Waste Canister Emplacement	$2,775,000
Borehole Sealing	$2,450,146
Total	**$40,151,333**

from Arnold et al. (2011)



- Faster
  - estimated time for drilling, borehole completion, waste emplacement, and sealing is about 186 days (not decades)
- Cheaper
  - low initial costs
  - low investment risk
  - scaled costs
  - estimated disposal costs are $158/kg heavy metal (compared to nuclear waste fund fee of roughly $400/kg, Gibbs, 2010)
- Better
  - extremely low peak dose assessments

Source: Polsky, Y., L. Capuano, et al. (2008) *Enhanced Geothermal Systems (EGS) Well Construction Technology Evaluation Report*, SAND2008-7866, Sandia National Laboratories, Albuquerque, NM

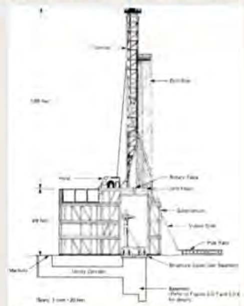
However…

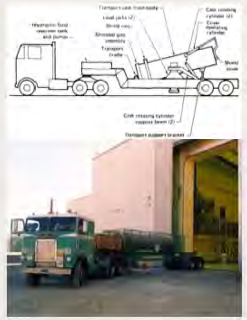
- Like 'paper reactors*' the same should be said of 'paper repositories'; things always look good on paper.
  - Thus, the desire to implement a field-scale demonstration
- The point is <u>not</u> that Deep Borehole Disposal is the best or only solution for geologic disposal.
- The point is the concept holds such significant promise that it warrants consideration of an effort to accelerate its pilot demonstration, and to vet its true feasibility and viability.
- The concept has merit for programs with both large and small waste burdens; it may be worth considering a multinational collaborative effort.

* Admiral H.G. Rickover, "Paper Reactors, Real Reactors" (5 June 1953)

Thank You

- Sit down before fact with an open mind. Be prepared to give up every preconceived notion. Follow humbly wherever and to whatever abyss Nature leads or you learn nothing. Don't push out figures when facts are going in the opposite direction. (Admiral Rickover)





from Woodward-Clyde Consultants (1983)

2.2 Brady P.: The US Deep Borehole Field Test (DBFT)

Patrick V. Brady, Kristopher L. Kuhlman, David L. Sassani, Geoffrey A. Freeze, Ernest L. Hardin, and Robert J. MacKinnon, Sandia National Laboratories, Albuquerque, New Mexico, USA.

2.2.1 Abstract

The US Department of Energy plans to spend ~$77M on a 5-year deep borehole demonstration that will select and characterize a site and drill two 5-km deep boreholes. One 8.5” diameter borehole will be used to characterize the site and demonstrate in situ testing and sampling technology. The second 17.5” diameter borehole will be used to demonstrate drilling and emplacement technology. The overall effort will be used to assess the viability of deep borehole disposal of nuclear waste.

2.2.2 Introduction

In 2014, the US Department of Energy initiated a deep borehole field test (DBFT) with drilling expected to start by September, 2016. The DBFT will consist of a relatively small diameter (8.5”) characterization borehole that examines the geologic, hydrologic, chemical, and mechanical characteristics of the site to 5 km depth. A larger diameter (17”) demonstration borehole will follow and demonstrate drilling and emplacement technology to 5 km depth. The DBFT site will be selected in early 2016 after an extensive geologic analysis of several volunteer candidate sites. The DBFT aims to more fully develop the option of nuclear waste disposal in deep boreholes and was specifically called for in the Blue Ribbon Commission Report on America’s Nuclear Waste Future issued in 2012 /BLU 12/. The DBFT will involve no radioactive waste, but is instead a science and engineering demonstration.

Deep borehole disposal conceptually involves the emplacement of nuclear waste in sealed canisters to a depth of 3 - 5 km in crystalline basement rocks (Fig. 2.2.1) in tectonically stable regions largely using drilling technology developed for oil, gas, and geothermal energy. The presence of “old” saline, and chemically reducing, waters at depth is a key to the success of deep borehole disposal. Old water that lost contact with the surface hydrosphere hundreds of thousands of years ago is evidence that there is little driving force for upward water movement. Prolonged water-rock reaction raises the salinity of subsurface fluids. The presence of dense, saline brines at depth is a barrier to buoyant upward movement of the water.

Lastly, oxygen-poor, reducing conditions at depth slows the corrosion of spent fuel and maintains many of the radionuclides in their lower valence, low solubility, and most strongly-sorbed forms (e.g. /BRA 09/).

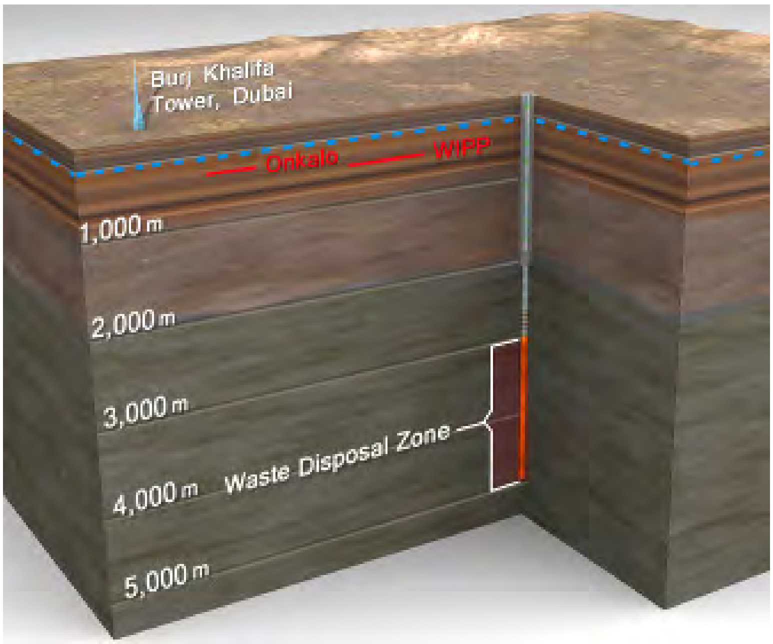


Fig. 2.2.1 Deep borehole disposal

Hydrologic conditions at depth should also limit upward advective flow of radionuclide-laden deep groundwater. Crystalline basement rocks have very low permeabilities. The only driving force for upward water flow would be expansion of water caused by heat from radioactive decay in the waste. The thermal heat pulse is an early feature that dissipates within the first few hundreds of years after emplacement, but depends on the makeup of the specific waste. Borehole seals of cement and/or bentonite would limit fluid movement during the early thermal pulse, and possibly for longer periods of time. Fig. 2.2.2 shows the types of US nuclear wastes. In addition to commercial spent nuclear fuel, volumetrically the largest fraction of the US inventory, there is DOE high level waste and DOE spent fuel from defense activities. Of particular note for borehole disposal are the Cs-Sr capsules, which account for ~ 40% of the radioactivity at the Hanford Reservation in Washington, but are volumetrically minor.

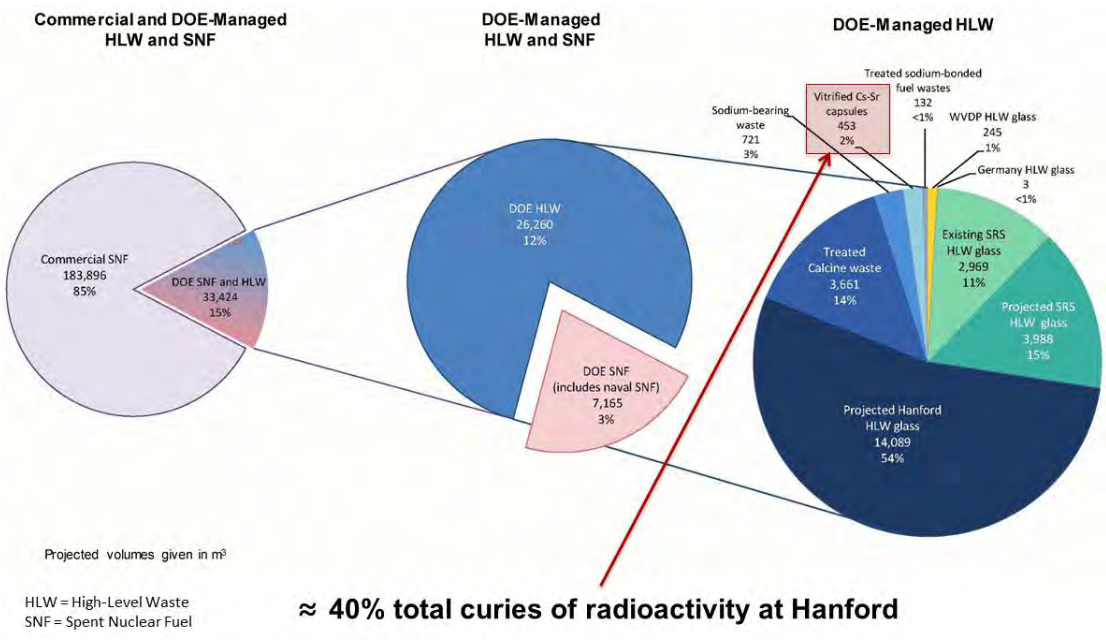


Fig. 2.2.2 Radioactive waste volumes in the US

After the Blue Ribbon Commission recommended that DOE more closely examine deep boreholes and field a deep borehole pilot, DOE revised its strategy for management and disposal of high-level nuclear waste and in 2014 issued a disposal options strategy that called for:

- Disposal of high-level waste and spent nuclear fuel in a repository,
- Disposal of some DOE-managed waste in a separate repository, and
- Disposal of smaller waste forms in deep boreholes.

Again, the most obvious of the smaller waste form candidates for borehole disposal are the Cs-Sr capsules from Hanford.

The DBFT has 3 tasks: site selection, site characterization, and drilling. A site must be selected using existing local and regional data – e.g. previous drilling experience and regional hydrology measurements. The site will then be characterized *in situ* with the small diameter characterization borehole to understand the sites mechanical, hydrological, and chemical properties. The larger diameter borehole will then be drilled and surrogate waste canisters emplaced, and retrieved.

2.2.3 Site Selection

The DBFT effort publicly solicited volunteer sites and at the time of this writing - late October 2015 - is determining which volunteer site is best. The primary criteria for candidate sites are: the presence of crystalline basement rock at < 2 km depth, little recent seismic or volcanic activity, little natural resource extraction (e.g. oil and gas, geothermal), and low geothermal heat flow. Fig. 2.2.3 shows areas of the continental US with basement depths less than 2 km, surface granitic rocks, Quaternary faults, recent volcanic activity, and recent seismic activity (ground motion > 0.2g).

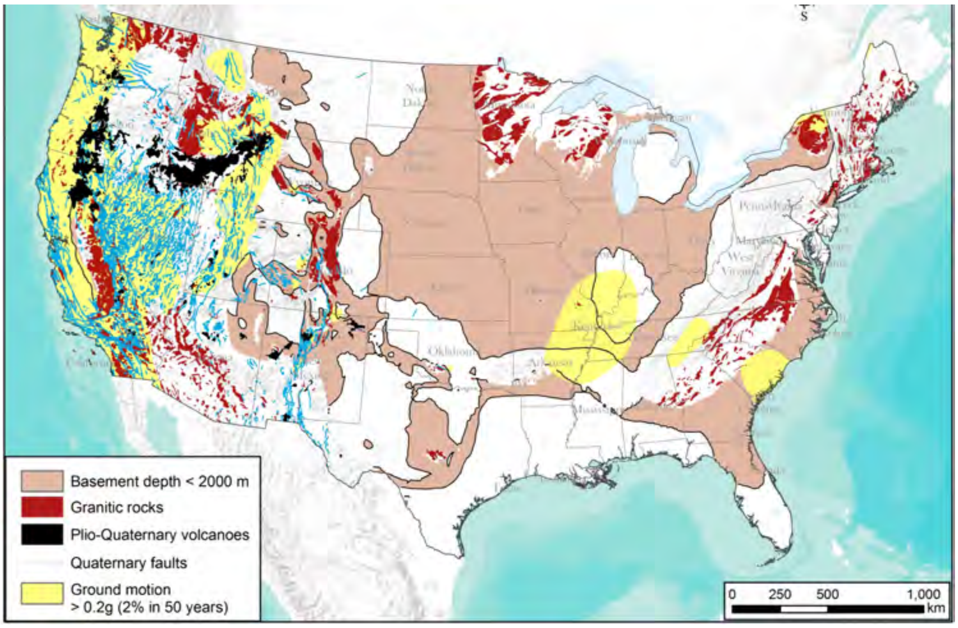


Fig. 2.2.3 Basement depth, Quaternary faults, volcanic and seismic activity

Fig. 2.2.4 shows the areal extent of US oil and gas exploration and production activity. Fig. 2.2.5 is a geothermal heat flow map of the US.

One can mentally overlap Fig. 2.2.3, Fig. 2.2.4 and Fig. 2.2.5 to identify areas of the US that have the largest areas free of faults, volcanoes, earthquakes, and oil and gas wells – and that might therefore possess the most DBFT candidate sites. Note though that Fig. 2.2.3, Fig. 2.2.4 and Fig. 2.2.5 do not show fine-scale detail and are therefore most useful for site-screening. Site-specific study must be done to finally settle upon a specific site.

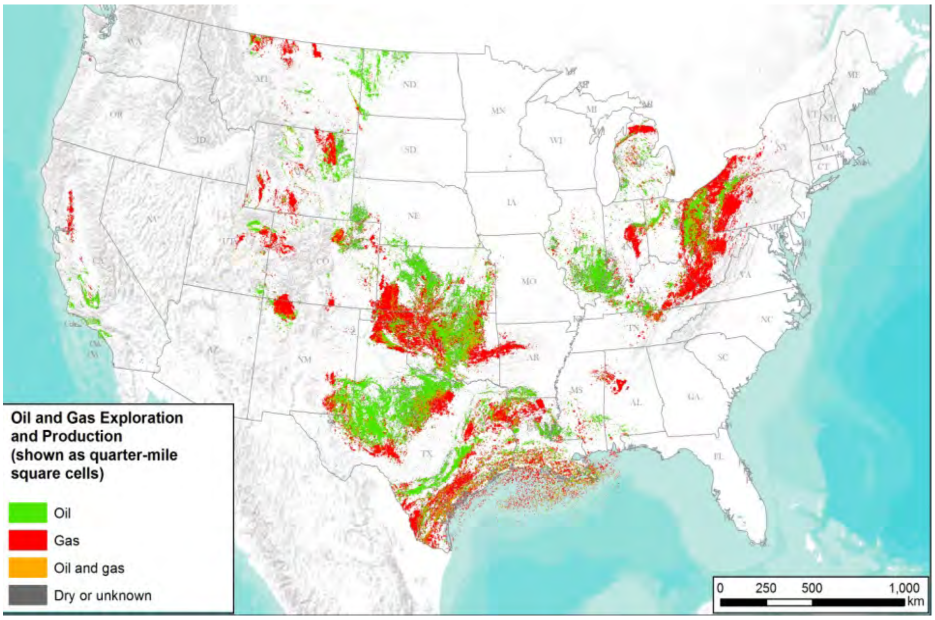


Fig. 2.2.4 US oil and gas exploration and production activities

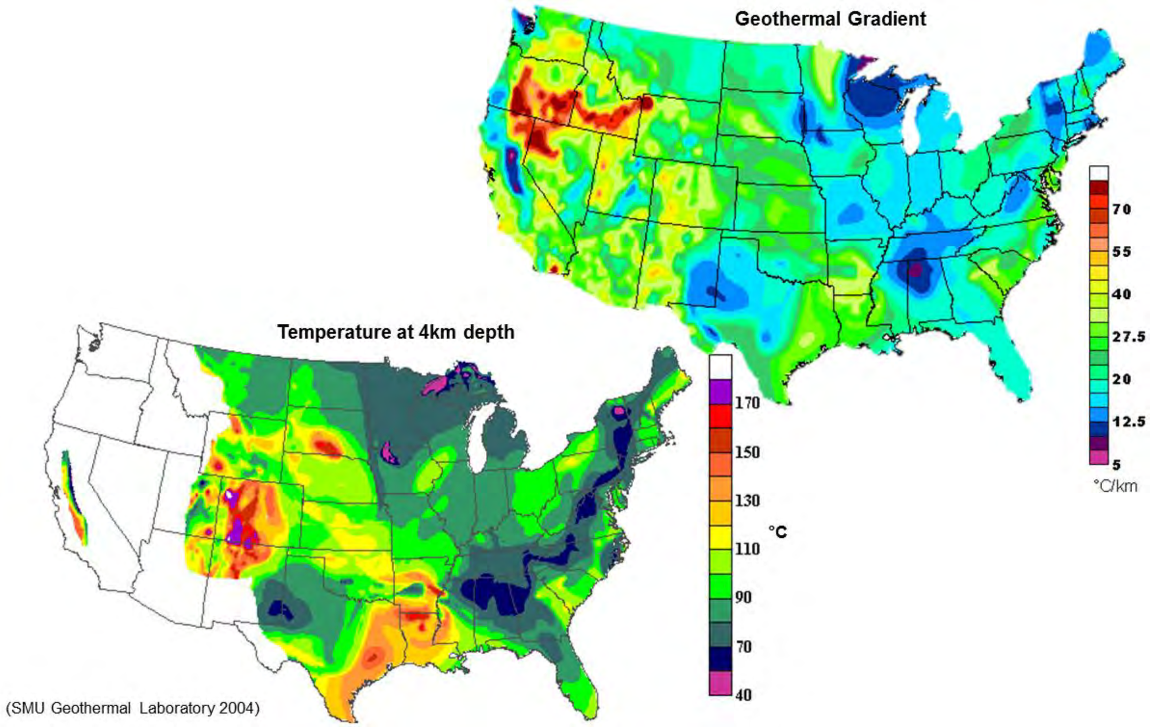


Fig. 2.2.5 Geothermal gradient and temperature at 4 km depth

2.2.4 Site Characterization

Once the site is selected and relevant permitting completed, the characterization borehole (CB) will be bored to 5 km depth (Fig. 2.2.6). Again, the CB will be 8.5” in diameter, and drillable with existing technology. The overlying sedimentary section will be drilled and cased with minimal testing. Drilling and coring of the crystalline basement will be more focused and will include coring of ~ 5 % of the total length. Testing and sampling will be done after borehole completion using a packer tool via a work-over rig. CB drilling will be done with the aim of maximizing collection of usable samples.

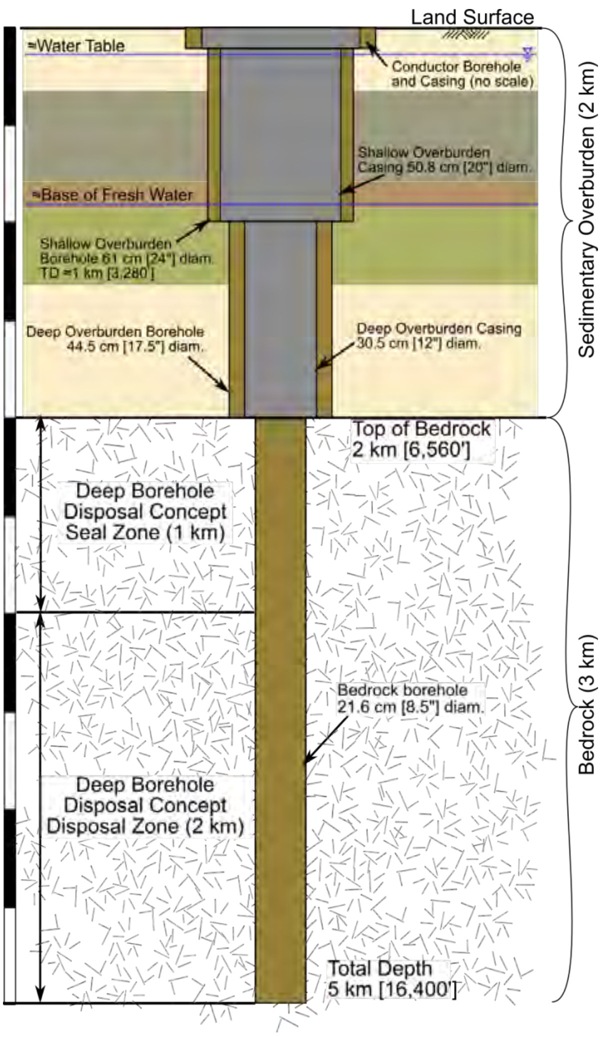


Fig. 2.2.6 Schematic of characterization borehole

Recall that establishing the relative age of waters in the crystalline basement is a key task of borehole site characterization. High salinity suggests long reaction with the rock, but is not a complete indicator of great age. Isotopic tracers provide a more comprehensive picture of groundwater age and provenance and will be applied where possible in the characterization borehole.

Hydrogeologic testing in the CB will include measurement of static formation pressure and permeability/compressibility - pumping and sampling in high permeability strata, pulse testing in low permeability strata. Vertical dipole testing will be done to understand transport pathways. Hydraulic fracturing test will be done to quantify subsurface stresses. A borehole heater test will be done using a surrogate canister with a heater to measure effects of a thermal pulse on borehole properties.

2.2.5 Field Test Borehole

The large diameter, field test borehole (FTB) will push the envelope of deep drilling technology. Fig. 2.2.7 shows the layout of the FTB. The aims of the FTB are to demonstrate the feasibility of: safely drilling large diameter boreholes to 5 km, successfully emplacing and removing surrogate waste canisters, and working out the surface handling steps required for an actual disposal site. A safety analysis will also be done which uses a fault tree hazard analysis to map out the high priority steps critical to operational safety.

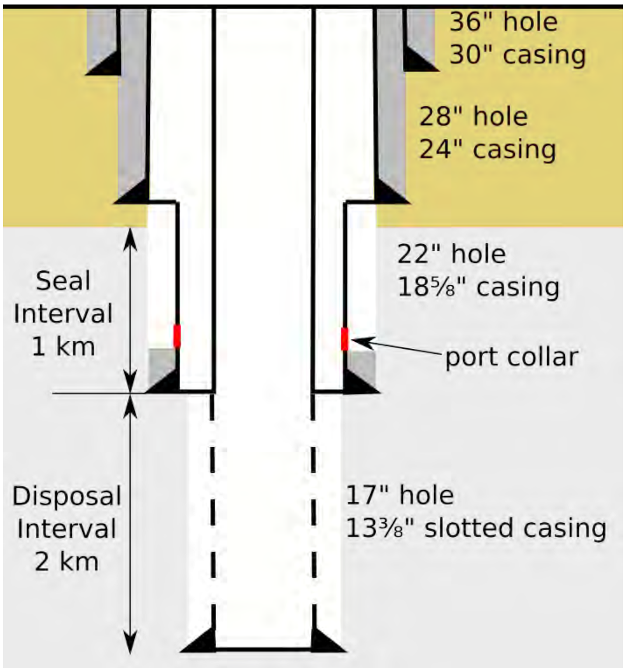


Fig. 2.2.7 Layout of large diameter borehole

2.2.6 Discussion

The priority goals of the DBFT are to: work out the steps of site selection and site characterization; to demonstrate the ability to drill large diameter boreholes to 5 km depth, and the ability to emplace and remove surrogate canisters from this depth. A lower priority is borehole sealing. Borehole seals will be most important during the thermal pulse period (<1000 years) when heat from short-lived fission products might favor water expansion and buoyancy. Again, upward motion of water must overcome an unfavorable density gradient caused by the increased salinity at depth. In parallel with the site-selection, characterization and drilling activities, the DBFT will examine the likely geochemical reactions that will occur between e.g. bentonite seals and corroding canisters, as well as non-traditional approaches to borehole sealing such as rock-welding (e.g. /GIB 08/).

2.2.7 Acknowledgements

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DEAC04- 94AL85000.

References

/BLU 12/ Blue Ribbon Commission on America's Nuclear Future: Report to the Secretary of Energy. 180 pp., 2012, available from http://energy.gov/sites/prod/files/2013/04/f0/brc_finalreport_jan2012.pdf, cited on 22 January 2016.

/BRA 09/ Brady, P.V., Arnold, B.W., Freeze, G.A., Swift, P.N., Bauer, S.J., Kanney, J.L., Rechard, R.P., Stein, J.S.: Deep borehole disposal of high-level radioactive waste. Sandia Report SAND2009-4401. Ed.: Sandia National Laboratories: Albuquerque, New Mexico, 2009.

/GIB 08/ Gibb, F.G.F., McTaggart, N.A., Travis, K.P., Burley, D., Hesketh, K.W.: High-density support matrices. Key to the deep borehole disposal of spent nuclear fuel. Journal of Nuclear Materials, Vol. 374, No. 3, pp. 370–377, DOI 10.1016/j.jnucmat.2007.08.017, 2008.

2.3 Bracke G.: Deep Borehole Disposal of Radioactive Waste as an Alternative Option for Germany? Regulations and Challenges

Guido Bracke, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Schwertnergasse 1, 50667 Köln, Germany, guido.bracke@grs.de

2.3.1 Introduction

The phase-out from nuclear energy in Germany is foreseen for 2022. Therefore the amount of radioactive waste is limited. The expected waste amount is given in the German report for the Convention on Nuclear Safety and in the Program for the Responsible and Safe Management of Spent Fuel and Radioactive Waste /BMU 15/. The mayor part of radioactive waste to find a disposal site is highly radioactive and heat-generating waste spent fuel from nuclear power plants, vitrified radioactive waste from reprocessing, and some spent fuel from research.

The deep geological underground is considered as a long-lasting and safe option for disposal of heat-generating waste. Different geological formations, technologies and concepts are currently discussed. Disposal technologies include excavation of mines with emplacement drifts or drilling of boreholes. Potential sites for final disposal are still not decided in Germany although the Gorleben site has been explored to some extent.

Disposal of radioactive waste in deep boreholes of has been considered previously but was rejected in favor of mine and engineered repositories at depth of a few hundred meters /BES 14/. The development of advanced drilling technologies and the coming up of new requirements for disposal of radioactive waste support a reassessment of this technology. Borehole disposal is not considered as a standalone option for all types of radioactive waste.

The following contribution presents shortly some basic information, the site selection law /BUN 13/ and the current German safety requirements /BMU 10/ and challenges for the context of a possible disposal option for high level radioactive waste using deep boreholes.

2.3.2 Heat generating radioactive waste in Germany

The major part of highly radioactive waste, which is classified as heat generating waste, for disposal in Germany is spent fuel, vitrified waste (Fig. 2.3.1) and spent fuel elements from research. The approximate amount of heat generating waste is shown in Tab. 2.3.1.

For non-heat generating radioactive waste are other options available or are currently discussed. Open issues are uranium tails, graphite and the possibly retrieved radioactive waste from the Asse salt mine.

Fig. 2.3.1 Vitrified waste containers and spent fuel element

Tab. 2.3.1 Heat generating radioactive waste in Germany /PFE /

spent fuel elements:	approx. 35 000 pc
vitrified waste containers:	approx. 8 000 pc
Spent fuel elements from research:	approx. 2 000 m^3

2.3.3 Options for final disposal

The favored option for final disposal of heat generating radioactive waste is currently deep geological disposal. The construction of a mine in different host rocks such as salt, clay or crystalline rock in depth down to 1500 m is investigated and pursued in several countries (Germany, Finland, Sweden, Switzerland, France). Deep borehole disposal can be considered as a variant of geological disposal.

Other options such as long-term interim storage, partitioning and transmutation have been less favored. All other remaining options, which have been discussed in the past such as disposal in the ocean, in space or in the ice shield are excluded as being too dangerous for the environment.

2.3.4 Estimation of the number of deep boreholes needed

The amount of heat generating waste in Germany will be limited due to the phase-out from nuclear power in 2022. About 35 000 spent fuel elements will then have to be disposed of.

The approximate length of a spent fuel element is about 5 m which are or will be in interim storage in CASTOR container. If these CASTOR containers with spent fuel elements are not directly disposed of, the rods can be repacked into smaller containers (see below). This will minimize the volume and needed borehole diameter. The structural parts of the assembly will be disposed after compaction in containers as well. Repacking the rods from fuel elements to container will generate about 12 000 containers. Assuming a length of about 5 m for each container the total length of all containers is 60 km. The conical shaped containers can be stacked on top of each (eventually some load spreaders are needed). If a borehole can be used from 3 to 8 km (5 km) depth only 12 (30 if 2 km usable length) boreholes for disposal would be needed (Fig. 2.3.2). This is clearly a minimum number since in some cases neither the whole depth nor the whole length of the borehole will be usable. It shows that the number of boreholes is relatively low, compared to the number of boreholes drilled routinely in gas and oil industry (hundreds of thousands). The difference to a routine borehole is the larger diameter and the depth.

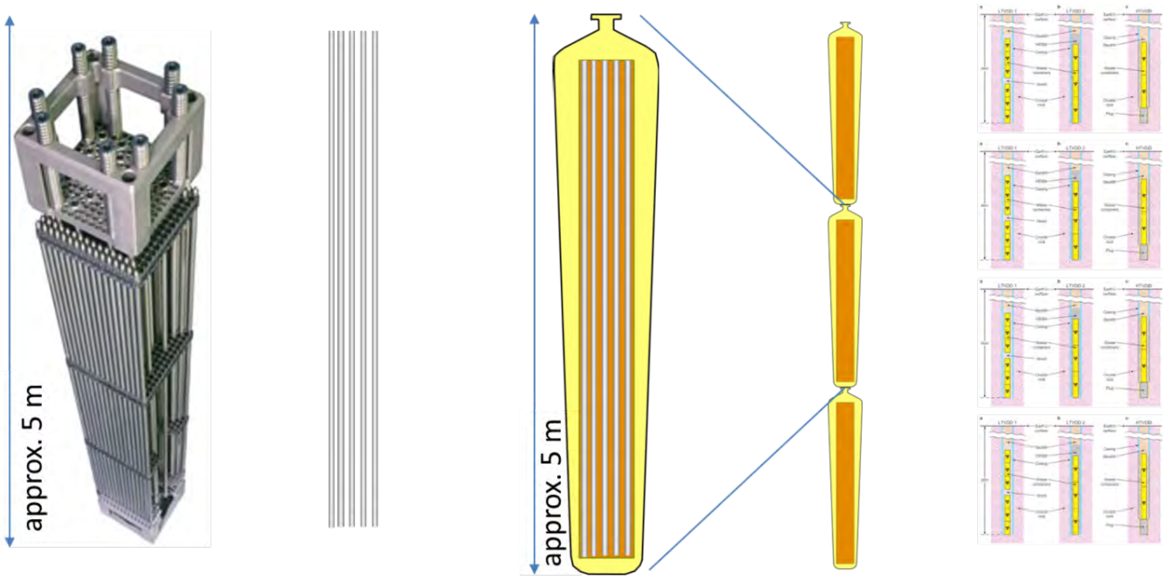


Fig. 2.3.2 Calculation of number of needed boreholes

2.3.5 Regulatory background in Germany

The important regulations concerning the disposal of heat generating radioactive waste are the site selection act (StandAG) from 2013 /BUN 13/ and the safety requirements from 2010

/BMU 10/. The recently issued site selection act ranks equally to the Atomic Energy Act /ATG 15/. This is shown in Fig. 2.3.3.

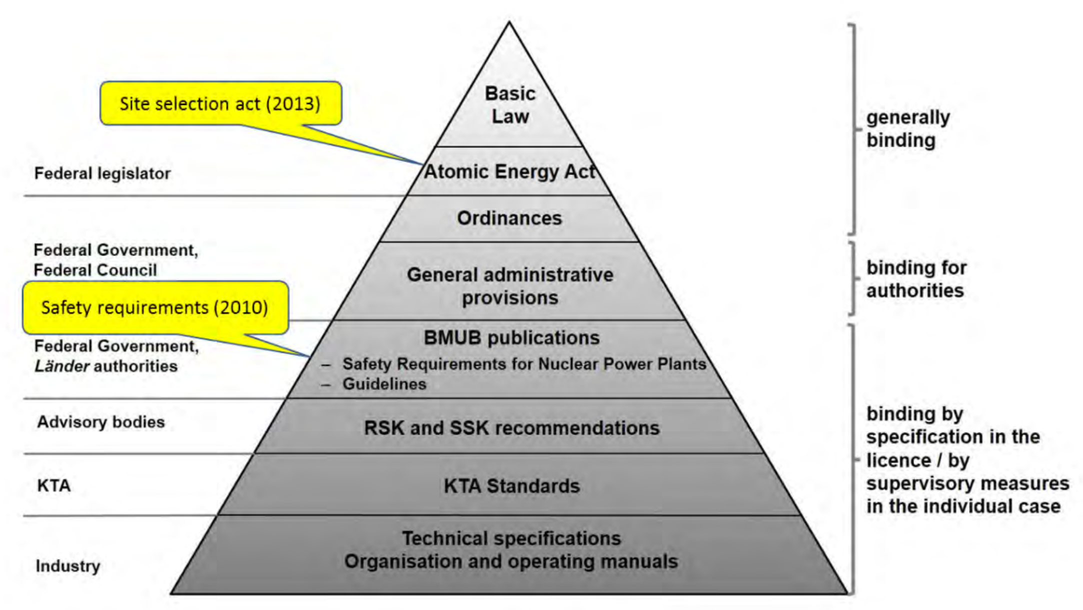


Fig. 2.3.3 Nuclear regulatory pyramid: Hierarchy of the regulations, the authority or institution issuing them, the degree of commitment and recently issued regulations

2.3.5.1 Site Selection Act (StandAG)

The purpose of the StandAG is to generate a strategy for selection of a site for final disposal of heat generating radioactive waste. A commission caked “Storage of high-level radioactive waste materials” was set up in 2013, which has to develop the strategy and criteria for a future site selection process. Although a time schedule is given in the StandAG the commission may recommend changes to the law.

The tasks of the commission according to the site selection act are to prepare proposals for:

- Assessment and decision whether alternatives to immediate disposal in deep geological formations should be studied and an interim storage of the waste should be done until finalization of these studies
- a basis for decision-making (safety requirements on storage, exclusion criteria, minimum requirements for suitability, weighing criteria, methodology for safety analyses)
- Criteria for error-correction (retrieval, recovery, detection, return to previous steps of the site selection process)

- Requirements for organization and procedure of the site selection process and alternatives
- Requirements for participation and information of the public

The commission will debate, analyze and recommend on other aspects as well. A report has to be prepared until mid of 2016. This report will be the basis for an evaluation of the StandAG by the German Bundestag. The exclusion criteria, the minimum requirements, weighing criteria and the basis for decision-making will be worked out as recommendations and passed as a bill by the German Bundestag.

§ 1 of the StandAG stipulates a selection of a site with the best possible safety for 1 million years. This is currently considered to be synonym to the best possible site. This site shall be found considering the current state-of-the-art of science and technology using a site selection procedure and the therein given and applicable criteria. This understanding is based on the objectives of the Safety Requirements from 2010.

The time line (Fig. 2.3.4) is drafted in the StandAG and has several milestones.

In 2013 according to § 3 the commission was set up to develop criteria and a site selection procedure. This commission has to finish its task with a report until 2016. Based on this report the German Bundestag shall implement criteria and requirements (§ 4) in a federal act. The site selection procedure starts with exclusion of unfavorable areas and preliminary safety assessment of favorable areas.

The German Bundestag (§ 14) shall settle the decision on the exclusion of unfavorable areas and the selection of favorable areas in a federal act. The exploration of sites from above ground is started and more advanced preliminary safety assessments are performed. Finally, sites for a detailed geological exploration shall be proposed.

In 2023 (§ 17) a further federal act by the German Bundestag shall settle the decision on sites for detailed underground exploration with a comprehensive safety assessment.

After a detailed geological exploration including a site comparison a site proposal shall be made. § 20 foresees again a federal act by the German Bundestag, which shall settle the final decision on the site for the licensing procedure. The site selection procedure for the site to be licensed shall be finished in 2031 according to § 1.

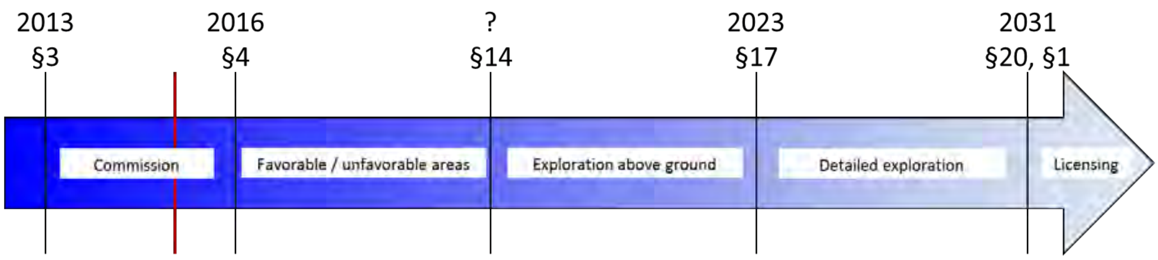


Fig. 2.3.4 Time schedule of the StandAG

2.3.5.2 Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste

The Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste /BMU 10/ are the basis for safety analysis and assessment of a repository. Some its main principles and requirements are outlined in the following chapters.

The general objectives are the protection of man and to avoid unreasonable burdens and obligations for future generations.

2.3.5.2.1 Safety principles

The main safety principle is the concentration of radioactive and other pollutants in a **containment providing rock zone** (**CPRZ**). It is required that any release, if at all, of radioactive substances increases only negligibly the risks associated with natural radiation exposure. This is a criterion, which has to comply with for each site. For practical purposes a stylized exposure scenario can be used.

Further safety principles are that the species diversity must not be endangered, natural resources must not be restricted and that any effects beyond Germany must not be greater than in Germany.

A safety principle is also, that no intervention or maintenance work shall be required during the post-closure phase to avoid unreasonable burdens and obligation for future generations. A quick construction of the repository is sought. Finally, the financial assets must be made available.

It is outlined how the protection from damage caused by ionizing radiation can be provided. It has to be shown that the geological integrity of the CPRZ is provided using a stress criterion.

In all probable developments of the repository systems a radiation exposure should be at maximum peak in the range of 0.01 mSv/a or less. Less probable developments should have a maximum peak radiation exposure of less than 0.1 mSv/a. Improbable developments of the repository system should be checked, if a mitigation of the calculative radiation exposure is possible. This mitigation should not hinder an optimization of the repository system. The safety requirements do not explicitly foresee a limit for the radiation exposure in case of unintentional penetration into the repository. An intentional penetration is not to assess since the intruder is supposed to be aware of any risk.

2.3.5.2.2 Containment Providing Rock Zone (CPRZ)

The CPRZ is the key element for the design of the repository and the safety assessment. The long-term safety analysis refers to the features of the CPRZ and how to prove its features in order to show credibly in the safety assessment the complete containment of radionuclides. No radionuclide shall be released to the outside of the CPRZ and to the human biosphere.

The Fig. 2.3.5 shows the principle in a sketch. The repository (that is where the waste is emplaced) is completely enclosed by a rock zone, which shall ensure the safe containment of any radionuclide, which could be released from the waste packages. Any excavations in the CPRZ introduced by mining have to be closed by technical seals. These seals shall restore the features of the CPRZ for the short and long term. Except for the drifts or shafts the CPRZ and the overlying rock shall be undisturbed. The size of the CPRZ shall be as small as possible but can be very large when using a mine for disposal. The surrounding host rock and overlying rock shall ensure the permanence of the CPRZ but does not to belong to the CPRZ. This concept of CPRZ is well discussed for disposal in an underground mine in salt and is considered feasible.

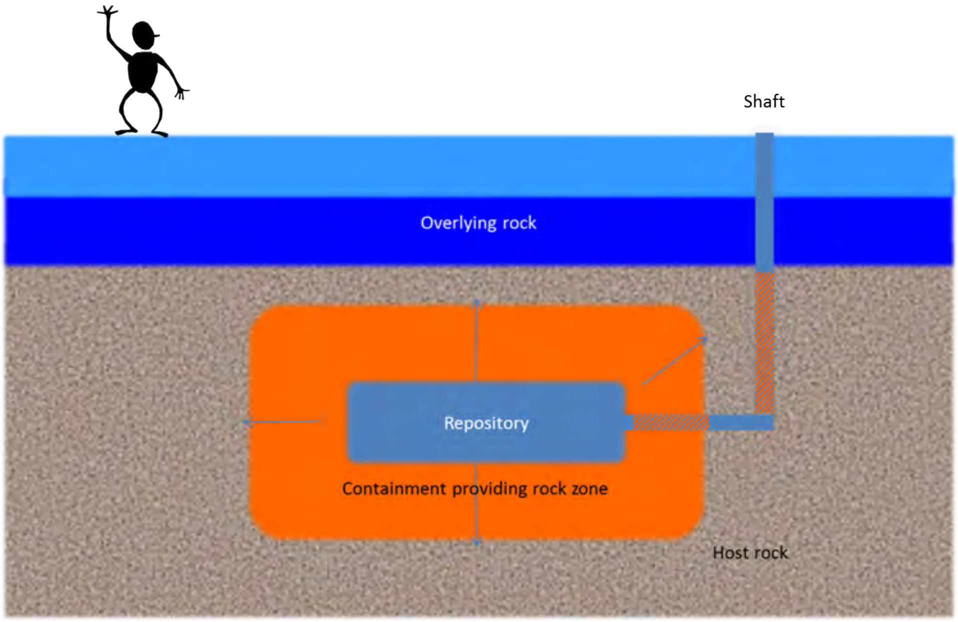


Fig. 2.3.5 Containment providing rock zone for a geological mine

When deep boreholes are considered for disposal, this concept should be applied similarly according to the safety requirements. A drift is not provided. Consequently, there will be several boreholes and several possibilities to define a CPRZ.

The first possibility is to define a CPRZ for each single borehole over the whole length of emplacement. This would include technical seals in the borehole itself to restore a CPRZ. The second possibility would be that several boreholes are encased by the CPRZ. The technical seals in boreholes would be installed several times to restore the CPRZ. The third possibility would foresee several CPRZ´s within a single borehole, e.g. a CPRZ for each disposed container. This would require seals between the containers (Fig. 2.3.6).

Therefore, the definition of the CPRZ depends on the design of the repository system and the features of the host rock of the selected site.

Using deep boreholes would allow considering additional safety barriers and sealing techniques. Details are outlined in /SCH 15/ in this proceeding /BRA 15b/.

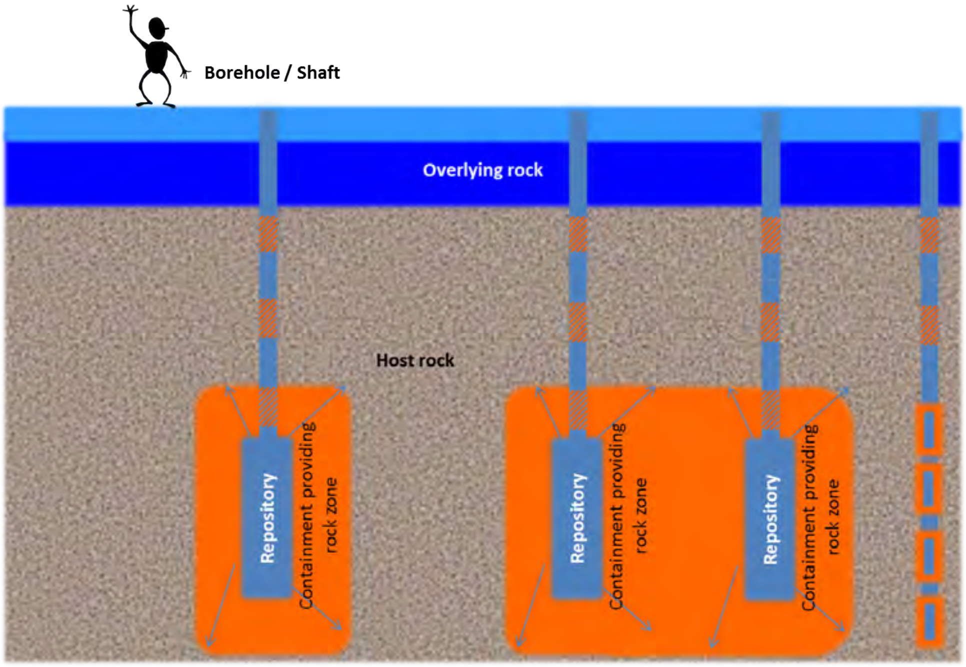


Fig. 2.3.6 Possibilities for containment providing rock zones for boreholes

2.3.5.2.3 Safety case

Safety analyses are foreseen and required for all operational and post-operational phases of the repository. The site specific long-term safety analysis of the post-operational phase shall cover 1 Mio years and provide a long-term radiological statement. The result of the safety analysis is used to assess the suitability and eligibility of site. The integrity of the CPRZ has to be guaranteed. The robustness of technical components has to be shown, if they are required for the safety. The exclusion of criticality has to be shown.

Within the final safety case numerical analyses have to be done, which may be deterministic or probabilistic. The uncertainty of the radiological statement has to be assessed.

Within the safety case a monitoring program during the operation phase of the repository and for a limited time period after decommissioning (closure) has to be installed. The safety relevant properties and requirements for the emplaced containers and their compliance with emplacement conditions have to be provided. The selected site has to be explored and site specific data has to be collected. This includes the knowledge about naturally occurring radionuclides in the repository system.

2.3.5.2.4 Design of the repository

The safety requirements outline already requirements onto the design of the repository. The proposed safety functions during the operational phase have to be reliable and robust. The number and size of holes (such as drifts, boreholes for exploration) within the CPRZ should be kept at minimum. The designated CPRZ should have a sufficient distance from geological faults. The waste containers should be handled aside from mining work and placed separately in an emplacement zone. A robust, graduated barrier system in a passive, maintenance-free design is necessary and a decommissioning concept has to be provided.

The most important requirement imposed for the design of the repository is that a manageability and handling of the disposed waste containers must be guaranteed for 500 year after closure of the repository.

2.3.5.2.5 Potential radiation exposure

The potential radiation exposure is calculated using a generic exposure model for 10 persons exposed to all released radionuclides in every scenario. A cumulative radiation exposure K_{RII} of less than 0,1 mSv/a is considered insignificant for probable scenarios.

A radiological insignificancy index (RII) has been developed in the project VSG /MÖN 12/, /BRA 15a/. The index RII is calculated from the annual radionuclide flow S_i [Bq/a] via the boundaries of the CPRZ and technical seals. If the CPRZ is entirely impermeable this flow is calculated from the technical seals only. Using dose conversion coefficients DCC_i [Sv/a/Bq/m^3] for each specific nuclide i the index RII is calculated relative to the insignificant exposure K_{RII} [Sv/a].

$$RII = \frac{10 \cdot \sum_i S_i \cdot DCC_i}{W \cdot K_{RII}} \tag{2.1}$$

If the RII is less than 1 then the release is insignificant.

Within the project VSG the RII was calculated using the following figures:

- All released radionuclide were distributed in a volume of water of 5000 m^3/a for a group of 10 persons. The volume of water, W, per person is therefore 500 m^3/a.
- The dose conversion factors are applied according to /BMU 12/.

- The guidance value for an insignificantly radiation exposure K_{RII} for probable scenarios is 0.1 mSv/person/a, for less probable scenarios it is 1 mSv/person/a.

The proposed assessment procedure for probable and less probable scenarios using the RII has four steps (Fig. 2.3.7).

1. If a complete containment is given and no radiation exposure is occurring since there is no contact between solutions and waste or no release from the CPRZ then the RII is zero and complete containment is shown.
2. If there is any diffusive or advective transport of radionuclides beyond the CPRZ and the RII is less than 1 then proof of safe containment is given.
3. If the RII is higher than 1 but the criteria of the safety requirements are met then a proof is also given by a simplified procedure.
4. If the RII is higher than 1 and the criteria are missed then the proposed repository design is not feasible. No RII is calculated for unlikely scenarios.

Any information on potential radiation exposure from unlikely scenarios can be used for optimizing the repository design to mitigate the potential consequences.

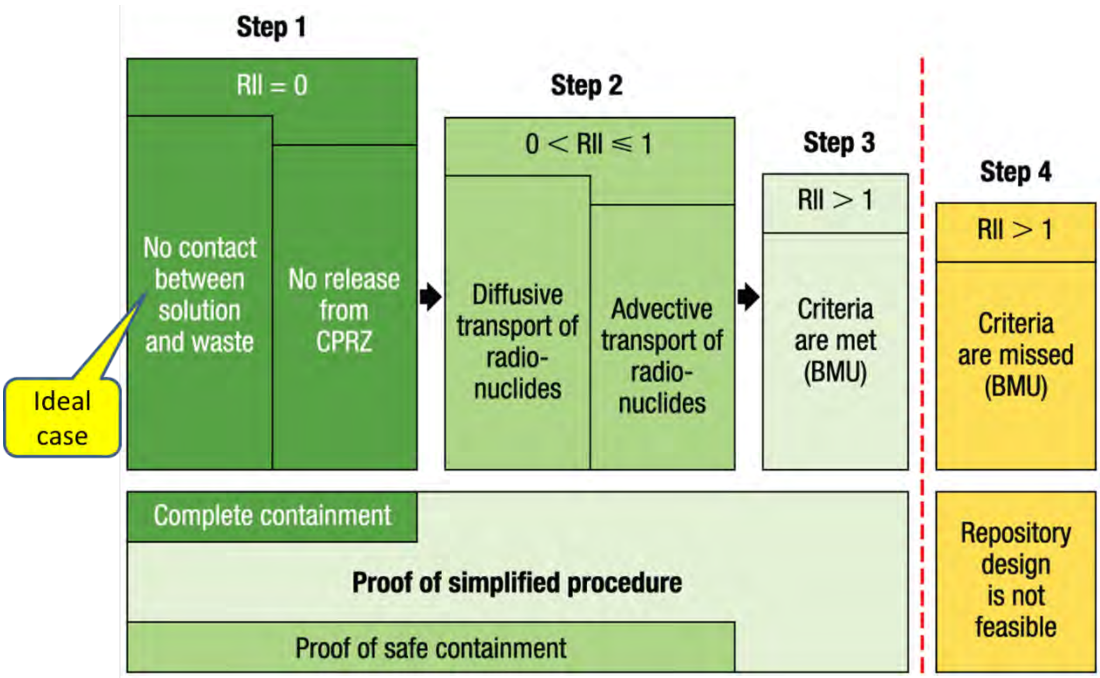


Fig. 2.3.7 Radiological Insignificany Index (RII) for safety assessment

2.3.6 Technical status of bore hole disposal

Disposal of radioactive waste in boreholes was already discussed in the project VSG /BRA 15a/. A conceptual design was drafted including boreholes (Fig. 2.3.8) and emplacement devices were tested (Fig. 2.3.9). The conceptual design foresaw a depth of 300 m in salt rock with stacked disposal of containers in liners. The boreholes would be drilled after the excavation of a mine. The technical feasibility was discussed and considered feasible in general, but licensing requirements concerning operational safety and the deduction of technical requirement (e.g. accuracy of borehole drilling) were solved only on theoretical basis. A practical demonstration with an in-situ testing was proposed. The set up and operation of an emplacement device has been tested with positive results above ground already /BOL 08/, /FIL 11/.

As a challenge was found, that the ability to release and excavate emplaced containers needs to be shown in practice. This is necessary in order to comply with the safety requirements in term of retrievability. Retrieval methods may be suction of the filling with rocking of the container. It has to be tested if the initial design used in the VSG can be optimized and if the features of the filling for the annular gap could be optimized for its thermal properties and/or pourability.

It is proposed to study if this preliminary concept for 300 m depth can be expanded for 3000 to 5000 m depth.

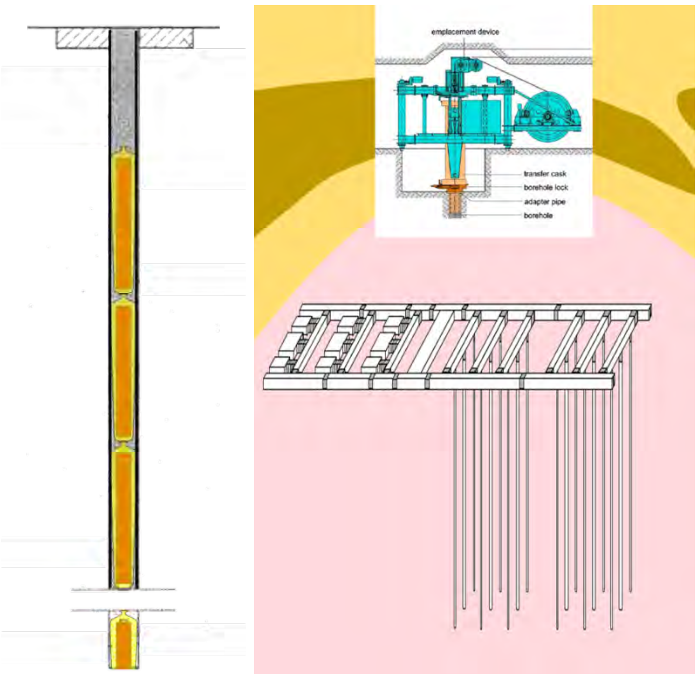


Fig. 2.3.8 schematical concept of stacking and arrangement of boreholes

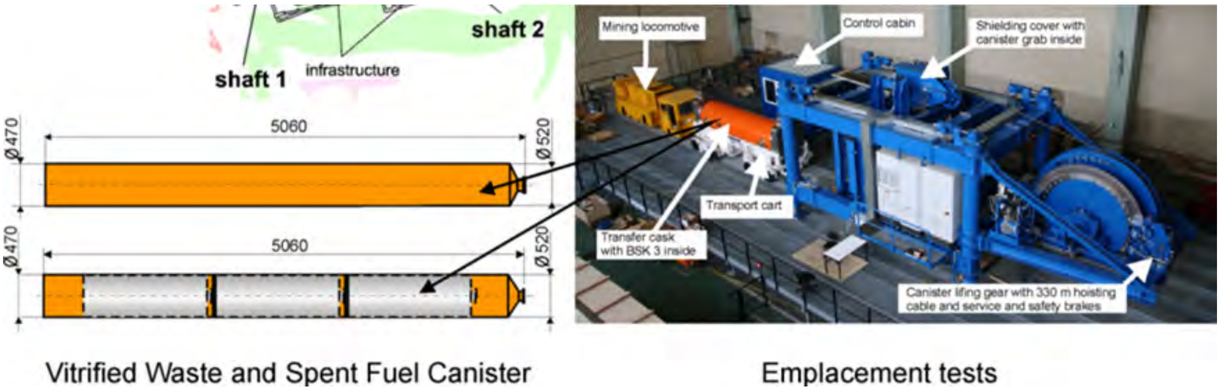


Fig. 2.3.9 Emplacement device for boreholes

2.3.7 Discussion

There are several challenges to be addressed when discussing disposal in deep boreholes compared to disposal in an underground mine, which is currently favored in Germany /DEU 15/.

When considering the depth of 3 to 5 km using boreholes compared to 300 to 800 m of a geological mine the distance of the radioactive waste to the biosphere and possible use of groundwater resources is significantly increased. Through the depth multiple geological barriers can be possible and possible pathways to the biosphere seem less likely. Nevertheless the geological situation has to be checked in detail for every site under consideration for its compliance with the safety requirements.

The technical feasibility of drilling has to be shown for relatively large diameters and depths of the anticipated borehole. Although the drilling technology has been greatly improved in the past the size of the borehole and the depth remains a challenge and is costly but may be less costly than excavating a geological mine.

A repacking or reconditioning of spent fuel from CASTOR containers into container which are suitable for borehole disposal seems necessary. Although direct disposal of CASTOR containers in a mined repository has been discussed it seems unlikely that this will be performed for borehole disposal because of the size and weight of the CASTOR containers.

Exploration and monitoring during and after disposal seems to be more difficult, since direct access in boreholes is not possible by humans. Due to the larger depth the transmission of information for monitoring of the underground after disposal will be more difficult.

The current German safety requirements foresee the possibility of retrieval during disposal and recovery after disposal for 500 years. Due to larger depth and inaccessibility by human compared to a mined repository this seems to be more difficult in borehole disposal. Also error correction may be more difficult.

The time needed and footprint on the surface of a borehole and the infrastructure in the underground is supposed to be smaller than for a geological mine but several sites would be necessary or a borehole field with deviated boreholes. Several sites would provide the possibility to distribute the burden of radioactive waste disposal. If there are more sites this would mean more exploration and an increased effort for safety assessments.

The boreholes will have smaller diameters compared to shafts and drifts of an underground mine for large containers. The total length of a borehole may be similar to the total distance from the top of the shaft to the end of an emplacement drift. The distance between boreholes when using a borehole field will depend on geology, drilling technology and heat generation of the waste and may vary.

The time needed disposal will be faster since less manipulation of the containers is necessary. Due to smaller diameter and a restricted accessibility for maintenance the operating lifetime of boreholes will be shorter than the operating lifetime of a geological mine. Closure and sealing of the borehole will be faster. So the total needed operating time of a single borehole will be significantly shorter than for a geological mine.

It is estimated that the operating costs for borehole are lower or at least comparable to the operating costs of an underground mine. Today’s drilling technologies are using fluids for fast drilling and to minimize costs.

The CPRZ for boreholes could compromise very small and/or multiple CPRZ (e.g. a rock zone surrounding a single container or borehole) or a very large CPRZ (rock zone surrounding a borehole field) depending on the features of the host rock and containers.

2.3.8 Conclusion and summary

Following from the preceding there are a number of challenges to be addressed when considering deep boreholes for radioactive waste disposal. These challenges can be grouped for technical, regulatory and socio-economic aspects. Technical challenges arise from depth, expected temperature and hydraulic pressure, size and weight of containers, radiation shielding and safety, requirements on reversibility, monitoring and operational safety.

Regulatory challenges arise from requirements how to show long term safety by an analysis and assessment, whether the development of a site selection procedure will include a possible disposal in boreholes, and what are the conditions for application and licensing of one or more sites for disposal.

The public acceptance is a further challenge, which is going to be required for any selected site although several sites may be suitable when considering borehole disposal. Any site that shall be found, has to consider the current state-of-the-art of science and technology in its safety assessment, is to find according to a site selection procedure and the given and applicable criteria, which are still under development. If several sites are available a comparison of sites, concepts and technology is required to find the „best possible site“. This may be based on robustness which means ruggedness against disturbances and the certainty of the safety statement.

A lot has to be done until the concept of borehole disposal can be considered at eye level with disposal in a geological mine.

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3 Geological and Physical Barriers (Geologische und phys. Barrieren)

3.1 Minkley W.: Integrität von Salzbarrieren und Endlagerung Wärme entwickelnder radioaktiver Abfälle in tiefen Bohrlöchern in Salzformationen

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3.1.1 Isolationspotential von Salzgesteinen

Der mögliche vollständige Einschluss in Salzformationen basiert auf den visko-plastischen Eigenschaften der Salzgesteine und der Impermeabilität der Salinarbarrieren gegenüber Flüssigkeiten und Gasen bei Fluiddrücken bis zum lithostatischen Teufendruck (Minimalspannungskriterium, /MIN 12/). Physikalischer Hintergrund für das Einschlussvermögen sind die sehr geringe Porosität und der sehr geringe Feuchtigkeitsgehalt von Salzgesteinen. Eine Migration ist nur durch den extrem langsamen Prozess der Festkörperdiffusion möglich. Hierin liegt ein Unterschied zu anderen potentiellen Wirtsgesteinen wie z.B. Tonstein, wo Diffusion im flüssigkeitsgefüllten Porenraum mit einer um mehrere Größenordnungen höheren Geschwindigkeit abläuft /BRA 08/ oder bei Kristallingesteinen, wo zusätzlich Advektion als Transportprozess in der Barriere stattfinden kann.

Abb. 3.1.1 CO_2-Gletscher nach einem Gasausbruch am 30.08.2003 aus einer Erkundungsbohrung in 950 m Tiefe im Salzgestein

In der Zechsteinlagerstätte im Werra-Revier im Zentrum Deutschlands liegen bemerkenswerte natürliche Analoga /MIN 14/ zum Isolationspotential von Salzgesteinen vor (Abb. 3.1.1). Dort ist CO_2 angetroffen worden, welches im flüssigen, gasförmigen und superkritischen Aggregatzustand unter hohem Druck in kavernösen Hohlräumen mit Volumina bis 100.000 m^3 eingeschlossen war (Abb. 3.1.2) und aus der Zeit des Tertiärvulkanismus vor 20 Mio. Jahren stammt. Die eingeschlossenen Fluide standen aufgrund der visko-plastischen Eigenschaften der umgebenden Salzgesteine unter lithostatischem Überlagerungsdruck. Das Einschlussvermögen und die Integrität von Salinarbarrieren werden durch diese "geologischen Langzeitexperimente" auf eindrucksvolle Weise gegenständlich belegt.

Zum Vergleich sei angemerkt, dass das gesamte Volumen der in Deutschland vorliegenden Wärme entwickelnde radioaktive Abfälle einschließlich Behälter bei einer Bohrlochlagerung nur 10.000 m^3 beträgt und im festen Aggregatzustand vorliegt.

Abb. 3.1.2 Blick in den Eingangsbereich des Kavernenhohlraums nach dem CO_2-Ausbruch vom 01.10.13 in dem 100.000 m^3 CO_2 im superkritischen Zustand 20 Mio. Jahre eingeschlossen waren

Ein Endlager im Salzgestein sollte deshalb so ausgelegt werden, dass möglichst ein vollständiger Einschluss ohne Freisetzung von Radionukliden erreicht wird. Die geologische Barriere aus Salinargesteinen kann diese Anforderungen erfüllen, wie durch die natürlichen Analoga belegt wird. Dabei bleibt nachzuweisen, dass die Integrität der geologischen Barriere auch unter den thermomechanischen Beanspruchungen der Wärme entwickelnden radioaktiven Abfälle erhalten bleibt.

3.1.2 Endlagerung Wärme entwickelnder radioaktiver Abfälle in tiefen Bohrlöchern in Salzformationen

Salzstöcke sind aufgrund ihrer großen Salzmächtigkeit von bis zu einigen tausend Metern in besonderer Weise für eine Endlagerung in tiefen vertikalen Bohrlöchern geeignet. Der Vorteil einer Endlagerung in großer Teufe besteht in der höheren Konvergenzgeschwindigkeit der Einlagerungshohlräume und damit eines schnelleren vollständigen Einschlusses im Salz.

Für den Salzstock Gorleben wurden im Rahmen der vorläufigen Sicherheitsanalyse /BOL 12/ thermomechanische Berechnungen u.a. auch für eine Bohrlochlagerung von BSK3 – Behältern in 300 m tiefen Bohrlöchern im Abstand von 50 m, ausgehend von der 870 m Sohle, durchgeführt. Die Berechnungen des IfG wurden mit dem visko-elasto-plastischen Stoffmodell für Salinargesteine und dem Schermodell für Schichtflächen und Diskontinuitäten durchgeführt /MIN 07/.

Durch die Wärmeentwicklung im Einlagerungsfeld dehnt sich das Salzgestein aus, was zu einer lang anhaltenden Hebung des Salzstockes im Meterbereich führt. Einige Jahrzehnte nach Einlagerungsbeginn fällt die minimale Hauptspannung durch die Extensionsbeanspruchung im Bereich des Salzstocktops temporär unter den anstehenden Grundwasserdruck ab. Dies führt zu einer fluiddruck-getriebenen Perkolation wässriger Lösungen, d.h. einem Eindringen von Salzlösung entlang interkristalliner Fließwege in das Salzgestein. Die Verletzung des Minimalspannungskriteriums kann bis zu einige hundert Metern unter den Salzspiegel reichen (Abb. 3.1.3).

Neben der vorrangig betrachteten Endlagerung von HLW in tiefen Bohrlöchern im kristallinen Gestein existieren auch einige Konzeptstudien zur Endlagerung in tiefen Bohrlöchern im Salzgestein. Die für geringe HLW- Abfallmengen in Dänemark erarbeitete Studie geht von 2500 m tiefen Bohrungen in einem Salzstock aus (Abb. 3.1.4), wo in dem unteren 1300 m langen unverrohrten Bohrlochabschnitt mit einem Durchmesser von 0,75 m Abfallbehälter mit 15 cm Wandstärke gelagert werden, die dem lithostatischen Teufendruck im visko-plastischen Salzgestein standhalten /ELS 81/.

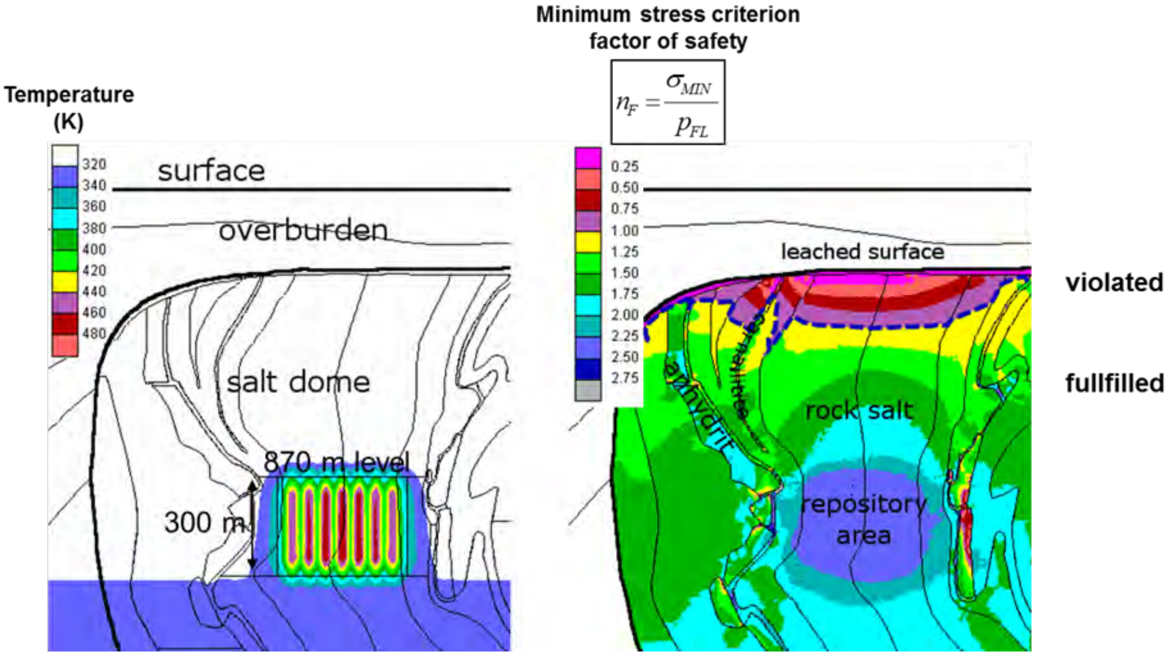

Abb. 3.1.3 Thermo-mechanische Berechnung 30 Jahre nach Einlagerung Wärme entwickelnder radioaktiver Abfälle in 300 m tiefen Bohrlöchern
links: Temperaturfeld, rechts: Minimalspannungskriterium

Untersuchungen in den Niederlanden kommen zu dem Ergebnis, dass die Endlagerung von HLW in tiefen Bohrlöcher in Salzstöcken, in Salzwällen und Salzlagern in Tiefen von 2 – 3 km so ausgeführt werden können, dass eine Rückholung über einen begrenzten Zeithorizont (50 bis 100 Jahre) möglich ist /NAS 99/.

Die in Deutschland für den Salzstock Gorleben neben der Streckenlagerung betrachtete Bohrlochlagerung in 300 m tiefen vertikalen Bohrlöcher (Abb. 3), ging ursprünglich von unverrohrten Bohrlöchern aus. Um eine Rückholung zu ermöglichen wurden Stahlverrohrungen mit einem Außendurchmesser von 0,8 m und einer Wandstärke von 5 cm untersucht, die einem lithostatischen Druck von 40 MPa standhalten und nach Einlagerung der Behälter mit Quarzsand verfüllt werden sollten /BOL 13/. Die Frage der Rückholbarkeit und Bergung bei der Bohrlochlagerung ist noch nicht abschließend geklärt. Für die Unterbringung des gesamten HLW-Abfalls in Deutschland wären bei diesem Bohrlochkonzept ca. 250 Bohrlöcher erforderlich.

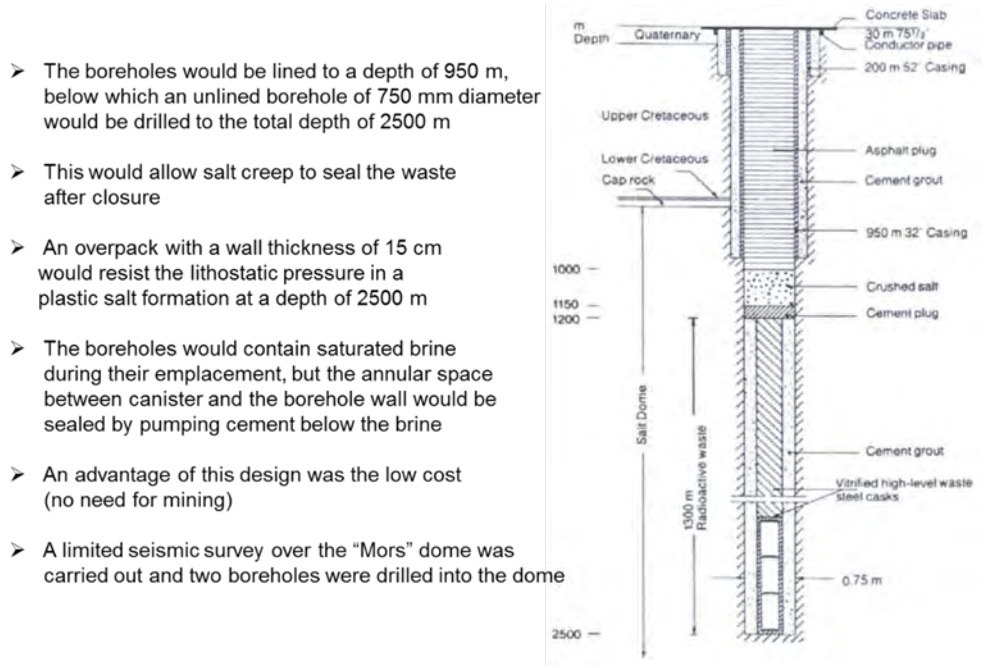

Abb. 3.1.4 Konzept HLW-Bohrlochlagerung in tiefen Bohrlöchern in einem Salzstock /NIREX 04/

3.1.3 Verschluss von tiefen Bohrungen im Salzgestein

Zum langzeitsicheren Verschluss von tiefen Bohrlöchern im Salzgestein liegen in Deutschland experimentelle Untersuchungen im Labormaßstab /IFG 10/ und eine feldtechnische Erprobung in situ in einer über 3000 m tiefen Bohrung in einer flachgelagerten Salzformationen vor /WUN 15/, die im Zusammenhang mit der CO_2-Speicherung im tiefen geologischen Untergrund durchgeführt worden sind.

Abb. 3.1.5 zeigt die Wirkung eines Druckes von 68 MPa, wie er im Gebirge in 3000 m Tiefe vorliegt an einem Steinsalzbohrkern mit einem zentralen Bohrloch, das durch Konvergenz aufgrund der visko-plastischen Fließeigenschaften des Salzgesteins bei 115 °C innerhalb von nur 3 Tagen eine Verringerung des Durchmessers um 50 % erfährt. Nach längerer Standzeit unter den hohen Druck- und Temperaturbedingungen wird das Bohrloch durch visko-plastischen Fließen verschlossen (Abb. 3.1.6). Füllt man das Bohrloch mit einer Salzsuspension entsteht innerhalb kurzer Zeit ein dichter Bohrlochverschluss. Diese durch Laborversuche /IFG 10/ und geomechanische Berechnungen /IFG 10/ entwickelte Grundidee zum Selbstverschluss von Bohrungen im Salzgestein in großer Tiefe wurde durch einen in situ-Test in einer Bohrung in 3096 m Tiefe durch GDF SUEZ überprüft. Die Dichtheit des Bohrlochverschlusses konnte durch einen hydraulischen Druckaufbautest bis 71,6 MPa, dies entspricht einem lithostatischen Druckgradienten von 0,023 MPa, nachgewiesen werden /WUN 15/.

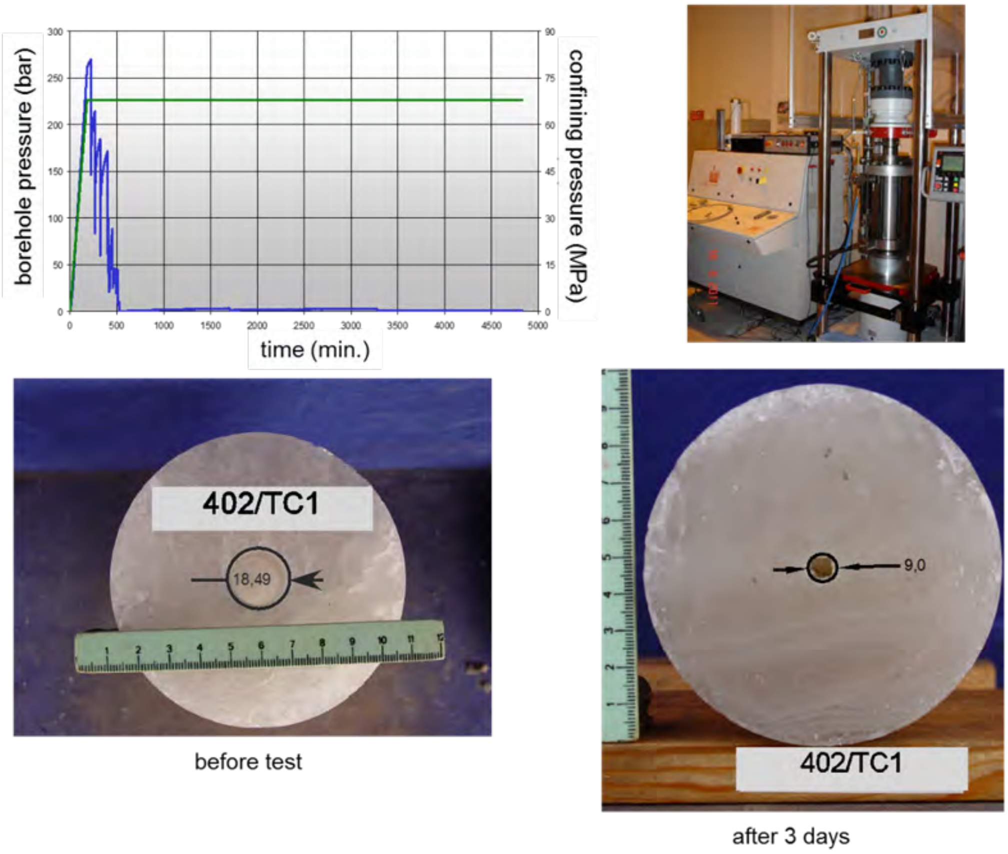

Abb. 3.1.5 Bohrlochkonvergenz bei einem in 3000 m Tiefe wirkenden Gebirgsdruck von 68 MPa und einer Temperatur von 115 °C im Salzgestein

Bei dem in der Kavernenindustrie praktizierten Verschlussverfahren wird im entsprechenden Dichthorizont im Steinsalz das Casing mit dem umgebenden Zement herausgefräst (Abb. 3.1.7) und ein Pfropfens aus Beton gesetzt. Bei der CO_2-Speicherung reicht eine in die Bohrung eingeleitete Salzsuspension, die nach Liften der darüber befindlichen Spülung nach relativ kurzer Zeit durch die Bohrlochkonvergenz in der großen Tiefe zu einem dichten Verschluss kompaktiert /KRE 09/.

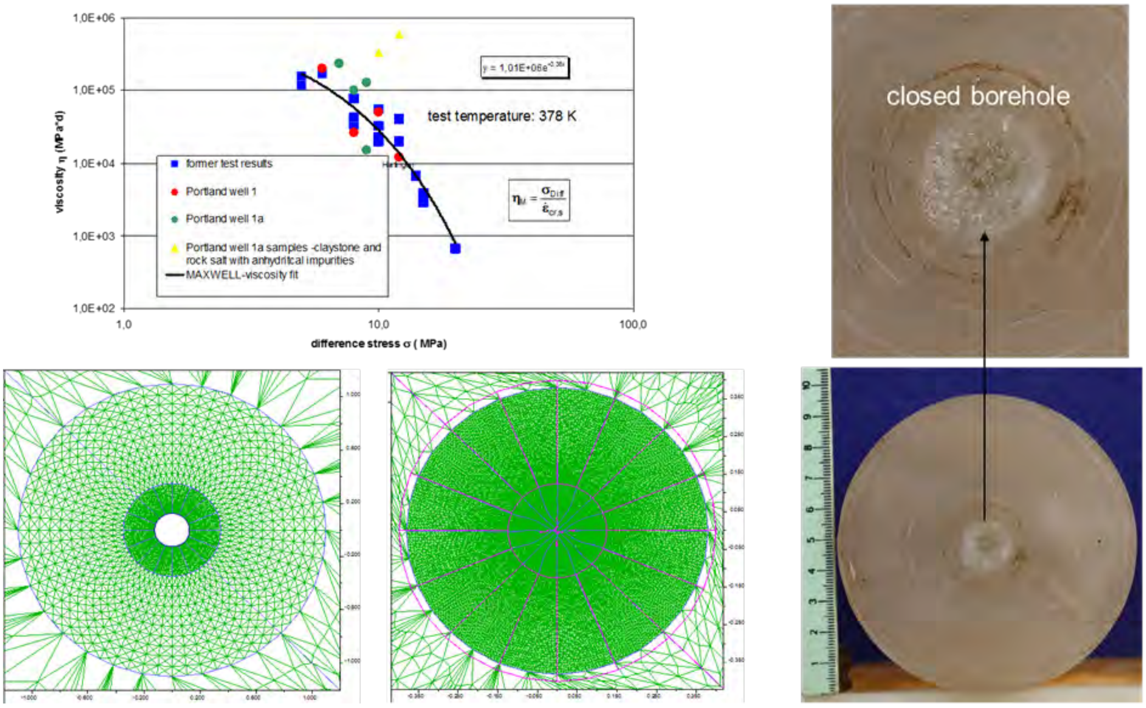

Abb. 3.1.6 visko-plastische Berechnung zum Selbstverschluss einer offen stehenden Bohrung in 3000 m Tiefe im Steinsalz und experimentelle Versuchsergebnisse

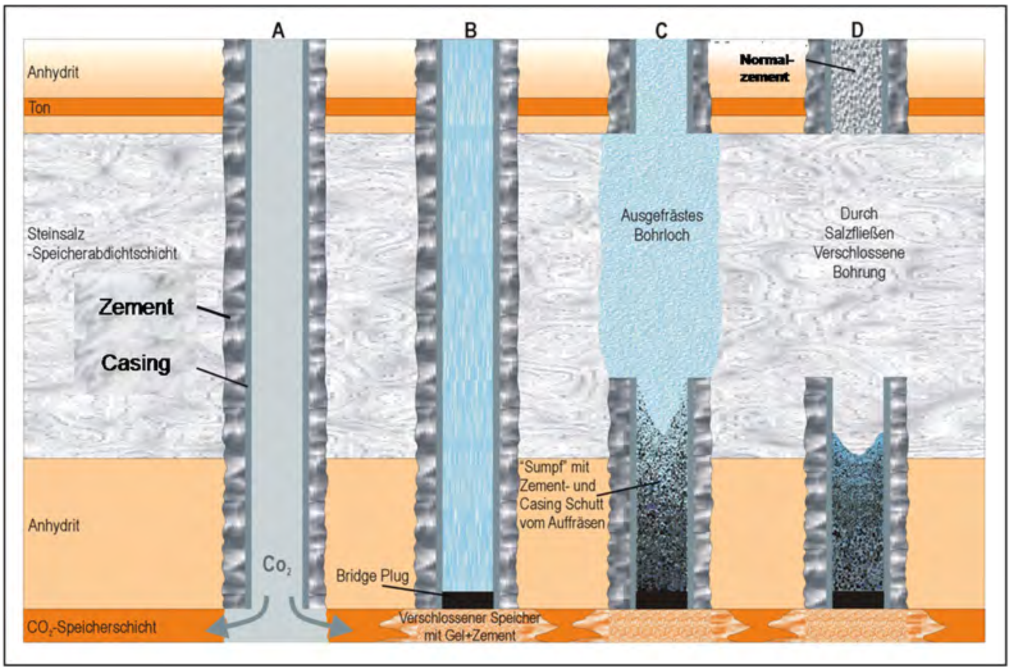

Abb. 3.1.7 Selbstverschluss nach Ausfräsen eines Fensters im Casing und Zement einer Bohrung in einer Salzgesteinsformation in großer Tiefe /KRE 09/

3.1.4 Eutektische Salzschmelzen als alternatives Verschluss- und Versatzmaterial bei der Bohrlochlagerung

Eine Alternative für ein Verschluss- und Versatzmaterial in tiefen Bohrlöchern im Salzgestein bietet die Verwendung von eutektischen Salzschmelzen (Schmelzpunkt 100…220°C), wie sie in der Solarindustrie als Wärme-Übertragungsmedium und zur Energiespeicherung als Flüssigsalzspeicher verwendet werden.

Zur Überprüfung des alternativen Konzeptes sind Testversuche am IfG durchgeführt worden. Als Probenmaterial wurde Hitec salt verwendet (53 % KNO_3, 40 % $NaNO_2$, 7 % $NaNO_3$), mit einer Schmelztemperatur von 142°C und einer Dichte ca. 2 g/cm^3 (Abb. 8). In den Testversuchen konnte gezeigt werden, dass die erstarten Salzschmelzen wie natürliche Salzgesteine impermeabel gegenüber Fluiden sind und erst bei Fluiddrücken größer als die minimale Hauptspannung ihre Dichtheit verlieren.

Bei einem Einsatz von geschmolzenem Salz als Verfüll- und Verschlussmaterial bei der Endlagerung von HLW- Abfällen in tiefen Bohrlöchern im Salzgestein wären folgende Schritte vorzusehen:

Der Liner im Tiefenintervall für den Einlagerungsbereich der Abfallbehälter wird bis zur Bohrlochwand mit geschmolzenem Salz hinterfüllt. Nach Einlagerung der Abfallbehälter werden die Zwischenräume im verrohrten Bohrloch ebenfalls mit geschmolzenem Salz verfüllt. Die Salzschmelze wird durch die Wärmeerzeugung der HLW- Abfälle über einen langen Zeitraum im flüssigen Zustand gehalten. Während dieser Zeit ist eine Rückholung der Abfallbehälter möglich. Bevor die Salzschmelze durch Rekristallisation erstarrt kann der Liner gezogen werden, um einen ungestörten vollständigen Einschluss der Abfallbehälter im Salzgestein zu erlangen. Die Bohrung wird im Salz vollständig mit der Salzschmelze verfüllt, am Salzspiegel mit einer Asphalt-/Bentonitdichtung verschlossen und darüber mit Beton verfüllt (Abb. 3.1.8).

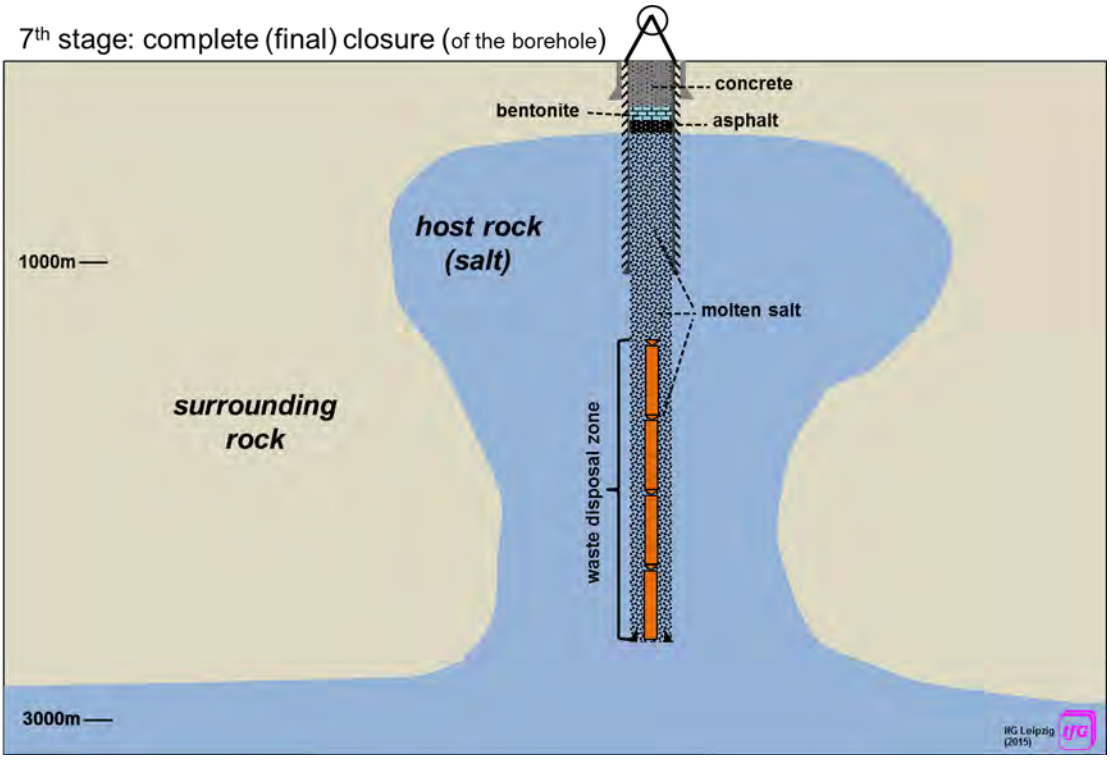

Abb. 3.1.8 Schema zur tiefen Bohrlochlagerung im Salzgestein mit Salzschmelze als Verfüll- und Verschlussmaterial

Das Verschluss- und Versatzkonzept auf Basis eutektischer Salzgemische als geotechnische Barriere bei der Endlagerung Wärme entwickelnder radioaktiver Abfälle in tiefen Bohrlöchern im Salzgestein bietet folgende Vorteile:

- Instantaner vollständiger Einschluss der Abfallbehälter in der Salzschmelze und später im auskristallisierten Salz
- Verhinderung des Zutritts von wässrigen Lösungen an die radioaktiven Abfälle aufgrund der hohen Dichte der Salzschmelze
- inkompressibles, nicht poröses Versatzmaterial wodurch der Antriebsmechanismus für ein durch Bohrlochkonvergenz getriebenes Auspressen von kontaminierten Lösungen ausscheidet
- technologisch einfache, vollständige Verfüllung der Bohrlöcher durch Salzschmelze mit geringer Viskosität
- Rückholungsmöglichkeit in der Betriebsphase, bevor die Schmelze erstarrt ist und Möglichkeit der Bergung z.B. durch ein Überbohren zu einem späteren Zeitpunkt
- Erdbebensicherer Einschluss im massiven Salzgestein

Ein wesentlicher Vorteil der Verwendung einer eutektischen Salzschmelze /MIN 15/ ist die Möglichkeit der Rückholbarkeit der Abfallbehälter bei Aufrechterhaltung der Vorteile, die aus den visko-plastischen Eigenschaften von Salzgesteinen hinsichtlich ihres Einschlussvermögens resultieren. Das Sicherheitskonzept, das die Ausweisung eines einschlusswirksamen Gebirgsbereiches (ewG) vorsieht ist vollständig umsetzbar.

3.1.5 Schlussfolgerungen

Im Vergleich zur Endlagerung Wärme entwickelnder radioaktiver Abfälle in einem Endlagerbergwerk ergeben sich bei der Endlagerung in tiefen Bohrlöchern im Salzgestein folgende Vorteile:

- Bohrungen mit Verrohrung/Linern von übertage in Salzformationen bis in Tiefen von 3000 m sind Stand der Technik /STA 04/
- Mächtige, robuste geologische Salzbarriere bis zu grundwasserführenden Horizonten
- Geringer ausgedehnte aufgelockerte Zonen (EDZ) um Bohrlöcher im Vergleich zu Strecken und Schächten und schnellere Verheilung aufgrund der hohen Gebirgsdrücke und Temperaturen in großer Tiefe im visko-plastisch reagierenden Salzgestein
- Reduzierung der erforderlichen Bohrungen für den gesamten HLW-Abfall in Deutschland von ca. 250 Bohrungen (Endlagerbergwerk) auf ca. 40 Bohrungen
- Möglichkeit zur Realisierung mehrerer Standorte für Endlagerung in tiefen Bohrlöchern in Salzformationen
- Kosteneinsparung

Das Konzept der Bohrlochlagerung von HLW im Salzgestein, ob von untertägigen Bohrungen in einem Salzbergwerk oder von der Tagesoberfläche in tiefen vertikalen Bohrlöchern bedarf weitergehender Untersuchungen.

Neben der Untersuchung der Lagerung von HLW Abfälle in tiefen Bohrlöchern im kristallinen Grundgebirge werden in den USA als mögliche Option auch Salzformationen der flachen und steilen Lagerung genannt /DRI 11/.

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3.2 Amann-Hildenbrand A.: Gas transport through water-saturated mudrocks and shales

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3.2.1 Abstract

Transport of gas in the subsurface is either controlled by molecular diffusion or by pressure-driven volume flow. Molecular diffusion, driven by chemical potential gradients, is characterised by a low transport efficiency but it is a ubiquitous process that, when acting over long periods of geologic time (>10^6 years), may be of relevance on length scales up to hundreds of metres. In comparison, pressure-driven viscous gas flow has a much higher transport capacity, which is controlled by gas/water saturation, effective stress, fluid-dynamic phenomena (laminar flow, turbulent flow, slip flow) and capillary effects. In originally water-saturated rocks the prerequisite for pressure-driven gas migration is the formation of interconnected gas-filled fluid pathways, either by drainage or dilation. Below this percolation threshold gas flow remains completely solubility- and diffusion-controlled. In compact clay-rocks and engineered barriers, effective gas permeability coefficients may be as low as 10^{-24} m². Here the limits of the continuum mechanics approach for fluid flow could be reached and a distinction between diffusive and advective transport is no longer possible.

3.2.2 Introduction

The quantification of gas migration through geological clay-rich barriers is of relevance in different contexts, such as the safe and long-term storage of radioactive waste or carbon dioxide, or natural gas and oil exploration and production. Reliable forecasts require robust and well-documented experimental data that can be integrated into different petrophysical transport models. The focus of this contribution is on diffusive transport and capillary-controlled viscous gas flow in (partially) water saturated rocks. Based on selected experimental results, we outline the different processes controlling gas migration through these barrier rocks. These information may be used for modelling of the dynamic gas leakage through geologic barrier systems in the case of gas pressure build-up/relief within an underground storage facility or reservoir.

Gas dismigration through an initially water-saturated rock can either occur by advection and diffusion of dissolved gas through the water filled pore space or by viscous flow of a free gas phase /DAV 09/, /GAL 00/, /HOR 99/, /KRO 86/, /MAR 05/, /PUS 83/, /THO 68/. Fig. 3.2.1 summarises the different processes, which must be accounted for /MAR 05/. Dissolution of gas in the pore water depends on the aqueous gas solubility, which, in turn, depends on salinity, pressure and temperature. The driving force for diffusion is the chemical potential gradient. In the dissolved state, the gas phase can additionally be transported with the advective flow of water along a prevailing hydraulic gradient. In cases where the gas generation rate exceeds the dismigration rate of the dissolved species, a free gas phase will be formed and gas pressure increases locally. This creates a pressure gradient over the capillary seal. Unless a critical pressure (capillary pressure) is exceeded this gas phase remains immobile in the largest pores. In capillary-controlled flow regimes, a certain pressure difference between the gas and water phase (critical capillary pressure) has to be overcome in order to force the gas phase into the pore system of the sealing rock. Thereafter, viscous flow through the rock is controlled by capillary forces and thus the prevailing pressures differences /AMA 15b/, /AMA 11/, /HIL 02/. Weak material will tend to dilate at a given threshold gas pressure which can lead to a leakage flow along re-activated fractures on the micro- and macro-scale (tensile fracturing) or within the matrix by pathway dilation, e.g. /AMA 15b/, /CUS 14/, /HOR 96/, /VOL 94/. Both viscous leakage processes are strongly dynamic. As gas pressure drops below a critical value, the system is re-saturated with water or dilatant pathways are closed again, and advective gas flow ceases /BUS 13/, /DAV 12/.

To obtain relevant transport parameters (diffusion, permeability coefficients, critical capillary pressures) flow experiments in the laboratory are usually conducted on relatively small samples (mm to cm-range). To yield realistic results, measurements are performed at in-situ pressure and temperature conditions, controlled fluid type and fluid pressures. Diffusion coefficients are derived in “through-diffusion” experiments from the increasing cumulative amount of the gas species monitored at the outflow side, permeability coefficients are determined from the volume flow rate on the low-pressure side and the critical pressures are derived from “gas breakthrough” experiments conducted at varying differential pressures. In low-permeable materials these experiments can be very time-consuming (months to years). The methods currently applied have been summarised in a recent publication /AMA 15a/. Extensive literature reviews and process descriptions were given by /GEN 14/, /MAR 05/, /ROD 99/.

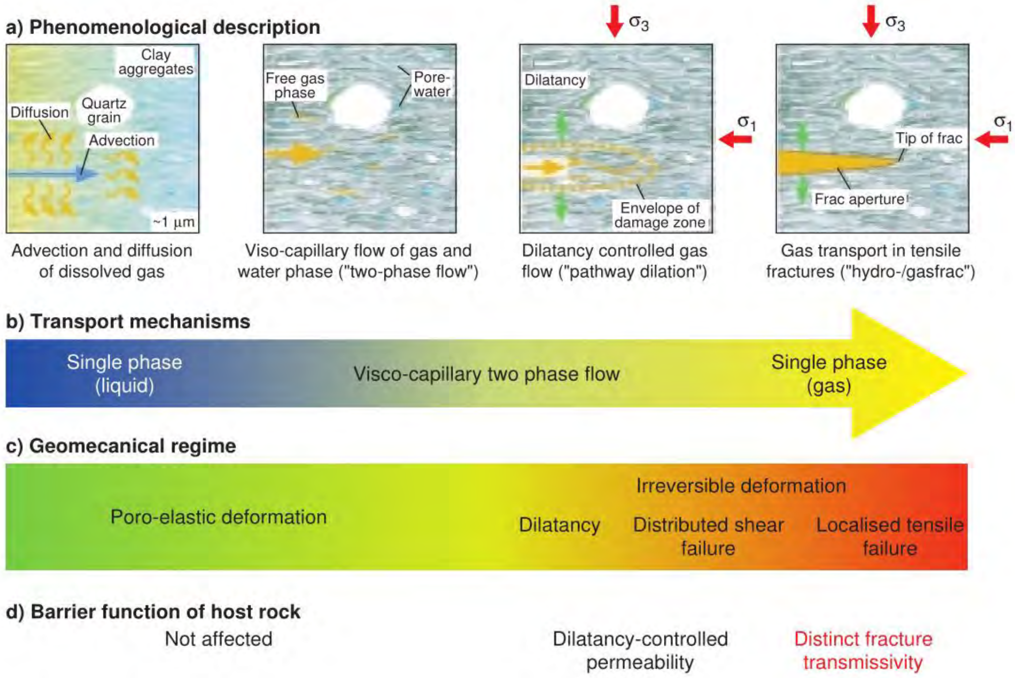

Fig. 3.2.1 Classification and analysis of gas transport processes in Opalinus clay: (a) phenomenological description based on the microstructural model concept; (b) basic transport mechanisms; (c) geomechanical regime; and (d) effect of gas transport on the barrier function of the host rock. Reprinted with permission from IFP, Figure 2 in /MAR 05/.

3.2.3 Transport processes, terms and definitions

3.2.3.1 Diffusion

Diffusion is a continuous and ubiquitous process with low transport capacity. When considering the diffusion of a dissolved species through a porous rock, different terms and definitions are found in literature and therefore, the definitions should be verified carefully before using diffusion coefficients for modelling.

Assuming that gas sorption to the mineral surface is negligible the bulk volume concentration of the dissolved gas, C_{bulk}, is defined as:

$$C_{bulk} = \phi * C_{pore\ water} \qquad [mol\ m^{-3}] \qquad (1)$$

with the porosity ϕ and the gas concentration in the pore water $C_{pore\ water}$. In this publication the term effective diffusion coefficient (D_{eff}) is used when the diffusive transport is expressed in terms of the bulk volume concentration gradient of the dissolved gas ($\partial C_{bulk}/\partial x$). The term pore diffusion coefficient (D_p) is related to the gas concentration in the liquid phase ($\partial C_{pore\ water}/\partial x$).

The diffusive mass flow through a sample is described by Fick's first law of diffusion /CRA 75/:

$$\boldsymbol{F} = -\boldsymbol{D}_{\boldsymbol{eff}} \frac{\partial \boldsymbol{C}_{\boldsymbol{bulk}}}{\partial \boldsymbol{x}} - \boldsymbol{\phi} \cdot \boldsymbol{D}_{\boldsymbol{p}} \frac{\partial \boldsymbol{C}_{\boldsymbol{pore\ water}}}{\partial \boldsymbol{x}} \quad \textbf{[mol m}^{-2}\ \textbf{s}^{-1}\textbf{]} \qquad (2)$$

Experimentally, the effective diffusion coefficient can be determined by flow-through experiments on plane parallel cylindrical plugs /JAC 13/, /KRO 87/, /KRO 92/, /SCH 98/, /SCH 04/. When a constant and homogeneous fluid pressure profile is maintained across the sample (pressure gradient $\Delta p/\Delta x = 0$), diffusion is the only transport process measured. The diffusion process is initiated by creating a gas concentration gradient across the sample. At given time intervals the gas concentration on the outflow side is measured until stable gas fluxes are detected. The above-mentioned references use a quantification procedure described by /CRA 75/ assuming diffusion through a homogeneous plane sheet of given thickness ($x = l$, Fig. 3.2.2).

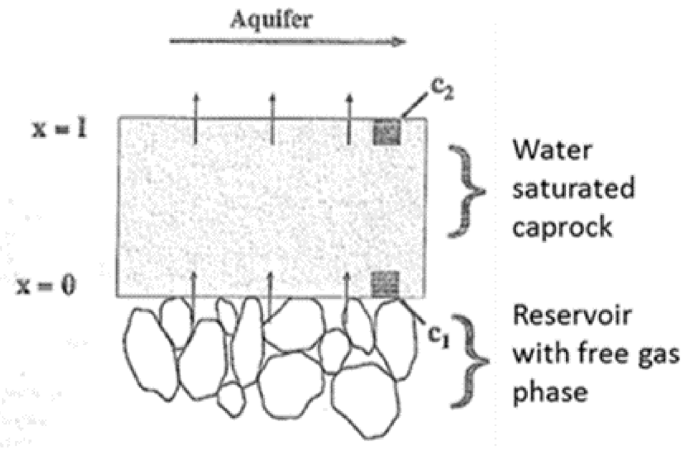

Fig. 3.2.2 Basic model for diffusion through a cap rock with thickness l, c_1 the constant bulk concentration on the reservoir/cap rock interface and c_2 at the top of the cap rock sequence ($c_2 = 0 = \text{const.}$) /SCH 98/.

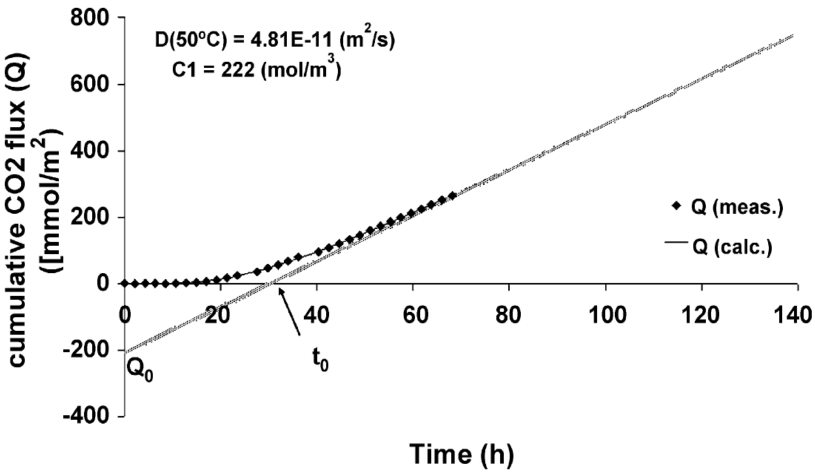

Fig. 3.2.3 Example of a diffusion experiment with CO_2 conducted on a shale plug at 50°C /BUS 08/. The cumulative amount of gas diffused is plotted as a function of time. From the tangent fitted to the linear portion of the curve (steady state gas flux) the parameters t_0 and Q_0 are derived. These are used to calculate the effective diffusion coefficient, D_{eff}.

With the boundary conditions as defined in Fig. 3.2.2 the molecular gas flux out of the sample (Q_{out}) can be fitted with the following equation:

$$\frac{Q_{out}(t)}{l \cdot c_1} = \frac{D_{eff} \cdot t}{l^2} - \frac{1}{6} - \frac{2}{\pi^2} \sum_{n=1}^{\infty} \frac{(-1)^n}{n^2} exp(-D_{eff} \cdot n^2 \cdot \pi^2 \cdot \frac{t}{l^2}) \qquad (3)$$

D_{eff} is the effective diffusion coefficient. For $t \rightarrow \infty$ the equation simplifies to

$$\frac{Q_{out}(t)}{l \cdot c_1} = \frac{D_{eff} \cdot t}{l^2} - \frac{1}{6} \quad \Leftrightarrow \quad Q_{out}(t) = \frac{c_1 \cdot D_{eff} \cdot t}{l} + Q_0 \qquad (4)$$

The graph described by this equation intersects the x and y-axis at a lag time (t_0) and the Q0-value, respectively. From the latter parameters the effective diffusion coefficient, D_{eff}, can be derived with:

$$Q_0 = -\frac{l \cdot c_1}{6} \qquad (5)$$

and

$$t_0 = -\frac{Q_0 \cdot l}{c_1 \cdot D_{eff}} = \frac{l^2}{6 D_{eff}} \qquad (6)$$

An example of such an experiment is given in Fig. 3.2.3, conducted with CO_2 at 50°C on a Muderong Shale sample /BUS 08/. Based on this concept the dismigration from a storage site can be modelled as presented in chapter 4.1.

3.2.3.2 Viscous flow

3.2.3.2.1 Darcy flow

For the flow of incompressible media (i.e. water) the absolute or intrinsic permeability coefficients (k_{abs}) are calculated according to Darcy's law:

$$\boldsymbol{k_{abs}} = -\mathbf{Q\eta}\frac{\boldsymbol{\Delta x}}{\boldsymbol{\Delta p}} \qquad (7)$$

Here Q [$m^3/m^2/s$] is the volume flux, also denoted as the "Darcy velocity" of the fluid, η [Pa·s] is the dynamic viscosity of the permeating fluid and ΔP/Δx [Pa/m] is the pore pressure gradient. Complete water-saturation of the conducting pore system was assumed when constant single-phase flow was registered for an extended period of time. A common unit used for the permeability coefficient is Darcy, where 1 Darcy = $0.987 \cdot 10^{-12}$ m².

Darcy's law for compressible media is used to describe the pressure-driven volume flow of gases. This relationship accounts for the compressibility of the gas phase according to the ideal gas law. The gas permeability coefficient, k_{gas}, is calculated from equation 8:

$$\boldsymbol{k_{gas}} = -\frac{\boldsymbol{\eta\ 2\ \Delta x}}{\boldsymbol{A(p_2^2 - p_1^2)}}\frac{\boldsymbol{dV_2\ p_2}}{\boldsymbol{dt}} \qquad (8)$$

Here dV_2/dt [m³] is the gas volume flow rate on the downstream pressure side, p_1 and p_2 [Pa] are the upstream and downstream pressures, respectively, A [m²] is the cross section area, η [Pa s] is the viscosity of the gas, and Δx [m] is the length of the sample.

In the subsurface, the conductivity of the rock to the gas phase is influenced by different factors as outlined below.

3.2.3.2.2 Fluid-dynamic effects (slip flow)

At low gas pressures, the mean free path lengths of the molecules may become similar to the pore size of the respective rock sample, which results in more frequent collisions with the pore walls and a non-zero flow velocity at the pore walls. Accordingly, the average flow velocity is larger, thus gas permeability. Permeability is not a fixed rock parameter, as it depends on the applied fluid pressure conditions. Often the term apparent gas permeability is used. Usually this effect is taken into account by the so-called Klinkenberg correction /KLI 41/, where apparent gas permeability coefficients are plotted as function of the reciprocal mean pore pressure (Fig. 3.2.4). For dry and porous material linear extrapolation to infinite gas pressures ($1/p_{mean} = 0$) yields the permeability coefficient for a condensed ("liquid-like") phase, commonly denoted as "intrinsic permeability coefficient" (k_∞) and *b* is the gas slippage factor.

$$\boldsymbol{k_{gas}} = \boldsymbol{k_\infty} \cdot \left(\mathbf{1} + \frac{\boldsymbol{b}}{\boldsymbol{p_{mean}}}\right) \tag{9}$$

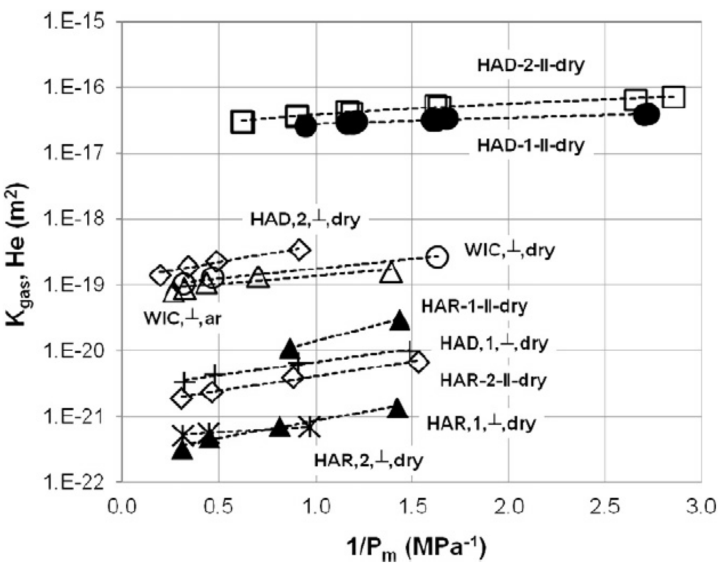

Fig. 3.2.4 Klinkenberg plot of different Posidonia Shale samples from the Hils Syncline, N Germany, drilled perpendicular (⊥) and parallel (II) to bedding. Measurements were performed in the dry and the as-received (ar) state at a confining pressure of 30 MPa (WIC = Wickensen, HAR = Harderode, HAD = Haddessen) /GHA 14/.

3.2.3.2.3 Variations in water saturation (drainage & imbibition process)

It is evident that water, blocking parts of the effective transport pore system, leads to a reduction of the effective permeability to the gas phase, k_{eff_gas}. Additionally, the contribution of slip flow to the total gas flow (slippage factor) will change, depending on the type of water saturation change (drying, water uptake by sorption/moisture equilbration, drainage/imbibition) and the distribution of the water phase within the pore system /ROS 48/, /FUL 51/, /EST 56/, /RUS 03/, /LI 04/. A reduction of the slippage factor is expected to occur when water only blocks the smallest pores in which slip-flow primarily occurs, while the largest pores remain open for gas transport /QIN 02/, /EST 56/, /ABB 99/, /RUS 03/. In contrast, increasing slip factors are associated with systems, where both phases flow in the same capillaries. As the gas-filled portion of the pore system decreases with increasing water saturation, the slip factor increases concomitantly (> 18% water saturation; /LI 04/). Both cases, however, are valid for relatively stable systems, i.e. where water saturation does not change dynamically with the applied fluid pressure gradient (immobile water phase).

Experiments starting with higher amounts of mobile water or even starting at 100% water saturation, yield values for the effective gas permeability as a function of the applied pressure difference. Gas flow under these conditions is clearly capillary pressure-controlled and the slip-flow effect is subordinate (Fig. 3.2.5, Fig. 3.2.6) /AMA 13/, /AMA 15a/. In experiments where the average mean pore pressure increases with increasing pressure difference (steady state experiments, with p_2 = const. at atm pressure) the “Klinkenberg line” may have negative slopes indicating the successive displacement (drainage) of water (Fig. 3.2.7, Fig. 3.2.8).

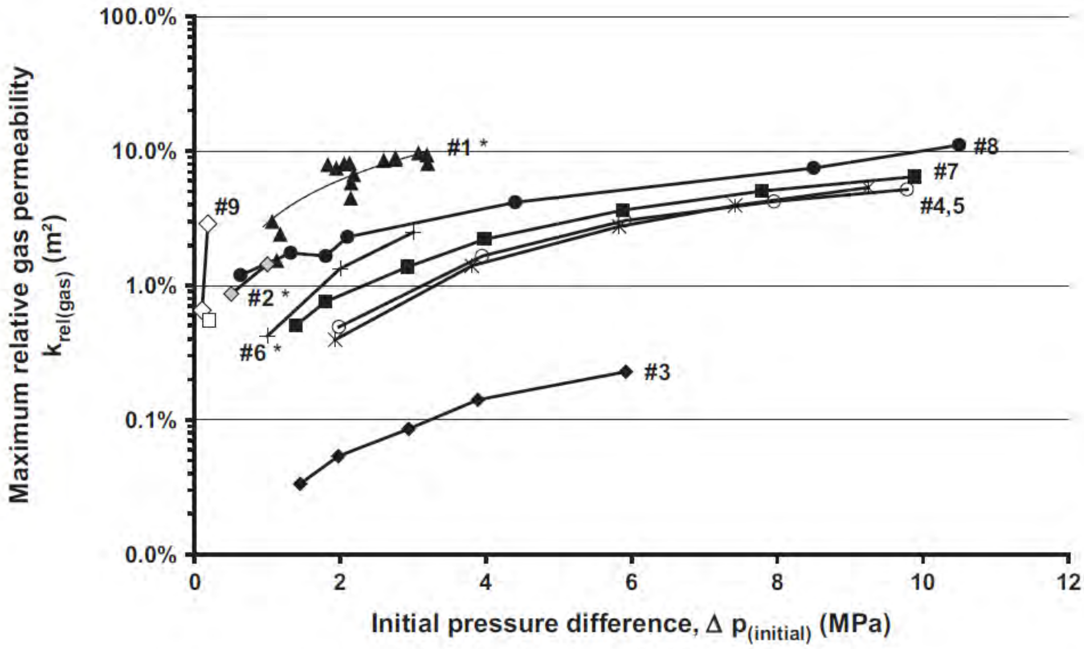

Fig. 3.2.5 Dependence of relative gas permeability on the pressure difference (capillary pressure) in gas breakthrough experiments. With increasing capillary pressure, successively more water is drained from the pore system and gas permeability increases. All samples were initially fully water-saturated. Data were obtained on a set of tight sandstone samples with intrinsic permeability coefficients ranging in between 10^{-16} and 10^{-19} m² /AMA 15a/

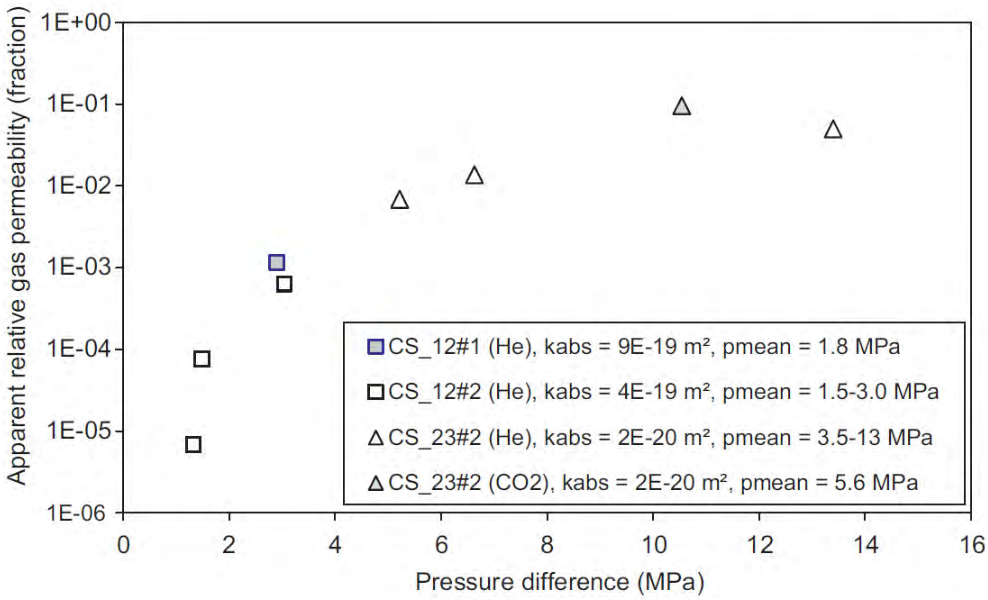

Fig. 3.2.6 Relative gas permeability coefficients for a mudstone and a limestone sample as a function of differential pressure. The absolute (water) permeability is in the order of 10^{-20} and 10^{-18} m² /AMA 13/.

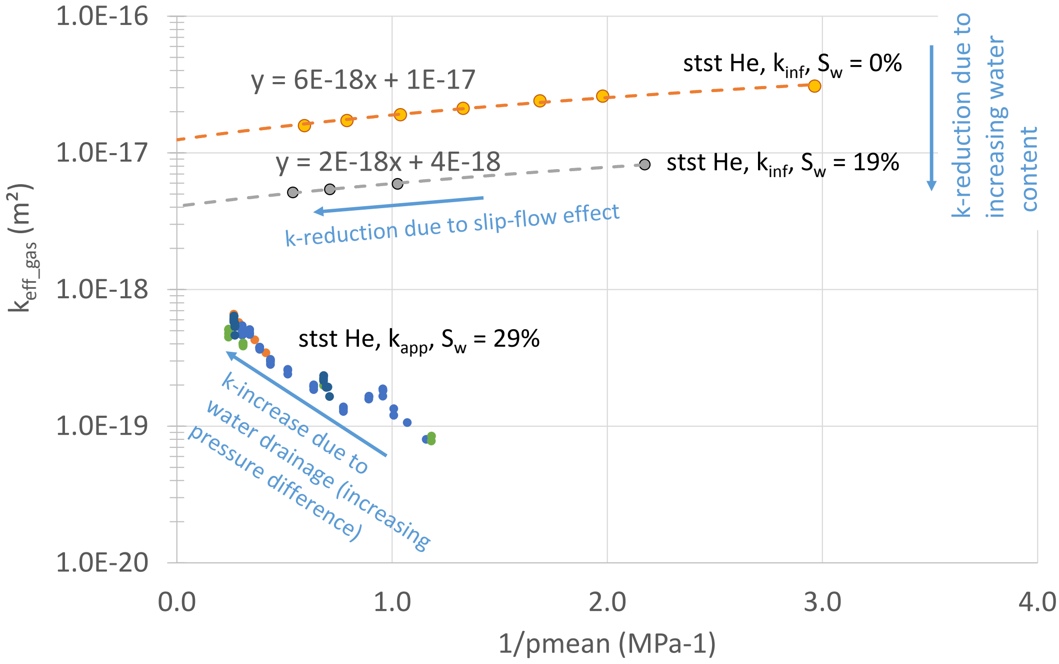

Fig. 3.2.7 Steady state gas permeability measurements conducted on a tight sandstone sample at different water saturations and a confining pressure of 40 MPa (S_w = 0%), 20 MPa (S_w = 19%), and 36 MPa (S_w = 29%). It is obvious, that permeability decreases with increasing water saturation (S_w = 0 and S_w = 19%). At even higher water saturations (29%) a negative slope is obtained, indicating capillary-controlled drainage.

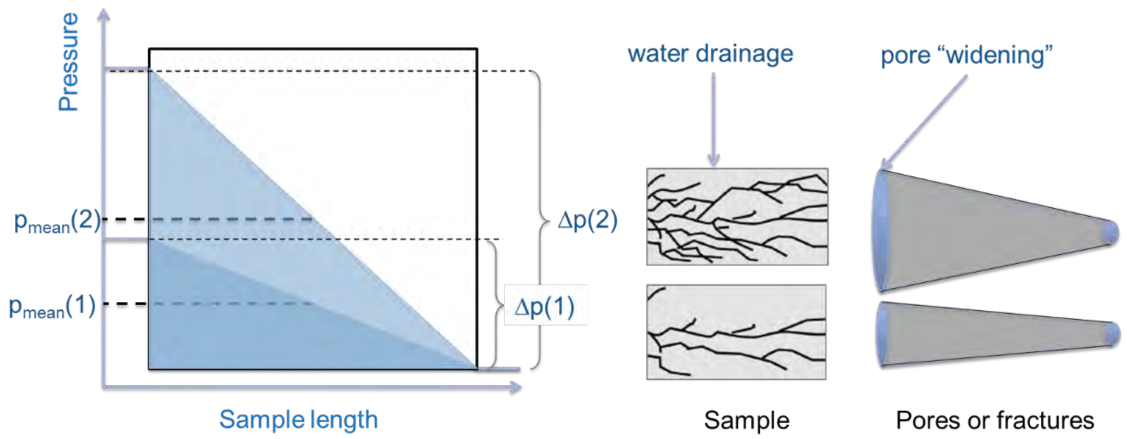

Fig. 3.2.8 Schematic sketch of different potential effects of changes in pore fluid pressure in typical steady state gas permeability experiments, where the gas pressure is increased on the high pressure side and kept constant at atmospheric pressure on the outflow side (left). Any increase in the gas pressure gradient leads to the displacement of mobile water and an increase in effective gas permeability. The increase in fluid pressure may also lead to the dilation of the pore system.

3.2.3.2.4 Stress dependend pore structure and permeability changes (compaction & dilation)

Effective stress changes result in pore structure changes which can be reversible (poro-elastic behaviour) or irreversible due to mechanical compaction over geologic timescales. As permeability is directly related to the transport pore system, changes in pore structure directly affect the permeability of a rock specimen. Increasing pore pressure (p_p) decreases effective stress (σ') following Terzaghi's principle with $\sigma'=p_c-p_p$. This has implications for gas migration through clay-rich barriers when pore pressure buildup below a seal decreases effective stress which increases permeability coefficients by dilation of the transport pore system. Stress-dependency of permeability can be expressed by an exponential equation:

$$\boldsymbol{k}_{\infty} = \boldsymbol{k}_{\infty,\mathbf{0}} \cdot \boldsymbol{e}^{-\propto \cdot \boldsymbol{\sigma}'} \qquad (10)$$

Where $k_{\infty,0}$ is the Klinkenberg-corrected permeability coefficient at zero effective stress ($\sigma' = 0$) and α a curve fitting constant describing the stress sensitivity of k_∞.

At a given confining pressure (lithostatic pressure), stress dependend (poro-elastic) permeability changes are counteracting fluid-dynamic and pore pressure dependend (slip flow) processes (chapter 3.2.3.2.2). In a Klinkenberg plot, this results in apparent gas permeability curves displaying distinct minima, representing the transition from poro-elastic to slip flow dominated flow regime (Fig. 3.2.9) (e.g. /GEN 14/).

3.2.4 Dismigration models

In the following paragraphs different models for diffusion and pure capillary controlled leakage are discussed. The models are based on previous studies, which were performed in the context of methane and carbon dioxide caprock sealing integrity projects /HIL 03/, /HIL 02/, /KAH 15/. However, the models can easily be adapted for quantification of leakage of gases from nuclear waste storage sites.

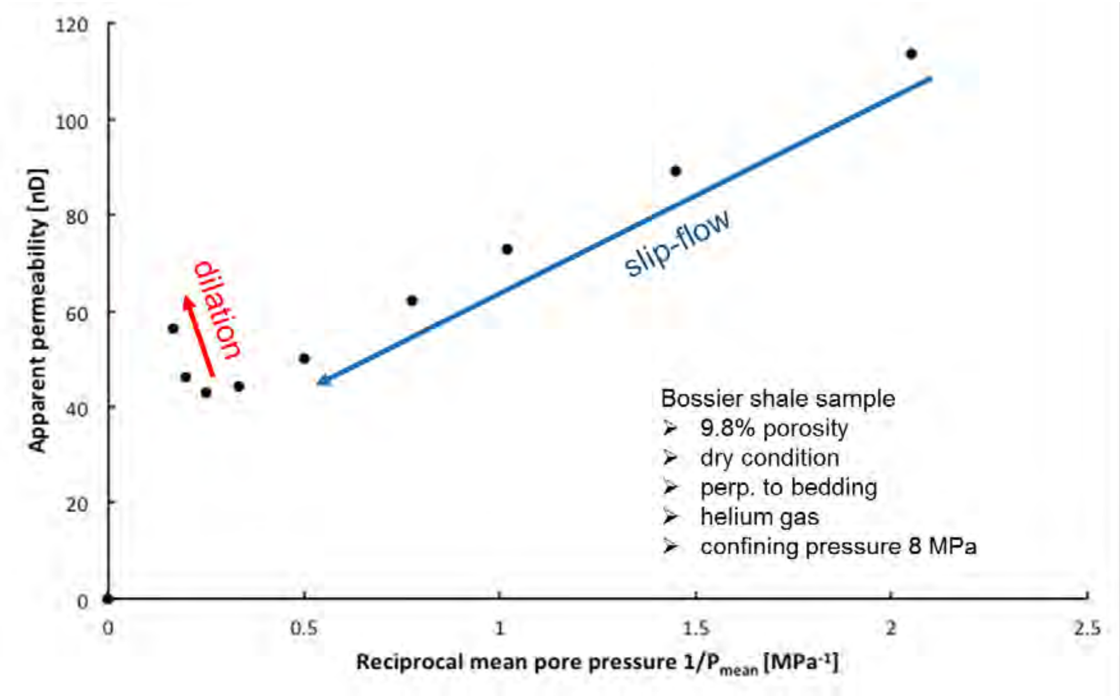

Fig. 3.2.9: Response of permeability on pore pressure changes. At low gas pressure the system is dominated by slip-flow and at high pore pressure dilation results in higher permeability values.

3.2.4.1 Diffusion through a water-saturated cap rock sequence

In a study addressing the long-term and safe storage of carbon dioxide (CO_2RINA Project, 2012-2015, BMBF-funded), the diffusive transport capacity across the caprock of a distinct storage site was quantified /KAH 15/ using the simplified model described in chapter 3.2.3.1 (diffusion through a plane parallel sheet). The bulk CO_2 concentration at the base of the cap rock ($c_1 = c_{pore\ water} \cdot \phi$) was calculated as a function of temperature, pressure and salinity /DUA 03/ and porosity. The concentration at the top of the cap rock (c_2) was assumed to be constantly zero. For this scenario the following parameters were defined: 160 m caprock thickness, D_{eff} of $5 \cdot 10^{-10}$ m^2/s, porosity of 12%, constant temperature of 34°C, pressure at the base of the caprock 6.3 MPa, and the salinity of pore water 1.1 mol NaCl/kg water. The results indicate that a detectable diffusive flux of CO_2 at the top of the caprock layer is expected to occur only after a period of >0.1 million years (Fig. 3.2.10).

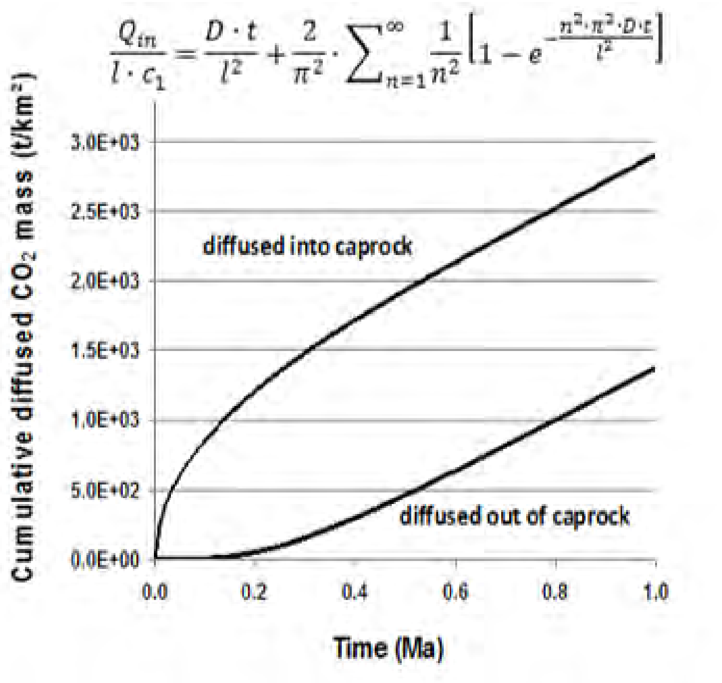

Fig. 3.2.10: Cumulative mass of CO_2 diffused into (Q_{in}) and out of (Q_{out}) 1 m^2 of a cap rock layer of 160 m thickness /KAH 15/. Input parameters were: Δx = 160 m, ϕ = 12 %, T = 34 °C, p_1 = 6.3 MPa, salinity 1.1 mol NaCl/kg water. The effective diffusion coefficient assumed for this calculation ($5 \cdot 10^{-10}$ m^2/s) is at the upper boundary of values reported in literature, ranging from 10^{-10} to 10^{-12} m^2/s for shales, clays and carbonates /BUS 08/, /SON 13/.

3.2.4.2 Generic storage/leakage scenario – viscous & capillary controlled flow

This model assumes leakage by pure capillary-controlled viscous gas flow. As outlined above in chapter 3.2.3.2.3 the effective gas permeability increases with increasing capillary pressures. Before gas leakage (gas breakthrough) occurs, however, the pressure of the gas phase must exceed a critical threshold value. Otherwise the system is assumed to be "tight", and gas flow across the seal is considered to be purely diffusion-controlled. In a model shown in Fig. 3.2.11 gas is allowed to accumulate below a barrier rock layer /HIL 03/, /HIL 04/. As long as the injection or generation rate (J_g) is larger than the dismigration or leakage rate (J_k), the gas pressure in the reservoir will increase. Once the gas pressure exceeds the critical threshold, capillary breakthrough occurs and viscous flow will become the prevailing transport mechanism. The leakage rate increases according to the input parameters given in Fig. 3.2.12 (a). As the gas pressure increases, the originally water-saturated pore system of the seal rock will be successively drained and gas saturation as well as gas permeability increases. This results in an increase in leakage rate (Fig. 3.2.12). In the worst case scenario shown in Fig. 3.2.12, an effective gas permeability of 10^{-21} m² would persist at a pressure difference of approximately 9 MPa (15.3-4.7 MPa). Corresponding gas losses would equal to 15 tonnes of CO_2 per year and square kilometre. As the gas reservoir depletes and gas pressure decreases, the effective gas permeability is reduced again as water re-imbibes into the sealing rock. When the gas pressure drops below the critical pressure at which the system seals again (capillary snap-off pressure), gas flow ceases and a residual amount of trapped CO_2 remains below the barrier. The capillary snap-off pressure is somewhat lower than the initial breakthrough pressure /BUS 13/.

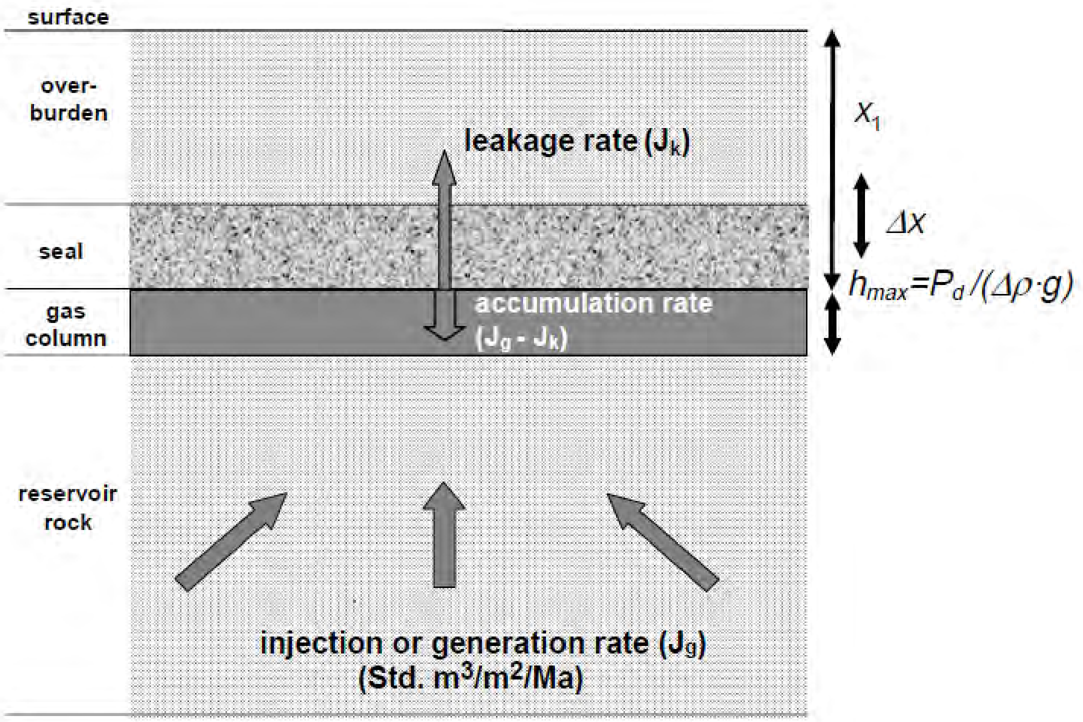

Fig. 3.2.11: Schematic sketch of the accumulation-leakage scenario: x_1 is the depth of the reservoir/caprock interface, Δx is the thickness of the seal, h_{max} is the maximum gas column height which is a function of P_d (the capillary displacement pressure), Δρ is the density difference between water and gas, g is the acceleration due to gravity. Leakage through the seal (J_k) occurs when the gas buoyancy pressure exceeds the critical capillary pressure and is calculated as a function of $k_{gas}(P_c)$. The effective accumulation rate is the difference between injection and leakage rate (J_g - J_k).

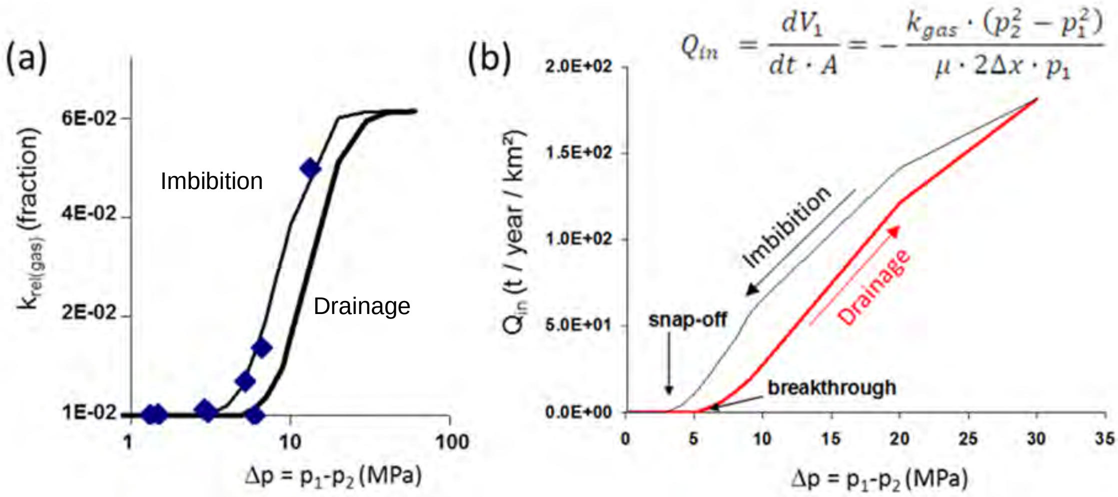

Fig. 3.2.12: (a) Relative gas permeability as a function of capillary pressure based on data from /AMA 13/. The intrinsic permeability of the caprock is 10^{-19} m².
(b) Leakage rate out of the reservoir into the sealing lithology (Q_{in}) by immiscible viscous gas flow.

3.2.5 Conclusions

In this contribution we have shown that gas transport through initially water-saturated rock occurs by different highly dynamic and coupled processes, depending on the boundary conditions and the rheology of the host rock. It is known that water-saturated argillaceous rocks can effectively retain a gas phase up to a critical pressure. Below this critical gas pressure the system will remain “tight” and gas can only be transported across it in the dissolved state, either by advective groundwater flow or diffusion. In the absence of a hydraulic pressure gradient, transport occurs exclusively by diffusion with very low transport capacities and only short distances. In the example discussed here, a period of 0.1 Ma is required for a significant portion of gas molecules (10 % of the steady-state flow) to cross a homogeneous barrier section of 160 m thickness assuming a diffusion coefficient of $5 \cdot 10^{-10}$ m²/s. The non-steady state and steady-state diffusive flux are controlled by the effective (transport) porosity, which here was assumed to be 12%. The pressure at which advective gas transport is initiated is either controlled by capillary forces or, in weak (unconsolidated) clays and mudrocks, by the creation of pressure-induced dilatant pathways. The effective gas permeability then depends on the prevailing fluid pressures (absolute gas pressure, capillary pressure), which control the proportion of the gas-conducting pore system. In mudrocks and engineered barriers effective gas permeability coefficients are well below 10^{-21} m². Considering a capillary pressure-controlled worst-case scenario after breakthrough, a gas overpressure of 9 MPa and an effective gas (CO_2) permeability of 10^{-21} m², the gas phase would dismigrate at a velocity of 15 tonnes CO_2/year/km². Re-sealing of the system after breakthrough is possible if gas pressure drops below a certain value (snap-off pressure). Gas permeability coefficients may drop to values below 10^{-23} m² and under these circumstances gas transport rates by pressure-driven volume flow become similar to diffusive fluxes.

The examples given above are strictly valid only for simple, homogeneous barrier systems. Risk assessment studies for specific storages sites, however, need to consider the pertaining scenarios, including different lithotypes (clay content), porosity, pore size distribution, wettability characteristics and rheology. This can only be achieved by detailed experimental investigations on the respective host rocks, combined with a profound knowledge of the geological subsurface system.

3.2.6 Acknowledgements

The experiments outlined above were conducted during the last decades in the frame of different research projects, all focussing on the gas sealing capacity of argillaceous lithologies: We greatfully acknowledge funding by the Deutsche Wissenschaftliche Gesellschaft für Erdöl, Erdgas und Kohle e.V. (DGMK), German Ministry of Education and Research (CO2Trap, CO2Seals and CO_2RINA within the GEOTECHNOLOGIEN program), the European Commission (NASCENT, RECOPOL, MOVECBM, CASTOR), and financial support from the industry (CCP project - http://www.co2captureproject.org, GASH - http://www.gas-shales.org), TGI and iLops - Wintershall Holding GmbH, and other projects funded by Shell International, NorskHydro/Statoil, EniTechnology.

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3.3 Juhlin C.: Appraisal of geological barriers in the upper crust based on some crystalline rock drilling projects and geophysical data: Focus on Sweden

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3.3.1 Background

/JUH 89/ suggested a geological model for the Swedish rock column in the Baltic Shield at great depth based on results from the Gravberg-l deep borehole that was drilled to about 6.8 km within the Siljan Ring area, central Sweden in the late 1980s. Their main conclusions were:

- The bedrock is highly fractured down to a depth of about 1200 m. Below this depth fracture zones, which typically extend over 2-20 m, occur at a frequency of about every 200 - 300 m.
- Hydraulic measurements between 1250 and 3200 m indicate a hydraulic conductivity within the interval 10^{-9} - 10^{-10} m/s. This conductivity probably corresponds to the most permeable zones in the rock mass.
- Highly saline fluids (salinities of 10 - 15%) are present below 6 km.
- Isotope data on calcite indicate groundwater may percolate to great depth (5 km).
- The temperature gradient is about 16 °C/km based on a measurement after a furlough period of 10 months.
- Data from different sources, including the Gravberg-l borehole, indicate a stress field where the vertical stress is lithostatic, the minimum horizontal stress is 2/3 of the vertical stress and the maximum horizontal stress is somewhat larger than the vertical stress

In a later study based on a more comprehensive review of data from deep boreholes /JUH 98/ proposed a conceptual model for groundwater circulation in the Baltic Shield (Fig. 3.3.1). They showed that prediction of lithology at depth based on surface geological information is difficult in volcano-sedimentary rocks due to the heterogeneous nature of these rocks. In granitic environments it is easier to predict the lithology in the upper 5 km. Therefore, the model in is more relevant for granitic areas in which the upper 1 km of crust consists of more fractured rock, or at least rock with more open fractures, compared to that below. In areas of low topography, this upper fractured interval limits the depth of meteoric water circulation and highly saline waters may be expected below 1 km. Closer to mountainous areas the topography greatly influences meteoric water circulation patterns with these waters possibly penetrating down to depths on the order of 10 km. The temperature field variations within the shield are small enough that they are not expected to have significant effect on the water circulation patterns. Earthquake activity is low in the shield area, in general, with higher concentrations along the west coast of Norway, the northeastern coast of Sweden and in southwestem Sweden. Even in these areas the earthquake activity is low compared to active southeastern Europe. The largest earthquakes occur deep in the crust due to increasing differential stress with depth. Earthquakes may be concentrated towards larger zones of weakness where water circulation may be expected to be enhanced.

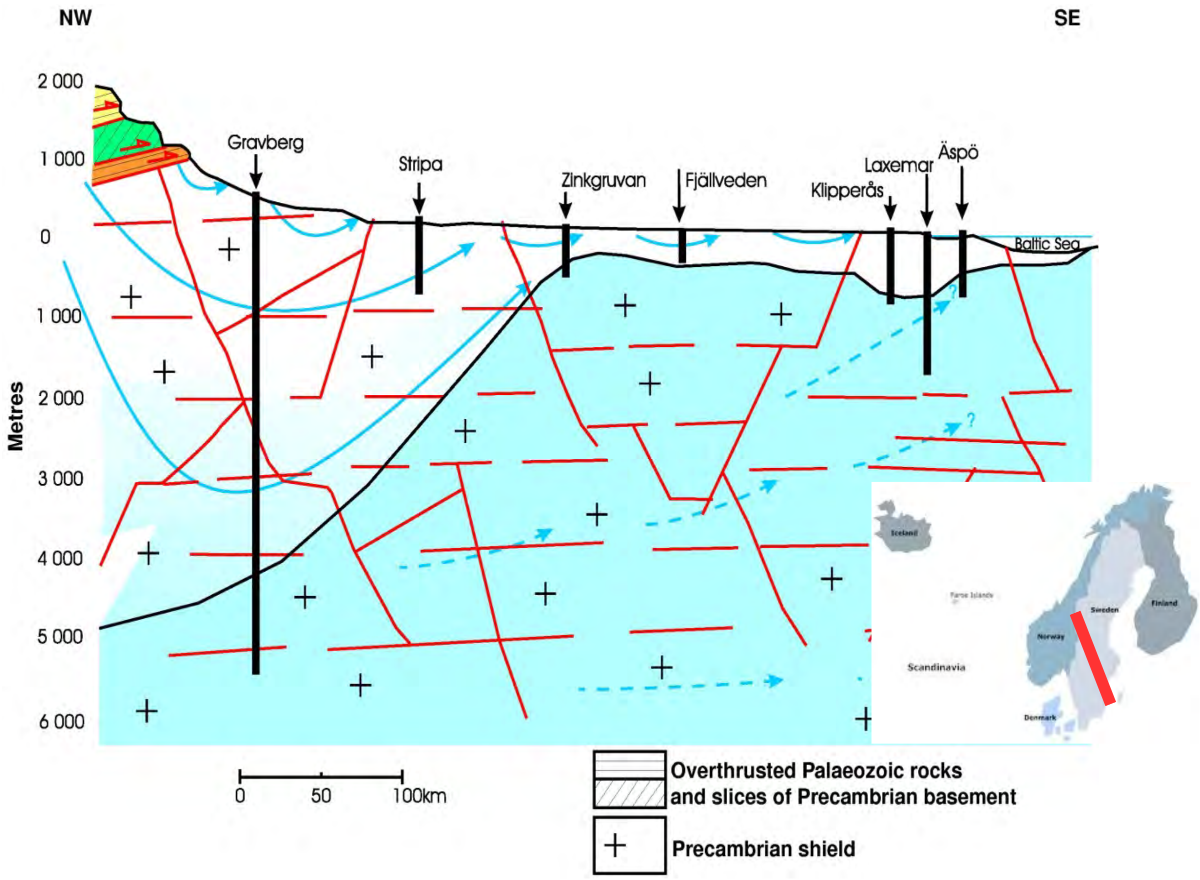

Fig. 3.3.1 Conceptual model for water circulation patterns along the profile shown by the red line in the overview map. The darker the shading the greater the salinity of the water. Meteoric water is driven deep into the crust by the hydraulic head in the mountains. This model is partly based on earlier work by /LAA 95/.

The above described model supports the original idea behind storing spent nuclear fuel in the depth interval 2-5 km as long as the storage location is in an area with relatively minor variations in topography. Large parts of Sweden and Finland have low topography and it is expected that the saline waters will be encountered at a relatively shallow levels (< 1 km) in these areas. If so, there would be no risk of radionuclides reaching the surface even if there is leakage (Fig. 3.3.2).

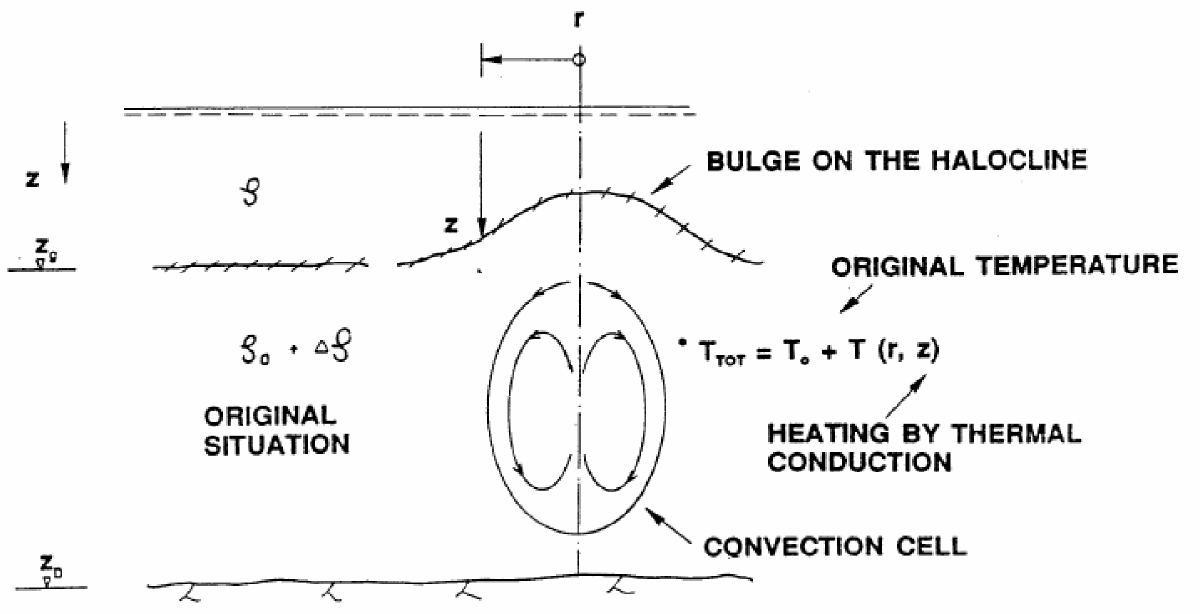

Fig. 3.3.2 Bulge on the halocline due to temperature increases from the stored spent fuel. If the density contrast is large enough between the water above and below the halocline then no saline water will circulate to the surface. (From /LAA 95/)

In this presentation I review some of the data behind the conceptual model presented in Fig. 3.3.1 and the model itself. I also present some new results from a recent deep drilling project in Sweden that supports the conceptual model /LOR 15/. In general, knowledge of conditions at depths below 1 km is lacking and more deep boreholes are needed to better understand the physical and chemical conditions in the depth range 1 to 6 km.

3.3.2 The Gravberg-1 borehole

The Siljan Ring structure, located in central Sweden, was formed by a meteorite impact that occurred in Devonian time about 360 million years ago. As a result of the impact the bedrock probably became fractured to great depth. The fracturing consists of both microfracturing within the rock matrix and large scale fracturing.

The ca. 6.8 km deep Gravberg-1 borehole /JUH 91/ was drilled in the late 1980s into the crystalline rock of the Siljan Ring impact crater in the search for abiogenic hydrocarbons (Fig. 3.3.3). No large quantities of gas were found, but the project did provide a number of scientific results of international interest, including the presence of highly saline (15 %) water at depths below 5 km /PED 92/. Recovered formation water from these depths contained significant quantities of formation gases, especially helium and nitrogen. The helium is nearly all crustal in origin /HIL 89/, being generated by radioactive decay in the surrounding granite. Analysis shows that the required time for the formation water to accumulate the observed quantities of helium is on the order of hundreds of millions of years /JUH 91/. The fact that formation waters can be stagnant for these time periods has significant implications for the large scale water circulation patters in the Baltic Shield and was part of the impetus for studying the very deep hole concept for storage of spent nuclear fuel by SKB /JUH 89/.

The surface seismic data and later acquired borehole seismic data at Gravberg-1 showed that the high amplitude reflections from the granitic bedrock correspond to sub-horizontal dolerite sills and that the upper 1 - 1.5 km of crust is highly fractured with more competent rock below. The dolerite sills furthermore act as marker horizons and show that a post-impact central uplift of about 3 km at 5 - 8 km depth.

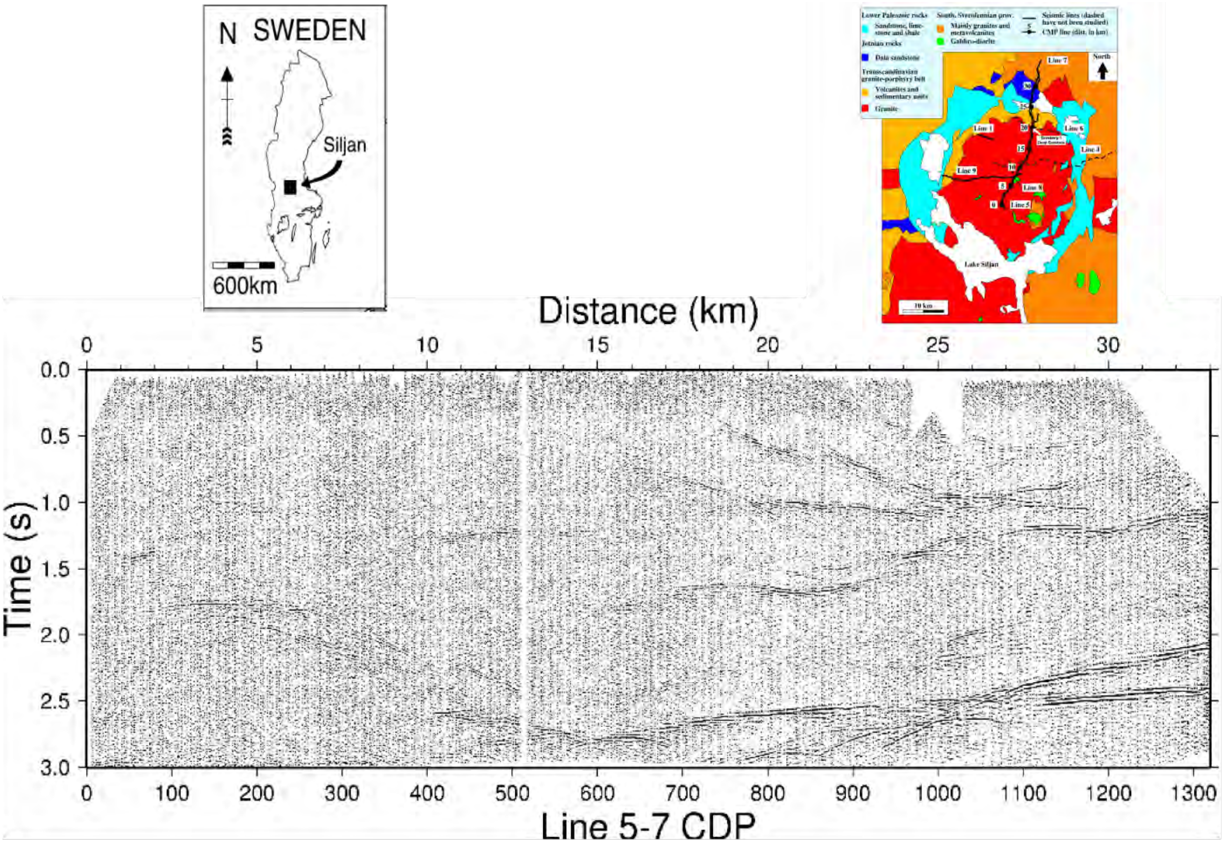

Fig. 3.3.3 Location of the Siljan Ring area in Sweden, simplified geological map and composite seismic section of the north-south striking lines 5 and 7. The Gravberg-1 borehole is located at a distance of about 20 km (CDP 800). See Fig. 3.3.4 for a depth section in the vicinity of the borehole.

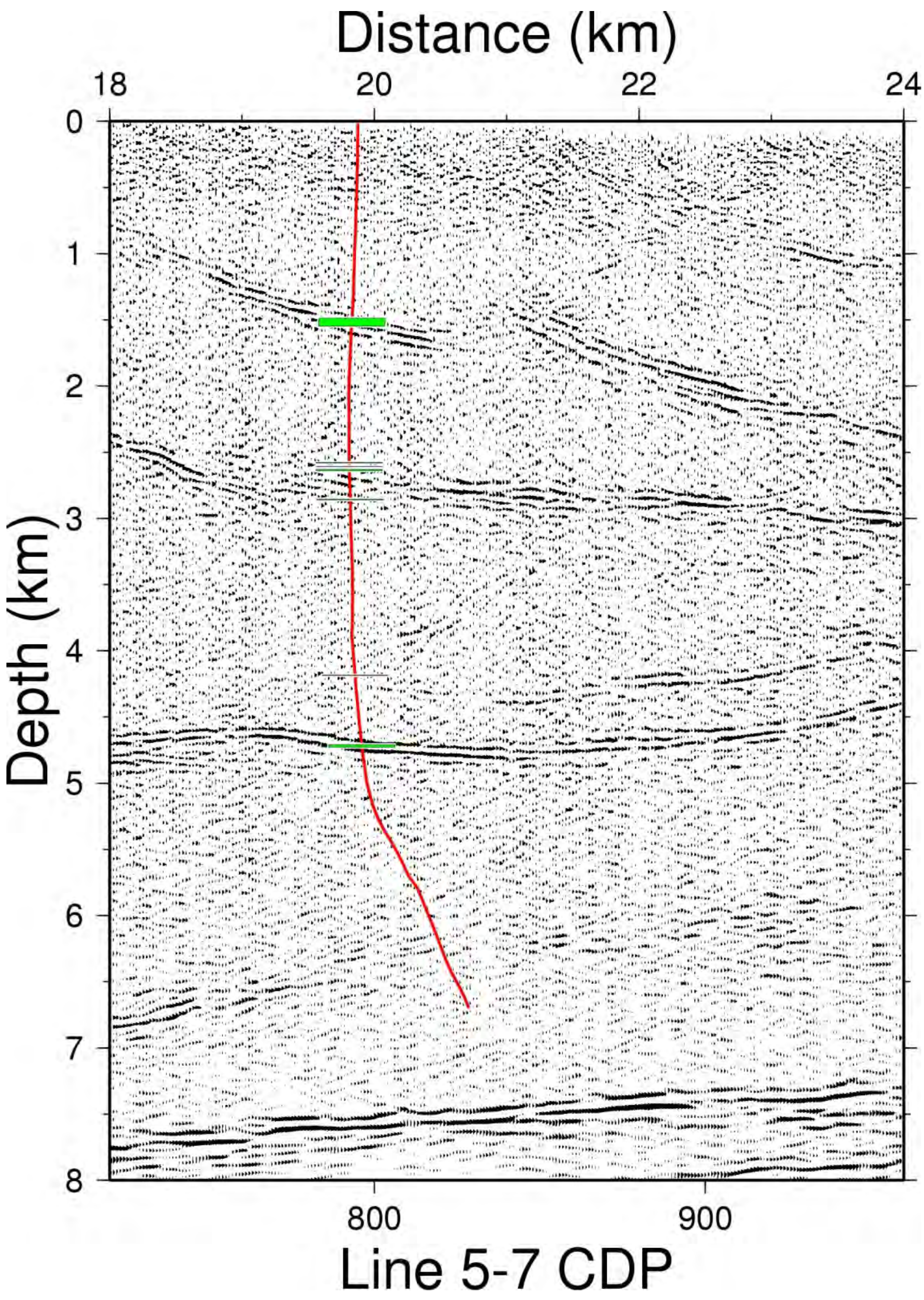

Fig. 3.3.4 Drilling of the Gravberg-1 borehole shows the marker reflections to originate from thin dolerite sills (green bars) in otherwise granitic bedrock. The date were pre-stack depth migrated. The diffuse reflections intersecting the borehole just below 6 km probably represent thin felsic aplitic intrusions

3.3.3 Lithology and fracturing

Geoscientific data from deep boreholes in crystalline rock show the presence of large structural and lithological heterogeneity both within and between drill sites. The structural complexity of the continental crust leads to difficulties in predicting the geology in deep boreholes prior to drilling. Major uncertainties are introduced by the presence of large scale orogenic structures such as complex folding, nappes, syn-tectonic thrust faults, and post-orogenic brittle faulting and fracturing.

The Kola, Krivoy Rog, KTB, and Ural boreholes all exemplify the heterogeneity in metamorphosed (i.e. crystalline) and deformed supracrustal rocks. Simple "pancake" models can generally not be used when describing, interpreting, and making extrapolations in volcano-sedimentary formations.

The geological information from the Kola and Krivoy Rog boreholes demonstrate the unreliability of three-dimensional models of the Proterozoic orogenic belts based on surface geological and geophysical observations /KAZ 92/. The predicted and actual geology differ greatly in lithology, tectonic elements and metamorphic grades at great depth. It can be assumed that the composition and structure of the upper continental crust is highly site specific in ancient metamorphic (i.e. pre- and syn-orogenic) Precambrian shield environments.

Geological environments with homogeneous and fairly persistent geology in three dimensions are restricted to large (> 1 - 5 km) intrusive bodies like granitoids. Different types of granitoids can be characterized with specific properties, as a result of their tectonic setting and relation to the orogenic development. In particular, post- and anorogenic (i.e., emplaced after the cessation of the latest orogenic event) granitoid plutons and batholiths can be considered to be reasonably predictable regarding three-dimensional shape, composition, and deformation structures. For example, the Laxemar borehole (Fig. 3.3.5) is situated in late- to post-orogenic granitic intrusives. Although the penetrated granitic bedrock column exhibits natural magmatic compositional variations, the general predictions regarding the lithology prior to drilling agree fairly well with observations in the borehole.

Some granite suites, especially the late orogenic types, are commonly related to high heat flow, due to a high content of radioactive elements. All types of granitoids may host mineralizations, such as breccias or disseminations.

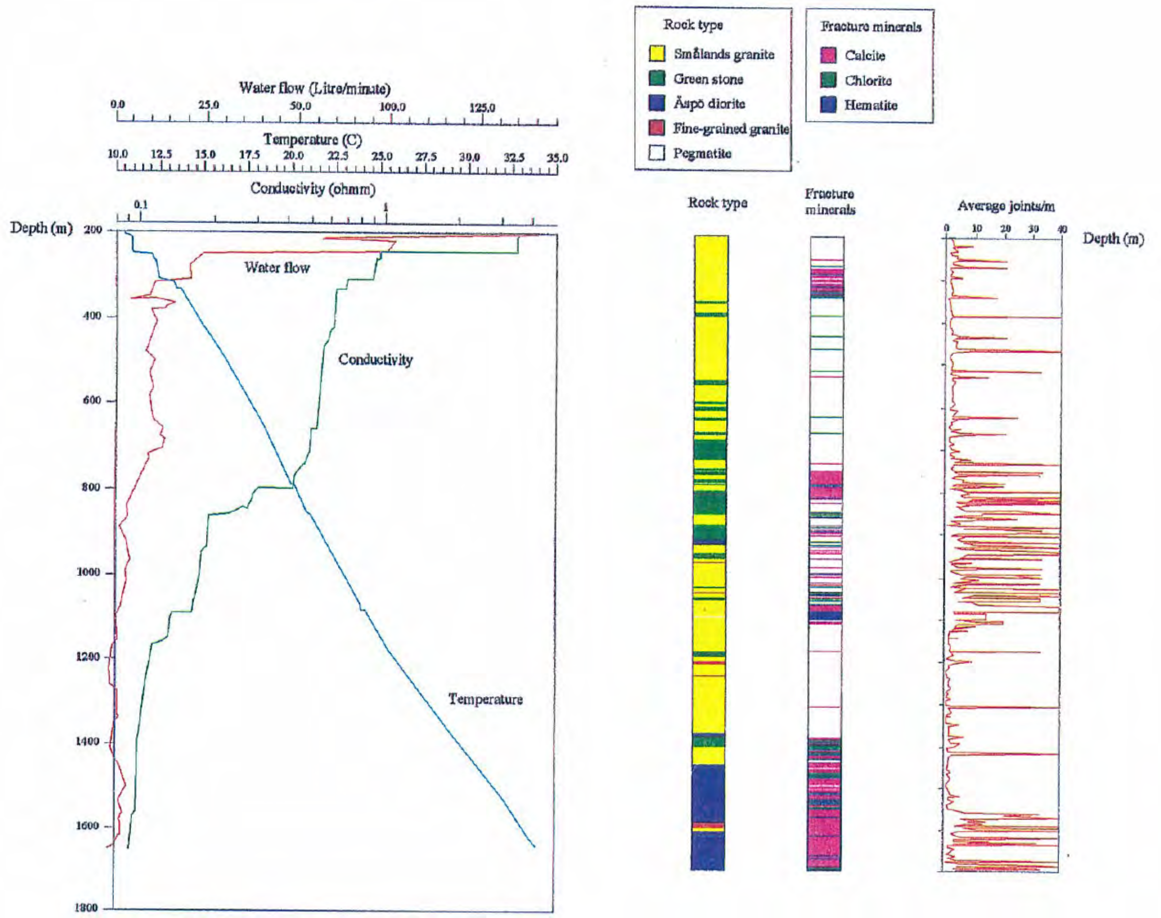

Fig. 3.3.5 KLX02 downhole groundwater logging profiles and lithological, fracture frequency and fracture mineral data (from /LAA 95/). Note the intense fracturing at 700 to 1100 m and below 1560 m. Laxemar is located at the southern end of the red line in Fig. 3.3.1. (From /JUH 98/)

3.3.4 Temperature

An inventory of heat flow in the Baltic Shield was carried out in 1992 during the European Geotraverse (EGT) project /BLU 92/. The estimate of surface heat flow is based upon measurements in shallow boreholes. Fig. 3.3.6 shows the distribution of the measurements in Sweden. Recent studies have added a few data points to the map, but the general pattern remains the same, heat flow is generally low compared to southern Europe.

In general in the Baltic Shield, the apparent heat flow calculated from boreholes penetrating a few hundred metres into the bedrock will be 5 - 15 mW/m^2 lower than the true heat flow due to climatic changes with the smaller correction being suitable for the north and the larger correction for the south.

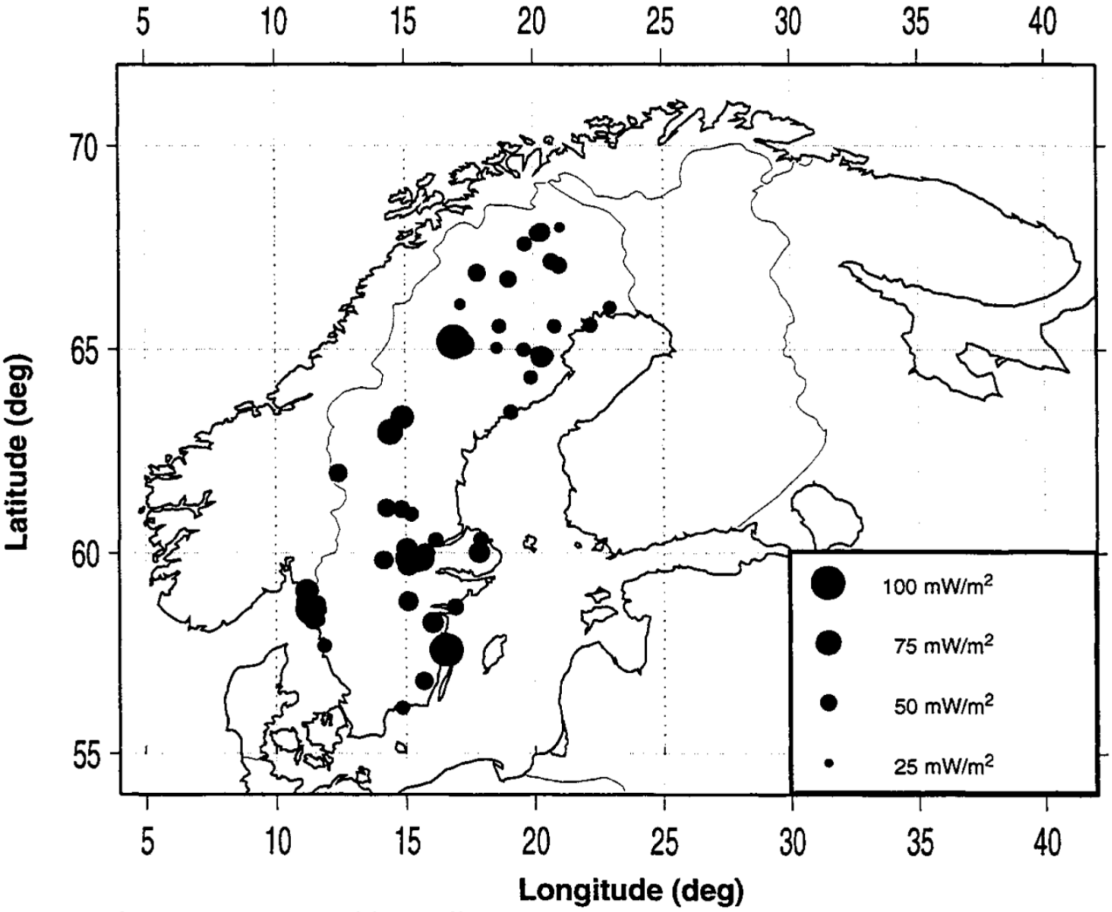

Fig. 3.3.6 Location of heat flow measurements in Sweden and corresponding values. (From /JUH 98/)

A number of studies have been carried out to predict the temperature at 500 m depth in Sweden based on heat flow observations and assumptions of the thermal conductivity and heat production at depth /AHL 95/, /ELI 94/, /SUN 95a/. The thermal conductivity and heat production estimates are based on measurements of rock samples which are often relevant for the areas under study. These studies predict temperatures of about 7.5 °C in northern Sweden and about 15 °C in southern Sweden at 500 m depth. Similar methods may be used to extrapolate the temperature to the depth interval 1 km to 5 km. These give a maximum temperature of about 80 – 105 °C at 5 km if the temperature gradient is 15 - 20°/km. These temperature gradients are also predicted in the uppermost crust from lithospheric modeling of heat flow in the Baltic Shield /BAL 95/. However, in the study by /AHL 95/ the observed gradients in 11 selected areas in Sweden are generally less than 15°/km implying that the temperature at 5 km may on average be somewhat less than 80° C and possibly as low as 60 °C in some areas. The sites studied in /AHL 95/ are believed to be representative for Sweden and the temperature gradients were calculated in boreholes which extended, generally, to at least a depth of 500 m.

The temperature gradient in the Gravberg-l borehole is nearly constant at about 16 °C/km, this is similar to that observed at Laxemar in southeastern Sweden. Variations in the temperature gradient in the Gravberg-1 borehole are probably due to groundwater entering the borehole at the time of logging. The temperature gradient in the SG-3 borehole on the Kola peninsula in Russia changes abruptly at 2800 m depth from about 13 °C/km to about 17 °C/km /NEDRA 92/. The reason for this increase in temperature gradient is not clear from the literature. Although there are some questions, the observed temperatures in the deep boreholes in the Baltic Shield generally agree well with those predicted from near-surface heat flow observations.

3.3.5 Hydrogeology and hydrogeochemistry

In-situ permeability measurements from depths greater than 1000 m have been reported from Gravberg /GUS 90/, Kola /NEDRA 92/, and Laxemar /FOL 93/, all within the Baltic Shield. These data provide a very limited database to allow any major conclusions to be drawn. Additional data from measurements in crystalline bedrock in other parts of the world supplement these and are shown in Fig. 3.3.7. These data have been divided into three groups:

- Baltic Shield
- Other shield areas and stable platforms
- Other crystalline bedrock

The criterion used to select the data used was that the measurements must represent natural, undisturbed conditions /WAL 96/. Additional data for representative bedrock exist in the reports and papers from the hot dry rock (HDR) geothermal energy research sites. However, these data have not been included since they reflect either hydraulic conditions after major hydraulic fracturing and fluid injections, or tests carried out at pressures high enough to induce significant fracture dilation and temporarily enhanced permeabilities.

Even after introduction of these additional data, the information from large depths is very limited. For comparison, the approximate range of permeabilities measured at SKB's study areas are also shown. The overall range of in-situ permeability values (10^{-19} - 10^{-13} m^2) from large depths agrees well with other compilations for crystalline rocks, e.g. /BRA 84/, who reported the range 10^{-18} - 10^{-13} m^2 for depths down to 3 km. /CLA 92/ compiled data from different types of experiments and studies in crystalline rock in an attempt to relate the data to scale effects. Clauser's data for borehole investigations fall generally within the range 10^{-20} - 10^{-12} m^2.

The data compiled in Fig. 3.3.7 represent in most cases transmissivity values divided by the length of the test section, which varies between one meter and about four kilometers. This implies that the effect of a highly permeable zone within a long, more or less impermeable borehole section is smoothed out. Higher permeabilities than those indicated in these figures can therefore be expected locally, especially within the long borehole sections.

Published analyses of depth trends in permeability down to 300 - 900 m in crystalline bedrock often show a zone of higher permeability in the upper 100 - 300 m. Below this zone the permeability appears to be roughly constant or decreases very slowly. According to Fig. 3.3.7, there appears to be a clear decrease in bulk permeability with depth. An interesting observation is the apparent log-linear decrease for the largest permeability values. The highest values observed seem to be about three orders of magnitude lower at 5000 m than at 1000 m. The number of measurements at depths greater than 2000 m are, however, rather few, and the database is, therefore, not considered sufficient to allow far-reaching conclusions to be made. A reservation should also be made with respect to the variations in section length described above. This compilation was done in 1998 and there are probably additional data that could be included now. This would be a useful exercise.

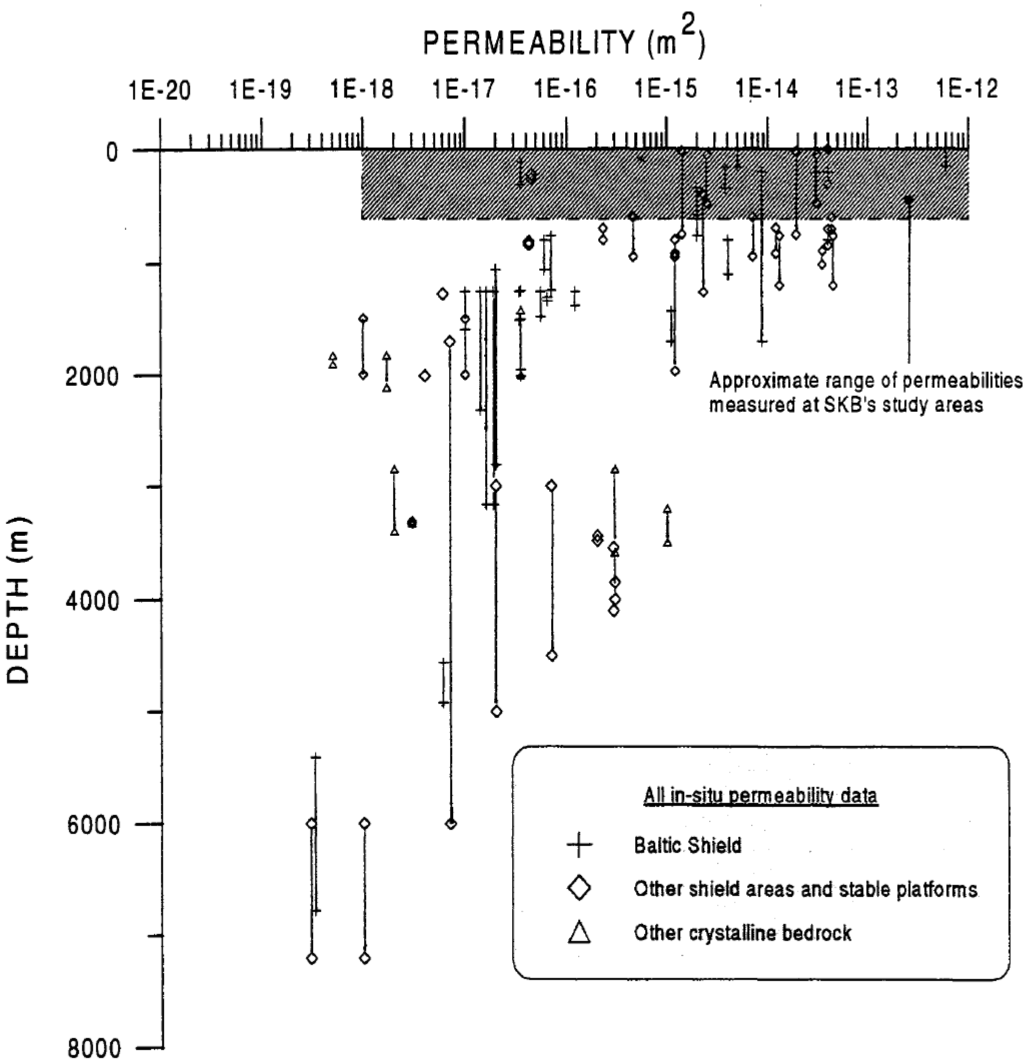

Fig. 3.3.7 Compilation of permeability measurements in boreholes in the Baltic Shield and other areas. References can be found in /WAL 96/.

In a crystalline bedrock environment, recharge groundwaters initially react with the overburden (if present) and subsequently with the fracture surfaces during percolation through the bedrock to greater depths. Normal water/rock geochemical evolution during percolation results in groundwaters becoming more alkaline and increasing in dissolved salt content (TDS) with increasing depth, in particular accommodating greater amounts of sodium and/or calcium, chloride and sometimes sulphate. The accumulated amounts of TDS very much depends on the groundwater flowrate through the rock, i.e. the greater the flowrate the less water/rock reaction time and the lower the TDS. Fresh to brackish groundwaters therefore tend to characterize the upper approximate 500 m or so, where groundwater flow is driven by head differences based on topographical variations and where there is a greater number of conducting fractures. Groundwater mixing from different sources may also contribute to changing hydrochemical properties. Approaching 1000 m depth groundwater flow conditions usually change; flowrates are less active and tend to be associated with more discrete, isolated water-conducting fracture systems. In this environment groundwaters are often more saline in character due to increased rock/water interaction. These waters, however, are still to some extent influenced by surface-derived input components under favorable hydraulic conditions. For example, in the case of the Baltic Shield, from recent precipitation, ancient and modern marine waters (i.e. coastal localities) and cold climate waters (e.g. glacial melt waters).

Based on data from mining activities in the Canadian Shield and deep exploration drilling in the Baltic Shield, saline waters (TDS 10000 - 100000 mg/L) and brines (TDS > 100000 mg/L), are found to be relatively commonplace at depths greater than 1000 m (Fig. 3.3.8). Many of these brines are Ca-Na-Cl in type with a Ca/Na ratio of around 1.5 - 3.0 (e.g. Gravberg between 5453 - 6967 m has a value of 3) and some are extreme in composition, containing up to 6 g/L Ca, 5 g/L Na and 20 g/L Cl in the Canadian basement at depths of 1500 m (see compilation by /SME 96/. In some cases (e.g. Aspo, Sweden) the Ca/Na ratio is nearer one, and in other cases (e.g. Olkiluoto, Finland) slightly less than one. Increased amounts of Na are considered to reflect water/rock interaction with more heterogeneous bedrock types than granitic varieties, for example the presence of Na-rich amphibolite units.

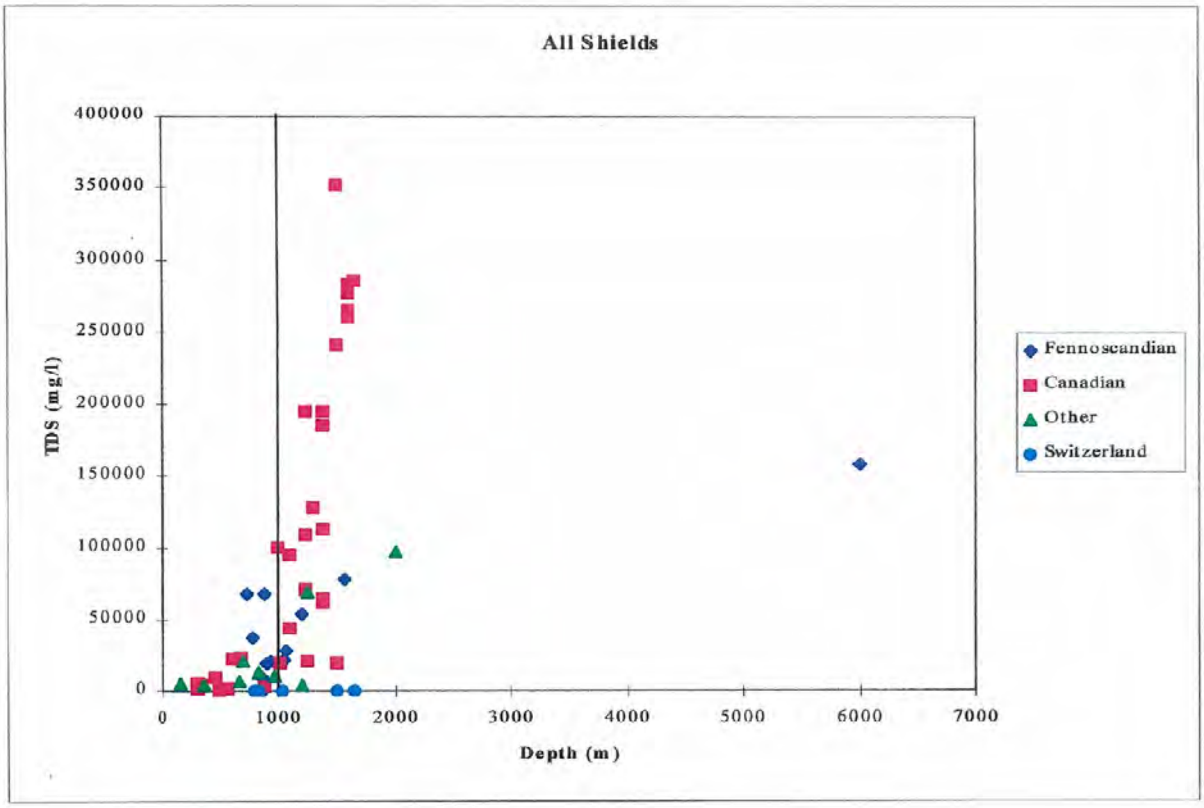

Fig. 3.3.8 Compilation of total dissolved solids in crystalline rock down to 6 km (from /JUH 98/)

3.3.6 State of stress

Stress data from deep boreholes in the Baltic Shield are extremely sparse. Furthermore, stress measurements at great depth may be assumed to include larger errors than what is normally anticipated. No direct stress measurements at great depth were carried out in the Gravberg-l borehole. However, constraints can be put on the minimum horizontal stress by considering leak off tests /MOO 90/, losses of large quantities of drilling fluid /JUH 91/, and downward focused hydrofracturing at total depth /LIN 89/. The minimum stress estimate from these tests and events are shown in Fig. 3.3.9. The estimated minimum horizontal stress in the Gravberg-1 borehole falls well within in bounds estimated from compilations of worldwide data /LJU 96/, /JUH 98/).

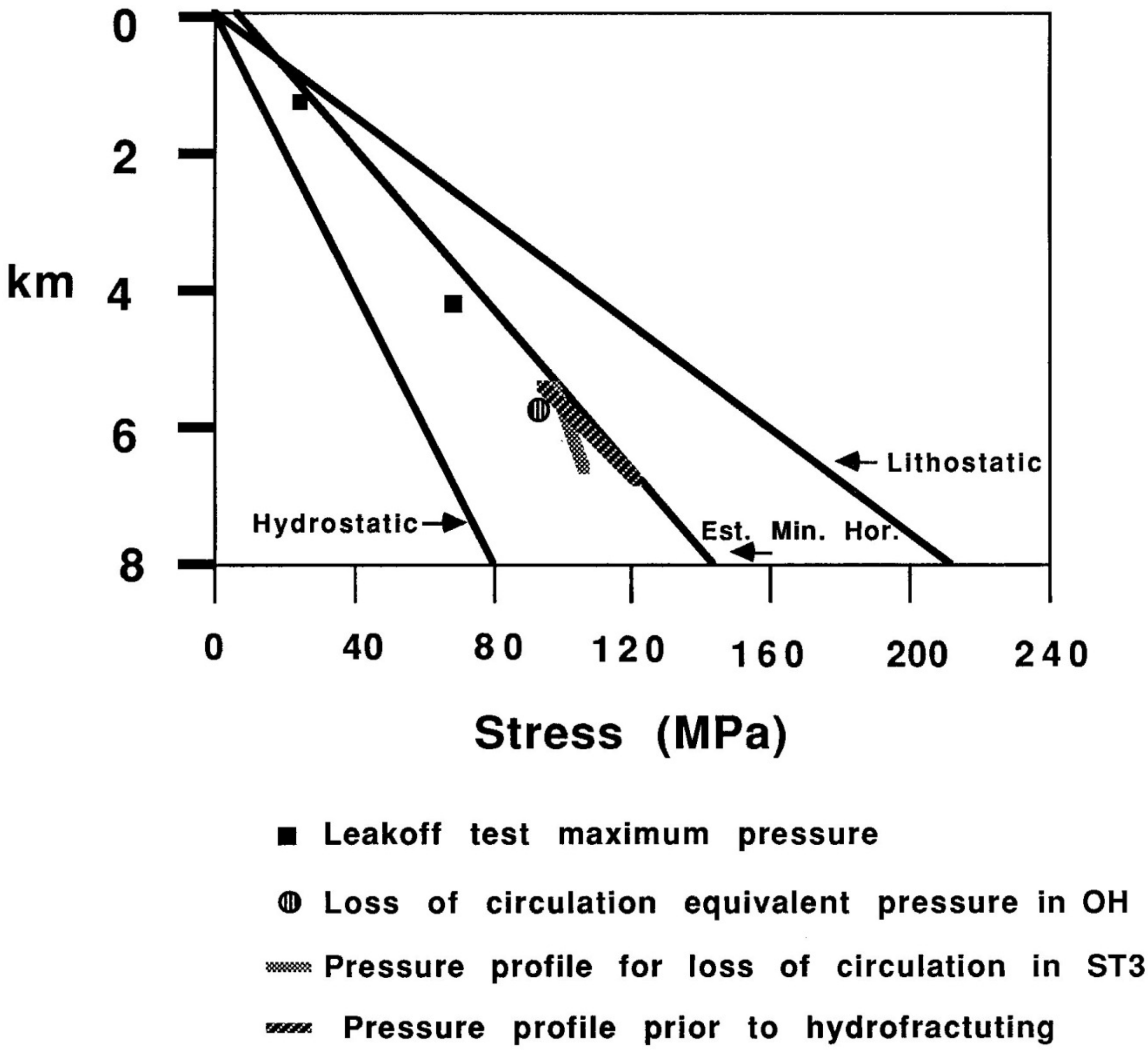

Fig. 3.3.9 Estimated state of stress in the Gravberg-1 borehole. The points where the formation was actually fractured in sidetrack 3 both during the fluid loss and hydrofracture operation are not known, therefore, a depth range of possible pressures is presented. Stress estimates and figure from /JUH 91/

3.3.7 Conceptual model

From the review of available data and its integration a conceptual model has been developed for the upper 5 km of crust in Sweden. In general, the upper c. 1 km of the crust appears to have more open fractures throughout the shield area and consequently the hydraulic conductivity can be expected to be higher. The increased amount of open fractures in the upper 1 km or so does not appear to be limited to the Baltic Shield. Similar features are expected to be found throughout Europe and even on the Arabian Shield, although the thickness and intensity of fracturing may vary. Below c. 1 km the crust is still fractured, but the frequency of open hydraulically conductive fractures is lower and the distance between fracture zones is greater. The upper 1 km is not only characterized by increased vertical to subvertical open fracture sets, but also regular open sub-horizontal fractures and fracture zones which further facilitate groundwater circulation and mixing. This assumption of enhanced porosity is based primarily on geophysical evidence, but also on the hydrogeological data. Note that geological data from deep boreholes generally do not discriminate between hydraulically open and sealed fractures. This lack of discrimination implies that the proposed increase in open fractures at shallow levels (principally reactivated pre-existing sealed fractures) is masked by the numerous amount of sealed fractures in borehole data.

Although the higher degree of open fracturing and increased permeability in the upper c. 1 km may be relatively universal, the hydrochemistry may differ drastically depending upon the geographical location. For this reason two models for the upper 5 km of crust in Sweden were developed in /JUH 98/, one for southern Sweden where the influence of topography is minor, and one for central/northern Sweden where topography plays a major role. The southern model is similar to the one derived by /NUR 88/ whereas the central/northern one differs in that the Caledonide mountain belt provides significant hydraulic head to drive meteoric water deep (5-10 km) into the crust (see /TOR 90/ for a conceptual overview). The flow of this water at depth is confined to a limited number of conductive fracture zones.

Below a depth of c. 1 km in southern Sweden and anywhere from 1 to 10 km further north, it is suggested there always exists highly saline water or brine (Ca-Na-Cl) that can be considered to have been near-stagnant for long periods of time (hundreds of thousands to several million years). This brine mainly developed by in-situ rock water interactions. Strong support for the long residence time of this water is found in the high concentrations of ^{4}He in the deep waters from the Gravberg-l and Laxemar boreholes. The concentrations in Gravberg-1 indicate the water has been stagnant on the order of 100s of millions of years /JUH 91/ and ^{35}Cl isotopic data from the deepest (>1000 m) Laxemar locations indicate residence times in excess of one million years /LOU 95/. This brine is encountered first at a depth of about 6 km in the Gravberg-1 borehole and at about 1 km at Laxemar.

The large scale stability of the rock mass at depth is governed by the existing stress field, the presence and characteristics of fractures or fracture zones and seismic activity. In the conceptual model the rock stresses increase with depth and it is further suggested that the absolute stress anisotropy will reduce at depths first greater than 5 - 10 km. The present stress field in Sweden, with a NW-SE trend of the maximum horizontal compression in southern and central Sweden, is mainly generated by gravitational and plate tectonic forces. The near-surface seismic activity is small /SUN 95b/. Typical magnitudes in Sweden of these events are less than 3 on the Richter scale.

In a simplified approach, the rock mass can be divided into homogeneous, large rock blocks surrounded by fracture zones. The rock blocks consist of the intact matrix and a fracture system. The fracture zones bound the rock blocks and constitute zones of weakness where properties such as strength and deformability differ significantly from that of the rock blocks. Consequently, these zones provide an efficient buffer to rock movement triggered, for example, by earthquake activity.

The general hydrogeological conditions in southern Sweden are influenced to only a minor degree by topography with the c. uppermost 1 km being more fractured and with higher permeability. Although the topography is minor, it still gives rise to pressure differences which cause groundwater flow. Large surface water reservoirs, such as Lake Vänen and Lake Vättern, may also have considerable influence on the lateral extent of the flow systems. In the conceptual model, the flow consists of meteoric water penetrating down to c. 1 km depth in the interior of the country (e.g. lowland areas of Fig. 3.3.1). Towards the coast the penetration is shallower and the groundwater composition is influenced by the present day brackish Baltic Sea and relict saline water of the Litorina Sea. Due to the decreased fracturing and low pressure gradients the meteoric water does not generally circulate to depths below c. 1 km in southern Sweden. However, there may be fracture zones which facilitate penetration of meteoric water to depths greater than 1 km. Topographic highs, such as the Southern Swedish Highlands, act as recharge areas on a regional scale and can be expected to significantly influence the groundwater flow directions at more shallow depths.

Further north and west in Sweden, the topography of the Caledonides greatly influences the meteoric water circulation pattern (Fig. 3.3.1). Even here surface reservoirs may have some influence on the groundwater circulation pattern. In the Gravberg-I borehole, relatively fresh water is found to depths of 5 - 6 km; below this depth the water becomes highly saline. Further towards the west, with greater topography and increased hydraulic heads, it is expected that meteoric water circulates even deeper than in the Siljan Ring area. Towards the coast the depth to the brine becomes shallower as the topographic driving force dissipates and the hydrogeological conditions become similar to those of southern Sweden.

The main difference between central/northern and southern Sweden is the depth of meteoric water circulation. Meteoric here implies water which has relatively recently been in contact with the atmosphere. The deep brines may originally have been meteoric water, but they have been stagnant so long that the meteoric signature has been lost. This meteoric circulation is much deeper in central/northern Sweden than in the south. Other parameters such as the thickness of the upper fractured layer, temperature gradient and rock stress are roughly similar in both areas.

3.3.8 The COSC project

The Swedish Scientific Drilling Program (SSDP) Collisional Orogeny in the Scandinavian Caledonides (COSC) project is a multidisciplinary investigation of the Scandian mountain belt /GEE 10/. Cenozoic uplift of the Scandes has exposed a lower- to middle-crustal level section through this Himalaya-type orogen, providing unique opportunities to better understand not only the Caledonides, but also on-going orogeny and the earthquake-prone environments of modern mountains belts. COSC will also contribute to our knowledge of mountain belt hydrology, provide the first information about deep thermal gradients for paleoclimate modeling and potential geothermal energy resources, contribute new information about the deep biosphere, and improve our understanding of the Cenozoic uplift history of the Scandes.

The COSC-1 borehole (Fig. 3.3.10 and Fig. 3.3.11) was drilled to 2496 m, with almost 100 % core recovery, during summer 2014 /LOR 15/. The top 1700 m consists mostly of sub-horizontal and shallowly dipping intermittent layers of gneiss and amphibolite, with lesser amounts of calc-silicates, metagabbro, marble and lenses of pegmatite. The first signs of increasing strain appear shortly below 1700 m in the form of narrow deformation bands and thin mylonites. Below c. 2100 m, mylonites dominate and garnets become common. A transition from gneiss into lower-grade metasedimentary rocks occurs between 2345 and 2360 m. The lower part of the drill core to TD is dominated by quartzites and metasandstones of unclear tectonostratigraphic position that are mylonitized to a varying degree. The base of the extensive high strain zone that begins at about 1700 m was not penetrated. Eight hydraulically conductive zones below 300 m were found, in an otherwise tight rock down to 2.5 km /LOR 15/. Pore waters appear to be relatively fresh throughout the borehole, suggesting deep circulation of meteoric waters. Bottom hole temperatures are close to 60 ºC after equilibration (about 20 ºC/km). The high seismic reflectivity in the uppermost c. 2 km is due to the large contrast in impedance between the gneiss and amphibolite. The hydrogeology, hydrochemistry and temperature gradient are what can be expected for a borehole in this location and are consistent with the conceptual model outlined in the previous section.

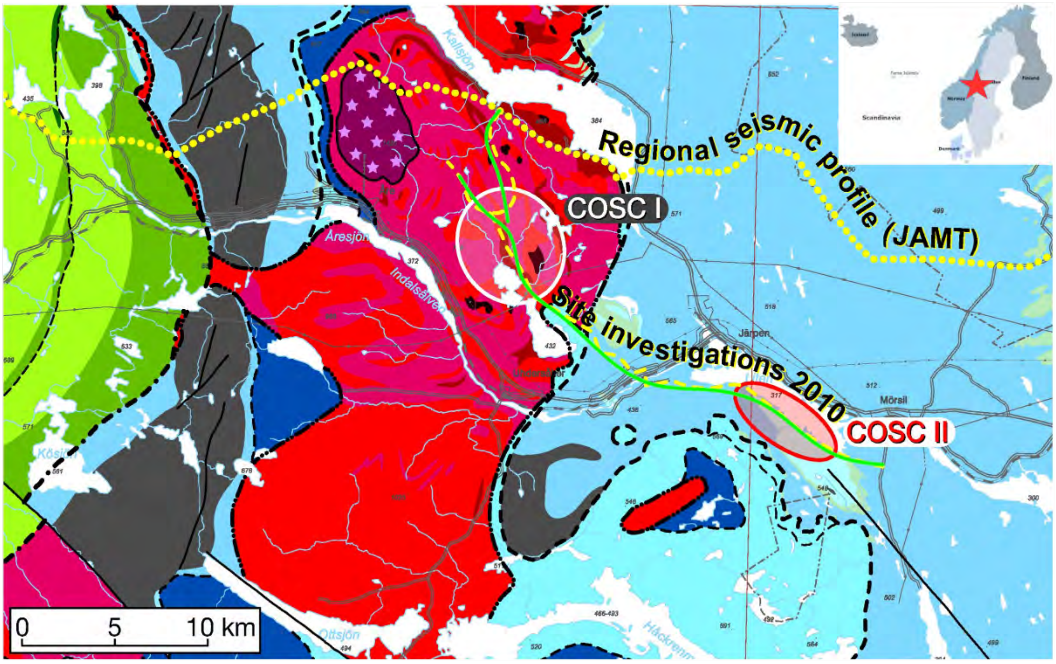

Fig. 3.3.10 Location of the COSC-1 borehole in the Scandinavian Caledonides and the seismic data shown in Fig. 3.3.11. Red star in inset shows the location of the map. (Figure based on /HED 12/)

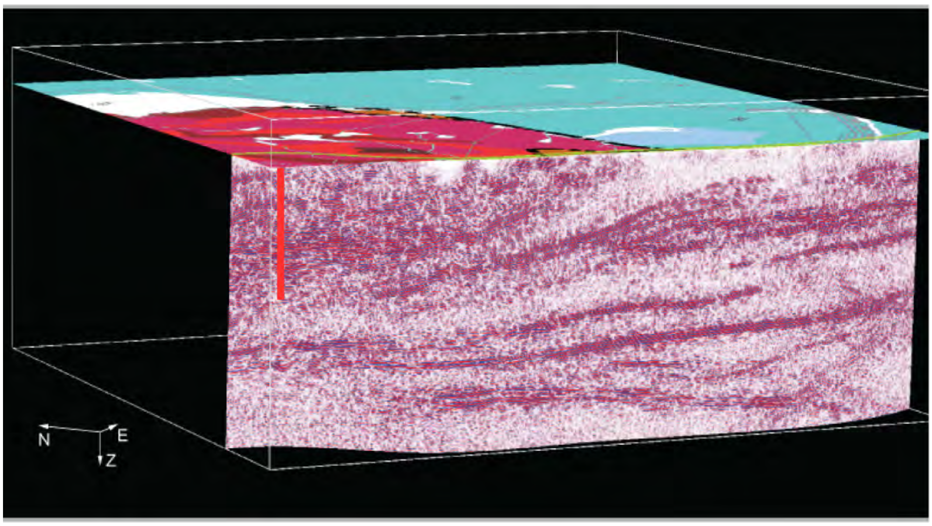

Fig. 3.3.11 Location of the COSC-1 borehole (red line) on the seismic section. The seismic section corresponds to the site investigation line 2010 in Fig. 3.3.10. The red unit on the geological map is the Seve Nappe and it is highly reflective.

3.3.9 Conclusions

Prediction of lithology at depth based on surface geological information is difficult in volcano-sedimentary rocks due to the heterogeneous nature of these rocks. In granitic environments it is easier to predict the lithology in the upper 5 km. Fracture mineralogy is indicative of how an observed fracture evolved and the paleo-fluid history. If the minerals are in equilibrium with the surrounding rock then the fracture probably developed under ductile conditions, otherwise it developed under brittle conditions. Brittle fractures are probably the ones which are most likely to be highly permeable. Prominent large scale sub-horizontal fracture zones, which may be highly difficult to predict from surface geological data, are identified at several localities in the Baltic Shield. These conductive zones have to be considered in studies of the fluid flow patterns.

Lower seismic and sonic velocities in the upper km can be attributed to open water filled fractures. Analyses of borehole geophysical data confirm higher levels of open fractures in the upper km not only in the Baltic Shield, but also in other crystalline rock areas. Measurement and extrapolation of borehole data give a temperature gradient in the Baltic Shield in of about 15 °C/km. This temperature gradient is also predicted in the uppermost crust from lithospheric modeling of heat flow in the Baltic Shield. The observed temperature gradient of about 20 °C/km in the COSC-1 borehole is somewhat higher, but still within expected values.

Although data are sparse, permeability data also indicate less open fracturing below 1 km. In the available data, the permeability is about 3 orders of magnitude lower at 5000 m than at 1000 m. In general, the pore pressure seems to be close to hydrostatic. Pore waters are relatively fresh down to at least 500 m throughout Sweden, but become more saline below this depth. At great depth, brines are present. The depth to these brines appears to be dependent upon geographical location and hydrostructural controls. High gas content may be observed in brines in Sweden and Canada.

The stress appears to increase linearly with depth down to 5 km, although quantitative measurements below 1 km are lacking. The vertical stress is generally the intermediate stress implying the tectonic regime is strike-slip faulting.

Based on the above observations a model for the upper 5 km of crust for the Baltic Shield ws developed based on the /JUH 98/. The upper 1 km of the crust consists of more fractured rock, or at least rock with more open fractures, compared to that below. In areas of low topography, this upper fractured interval limits the depth of meteoric water circulation and highly saline waters may be expected below 1 km. Closer to mountainous areas the topography greatly influences meteoric water circulation patterns with these waters penetrating down to depths on the order of 10 km. The temperature field variations within the shield are small enough that they are not expected to have significant effect on the water circulation patterns. Earthquake activity is low in the shield area, in general, with higher concentrations along the west coast of Norway, the north-eastern coast of Sweden and southwestem Sweden. The largest earthquakes occur deep in the crust due to increasing differential stress with depth. Earthquakes may be concentrated towards large zones of weakness where water circulation may be expected to be enhanced.

For the relevance of the Very Deep Hole concept for the storage of spent nuclear fuel the following conclusions may be drawn:

- The concept is more suitable in areas of relatively flat topography
- Stagnant saline waters may be expected at depths of 1 km or more in shield areas of low topography
- Permeability generally decreases clearly with depth, but water bearing zones are still present down to great depth

Drilling and investigations in the COSC-1 borehole support these conclusions.

3.3.10 Acknowledgments

I would like to thank my co-authors for SKB reports /JUH 98/ and /JUH 89/, as well as my co-authors of the Vattenfall report summarizing the results from the Gravberg-1 borehole.

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3.4 Schilling F.: Multiple Barrier System for Deep Borehole Repositories for Nuclear Waste

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3.4.1 Deutsche Zusammenfassung

Für die sichere langfristige Lagerung von radioaktivem Abfall werden international unterschiedliche Optionen diskutiert. Eine langzeitsichere Lagerung erfordert

- den sicheren Schutz von Menschen vor einer Schädigung die vom radioaktiven Abfall oder der Lagerhaltung ausgeht (Bevölkerung und der bei der Endlagerung Beschäftigten).
- den langfristigen Schutz von Schutzgütern (u. A. Trinkwasser und Biosphäre).

Kontrovers wird diskutiert, inwiefern eine Rückholbarkeit sinnvoll ist. Dasselbe gilt für die Art (Beschaffenheit) und Anzahl von geforderten technischen und natürlichen (z.B. geologischen) Barrieren.

Eine Lagerung an der Oberfläche bietet den Vorteil aber auch den Nachteil eines raschen Zugriffs auf das Material durch heutige oder spätere Generationen. Dadurch könnte das Material ggfs. durch neue Technologien besser genutzt oder sicherer verwahrt werden. Eine Lagerung an der Oberfläche birgt jedoch die Gefahr einer Verseuchung der Biosphäre im Falle einer Havarie, eines Angriffs oder eines Unfalls und erfordert eine aktive – über Jahrhunderte zu garantierende – Überwachung.

Daher wird international eine Lagerung in Bergwerken, in verschiedenen geologischen Formationen, in Betracht gezogen. Stark vereinfacht können folgende Eigenschaften den verschiedenen Lithologien zugeordnet werden. Die Standfestigkeit des Untertagebauwerks wird im *Kristallin* als großer Vorteil gesehen, insbesondere auch bei Fragen der Rückholbarkeit. Bei den untersuchten Standorten wurden jedoch unerwünschte Wasserzutritte über die Klüftigkeit des Gesteins beobachtet. *Salz* dagegen besitzt aufgrund seiner rheologischen Eigenschaften eine stark selbstabdichtende Wirkung. Diese rheologischen Eigenschaften (bei geringen Deformationsraten verhält sich Salz duktil) führen in Salzstöcke jedoch auch zu einer inneren Mobilität und zu einer raschen Konvergenz tieferer Untertagebauwerke. Als Vorteile vieler *Tongesteine* wird ihre Quellfähigkeit bei Zutritt von Wasser und ihr Immobilisierungsverhalten gegenüber Radionukliden zumindest bei tieferen Temperaturen. Die eigene Stabilität der Bauwerke ist jedoch vergleichsweise gering und limitiert die Tiefenlage einer auf Ton bzw. weichen Tongesteinen basierten Lagerung.

In diesem Beitrag wird im Zusammenhang mit der Lagerung in tiefen Bohrlöchern (Deep Borehole Disposal) eine synergetische Kopplung der positiven Eigenschaften der unterschiedlich wirkenden Barrieregesteine vorgeschlagen. Diese bietet den Vorteil, die Stabilität des Kristallins, das Nuklidrückhaltevermögen des Tons und die Duktilität des Salzes bei zusätzlicher Nutzung einer physikalischen Barriere zu kombinieren. Die unterschiedlichen hydraulischen und geomechanischen Eigenschaften der Gesteine werden zusätzlich durch entsprechende technische Maßnahmen – z.B. Verschluss des Lagers – ergänzt. In erster Näherung kann eine Endlagerung in tiefen Bohrlöchern als eine bergmännische Lagerung betrachtet werden, bei der der umgebende Gebirgsbereich (Salz, Ton, Kristallin) mit einer Flüssigkeit gefüllt ist und eine vergleichsweise große Distanz zwischen Lagerort und Schutzgut ermöglicht wird – z.B. in 4 000 m tiefen Bohrlöcher.

Die Lagerung in tiefen Bohrlöchern wird konkreter z.B. in Brasilien, Großbritannien und USA als effektive Alternative zur Lagerung in Bergwerken diskutiert. Von Mitarbeitern der Internationalen Atomenergiebehörde werden für die Lagerung in tiefen Bohrlöchern folgende Vorteile genannt.

- Es könnten dezentrale Endlager eingerichtet werden (Nähe zu Zwischenlagern – geringe Transportwege (Risiken))
- Mit vergleichsweise geringem technischem, überwachungs- und genehmigungstechnischem Aufwand könnten so Abfälle angemessen sicher von den Schutzgütern getrennt werden – eine Anforderung die z.B. für Entwicklungs- und Schwellenländer gestellt wird.
- Z.Z werden international Pilotprojekte für Spezialabfälle, wie diese z.B. in der Nuklearmedizin anfallen, diskutiert.

Für eine CO_2-Speicherung und Fracking-Vorhaben werden zur Risikominimierung in der aktuellen Gesetzgebung Multibarrierenkonzepte vorgeschrieben. Vor diesem Hintergrund wird an einem konzeptionellen Endlager die Chance einer Verwahrung in tiefen Bohrlöchern vorgestellt.

Durch die Wirkung multipler Barrieren bei gleichzeitig größerer Entfernung des radioaktiven Materials von den Schutzgütern kann ein maßgeblicher Sicherheitsgewinn in der Endlagerung erzielt werden. Auch bei einem frühzeitigen Verlust der technischen Barrierewirkung oder bei unerwarteten Havarien (z.B. durch ein starkes Erdbeben der $M_W > 6$) würde evtl. ein Bohrloch verloren jedoch nicht eine komplexe Infrastruktur. Durch die große Entfernung zu den Schutzgütern, und das auf verschiedenen physikalischen und mechanischen Eigenschaften beruhenden Multibarrierenkonzepts, werden die Schutzgüter nicht hochgradig gefährdet.

Bereits heute kann mit vertretbarem Aufwand in große Tiefen gebohrt werden und Messungen durchgeführt werden. Für eine effiziente Einlagerung müsste die Technologie im Hinblick auf die Bohrlochdurchmesser weiterentwickelt werden. Durch die vorhandene Expertise durch z.B. die Kontinentalen Tiefbohrung KTB in Deutschland (und das daraus hervorgegangene Internationale Tiefbohrprogramm ICDP – mit Sitz am Deutschen Geoforschungszentrum in Potsdam) bestehen in Deutschland besonders gute Voraussetzungen für eine Weiterentwicklung der Bohrtechnologie mit standardmäßig größeren Durchmessern.

3.4.2 Introduction

Poisoning and radiating waste need to be effectively separated from protected goods such as drinking water horizons or biosphere. Generally, the risk is decaying with increasing distance between waste and goods if appropriate and effective barriers are foreseen. This contribution will not focus on legal issues in different countries and possible risk assessment methodologies. Hence, the discussion here will be based on a more general safety strategy, which follows common approaches for standard technological applications. If we accept nuclear waste repositories to be more critical for our protected goods than many other technical facilities, at least the widely established rules for technical installations should be followed.

First rule of thumb: As higher a risk is regarded and as longer safety needs to be guaranteed, the more independent acting measures/barriers need to be functional. Independent acting measures require different and independent (physical) mechanisms and processes for self-sustaining security.

To clarify the idea of different mechanisms and processes as a technical example a high pressure apparatus for intermediate toxic chemicals is used. This could apply the following safety-approach, based on a specific risk assessment:

Multi-barrier system

- High-Pressure-Vessel itself, built of a ductile material and constructed to withstand the chemicals and the pressure. The layout will include at least 200 % of strength for security reasons. In other words, a 10 MPa vessel will be capable to still work properly at 20 MPa
- An enclosed basin will be emplaced to avoid the flow of chemicals outside a restricted predefined area. The basin will be designed in a way, that even in the case of a total loss of the first barrier (vessel), all chemicals are still in a secure and defined location.
- The surrounding will be paved with a spill over channel and e.g. oil separator. This will guarantee that even if the second barrier is defect, the protected good remains in safe conditions.

Predefined pathways for fluid-flow allow a surveillance even in case of failure of one or several barriers. Besides these passive barriers additional safety measures are used, based on different mechanisms and processes. For a long-term repository one should avoid active control[1], hence it is not discussed here.

- In all modern High-Pressure-Vessels, at least one security pressure release is mounted. If two are installed, usually different mechanical properties are used which react independently based on different physical properties.
    - E.g. a security valve based on a preloaded spring and a valve (applicable property: Young's modulus of the spring)
    - and a burst disc (property applied: fracture toughness of a e.g. steel plate)
    - In addition: valve(s) which can be operated manually.
- Pressure readings are usually based on different types of gauges: e.g. electronic and mechanical (optical) – Monitoring.

This presentation follows a similar approach for nuclear waste repositories:

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[1] Active control of pressure and or temperature. Usually an electronic controller is used to stay in the desired pressure and temperature range. This is often included into the control unit and is a procedure if a predefined value (often called alarm value) is reached. An automated shut off and valve opening is one of possible reactions. In cases of a power loss, all pressure valve will go into a safe position, meaning that usually a defined pathway for the fluids is opened to systematically reduce the pressure and to reach a secure operation mode. If the temperature reaches too high values, heating elements often are equipped with a fuse, which may melt at a predefined temperature (e.g. by melting).

- Rough first order risk assessment – which hazards need to be taken into account, if we want to securely handle nuclear waste – time span – e.g. low risk even for 1 Million years.
- Safety measures based on different physical properties to guarantee independency

Besides a standard risk assessment for geotechnical applications, for a one million year time span further events – such as several glaciation – need to be taken into account. As such a long time span is assumed here, higher earthquake magnitudes are expected: In many places in Germany $M_W > 6.5$ are possible (average frequency of 1/Million year). With a probability of 10 % even higher magnitudes with much higher energy release could occur. Glaciation will act as additional perturbation in the natural stress field and therefore modifying the probability of seismic events (higher risk) and will furthermore modify the uppermost geological coverage and barrier systems.

Apart from earthquakes, geological processes at depth can be regarded as rather slow. Geology has demonstrated that reservoirs of water, oil, or gas have remained stable over millions of years and merely changed their characteristic properties – at least not those that are essential for their function as reservoir rocks or cap-rocks. The oil and gas in the reservoirs are a proof that natural barriers (cap rocks) are effective hindering the transport of materials towards the protected goods, not only for heavy metals (diffusion processes) but also for low density materials (which have a strong tendency to migrate upwards) such as gas and oil. Going deep for nuclear waste disposal takes advantage of the general increase of safety due to distance to the protected goods. Furthermore, increasing depth enables to use an increasing number of different types of barriers. Each barrier has two functions:

1. to shield the waste against negative influence that could mobilize radionuclides and
2. the retention of the nuclides in the repository as long as the waste can cause harm to the protected goods.

During the time of high radioactive decay, technical and natural barriers are especially relevant for the safety of the biosphere. In this paper, a scientist’s view on waste disposal concept is presented, with a focus on deep borehole disposal.

3.4.3 A View on Storage Concepts

German Nuclear Power Plants will produce till 2020, then a total disposal for about 29 000 m³ high-level waste is required /RÖH 12/. This waste can be stored according to several disposal concepts: Surface Storage, mined repositories or deep borehole disposal.

3.4.3.1 Interim Storage at Surface:

In Germany 13 sites of interim storage at the surface (Tab. 3.4.1), mostly close to nuclear power plant sites, store up to 1 850 tons of spent fuel, in total about 50 MW of heat producing nuclear waste. Thus, more than 2 500 casks have to be stored at costs of 25 000[2] € per cask, summing up to 62.5 Million € annual costs.

Tab. 3.4.1 Interim storage of spent nuclear fuel in Germany /GAS 13/

Location	Mass in Tons (Mg)	Number of casks approved	Number of casks Taken by End 2013
Ahaus	3969	420	56
Biblis	1.400	135	51
Brokdorf	1.000	100	16
Brunsbüttel	450	80	9
Grafenrheinfeld	800	88	21
Grohnde	1.000	100	18
Grundrenningen	1.850	192	41
Isar	1.500	152	25
Krümmel	775	80	19
Lingen	1.250	125	32
Neckarwestheim	1.600	151	41
Philipsburg	1.600	152	36
Unterweser	800	80	8
total	22370	2513	711

[2] Für die Zwischenlagerung wird mit Kosten von ca. 25 000 Euro pro Jahr und MTR 3-Behälter gerechnet. Antwort der Bundesregierung auf Kleine Anfrage vom 8.12.2014, Drucksache 18/3516. (For interim storage ca. 25 000 € are required annually per MTR 3 cask. Answer of the German Gouvernement, document number 18/3516).

The surface storage sites are prone to a number of hazards such as violence, airplane crash or cask corrosion, etc.. In each case the small distances to protected goods, e.g. the drinking water horizons (few 10's of meters vertically along gravity) or to urban areas (few 100's of m laterally without any natural barrier), may be one of the most critical issues. Gas formation may endanger the nearby populated areas, whereas nuclides in solution tend, due to gravitational forces, to move downwards towards the drinking water horizons and to spread laterally with water movement. Thus, at the surface the technical barriers of the repository have to be supervised actively for the total duration of the storage. However, besides the risks discussed above, political and societal changes during history cannot be foreseen and need to be treated as an intrinsic hazard with respect to surface storage.

3.4.3.2 Geological Mine Storage Concepts

Mined repositories can take advantage from the barrier effect of the overlying rocks and a distance of several 100's of meters from waste to the surface. Mining is a traditional technique with a long history from prehistoric to present. A lot of expertise in mining technology from mining coals, salt or ore in crystalline rock has been gained. Underground mines are built with heavy machinery and are rather easy to access but require a number of technologies to guarantee a safe operation, especially in terms of geomechanical stability, which is a limiting parameter especially for mines in salt and clay. E.g. underground openings in salt tend to converge, which may even lead to subsidence at the surface. The subsidence can be monitored geodetically as shown for numerous salt caverns or mines /GE 04/. The convergence in salt can be used as a positive material property, as at certain depths it effectively encloses rather tightly the deposited waste. However, the retrieval may (depending on depth, temperature, internal heating) become more complex. In other mine types collapses are a hazard, mainly during mine construction but also during operation. Gases in mines require appropriate ventilation; otherwise, they pose a significant danger for the people working there and might even cause explosions leading to a mine disaster. However, modern practices have improved the safety in mines. Mines are already used today as proven repositories for hazardous waste. One of the major long-term risks are the manmade shafts and tunnels. The safe abandonment (closing) of the accesses is therefore of major importance.

Tab. 3.4.2 Examples for the geology and depths of mined repositories in different countries

Country	Facility Name	Waste	Geology	Depth [m]
Finland	Onkalo	spent fuel	granite	~400
France	Bure	high-level waste	mudstone	~500
Germany	Gorleben	High-level waste	salt dome	~800
Germany	Schacht Konrad	303,000 m^3 Low and Intermediate Level Waste	sedimentary rock	~800
Sweden	Forsmark	Spent Fuel	granite	~450
USA	Waste Isolation Pilot Plant	Transuranic Waste	salt bed	~655
USA	Yucca Mountain Project	70,000 tons High-Level Waste	ignimbrite	~300

The decision for the host rock in the mined nuclear waste repository is based on the availability of the rock in the country and their location with respect to goods. Different rock types (lithologies) require different retardation and barrier concepts to securely isolate the waste (Tab. 3.4.2). In mined repositories the casks are usually planned to be deposited in horizontal or vertical shafts and a special material will be filled in the space between the nuclear waste casks and the mine or shaft walls (e.g. bentonite clay). The characteristics of the potential host rocks for mined repositories are currently investigated in various underground rock laboratories and documented in numerous reports such as the BGR report “Endlagerformationen in Deutschland of 2007” (Table 3). Here, we briefly summarize the relevant properties of three host rocks, which are internationally considered for nuclear waste repositories.

Salt poses advantages due to its high thermal conductivity, extremely low permeability, isotropic stress conditions and viscoplastic characteristics that lead to closure of underground openings such as fissure or fractures. Therefore, salt is a very good barrier material as it hinders solids, gases[3] and fluids to migrate towards protected goods. Nevertheless, especially in diapiric salt formations, internal movements have been reported and large scale fractures may – for a short period of time – open pathways towards the surface.

Shales/Mudstones can vary considerably in their properties, but are appreciated mainly because of their swelling capability and sorption characteristics at lower temperature. Especially the swelling behaviour leads to a self sealing capability and hence to a low permeability.

[3] As long as no volume changes occur. If e.g. the waste or other reactions produce gas, an overpressure might occur.

Most oil and gas reservoirs have low permeable shale as cap rock and have proofed their long term barrier function. As the mechanical properties are temperature depending (irreversible reactions, dehydration, embrittlement), the temperature should not exceed 100 °C within the formation which acts as barrier. This temperature limitation might require a longer interim storage of high-level waste. In shales and mudstones – similarly to salt mines – the maximum depth of the repository will be given by closure of the man-made voids within the structures and the required time of an open mine.

Mines in **crystalline rocks** are considered for their high stability and temperature resilience. The higher permeability e.g. in granitic rocks requires long-term secure technical barriers (e.g. in the hard rock laboratory in Äspö (Sweden) the use of copper canisters is tested) in combination with low permeability infill between canister and mine wall. As in fractured rock – such as granitic or metamorphic rocks –the filling of the fractures (e.g. by clay) and the regional and local stress field are of great importance for the overall permeability.

Tab. 3.4.3 Relevant properties of host rocks and boundary conditions for nuclear waste disposal based and slightly modified after the BGR report "Endlagerformationen in Deutschland" of 2007. Traffic light lours denote a trend between unfavourable to favourable properties. The table is a very simplified summary and does not represent a detailed presentation

Property	**Geo Barrier Halite (Salt)**	**Geo Barrier Clay**	**Geo Barrier Crystalline Rock**
Permeability	Low	Low	Usually high due to fractures. In a first approximation, the fracture permeability decreases with depth
Stability	Medium	Low to medium	High
Deformation type	Ductile (long-term) Brittle (fast-deforming) Visco elastic behaviour	Visco-elastic behaviour	Brittle, frequently fractured
Stability of underground openings	Convergence rate depends on depth (stress)	Requires completion in deep mines	High in unfractured rock Low in fractured rock
In-Situ Stress	Isotropic	Anisotropic	Anisotropic
Solubility	High	Very low	Very low

Property	Geo Barrier Halite (Salt)	Geo Barrier Clay	Geo Barrier Crystalline Rock
Sorption of Radio-nuclides	Very low	Relatively high (at lower T)	Medium to high
Thermal Conduc-tivity	High	Low	Medium
Thermal resilience	High	Low	High
Maximum disposal depth	900 m	500 m	500 - 1200 m
Max. temperature for disposal	200°C	100°C	100°C
Interim Storage re-quired	>15 years	>30 - 40 years	>30 - 40 years

3.4.3.3 Geological Multiple barrier Concept for other geotechnical applications

The intention of a multi-barrier concept is to enhance the safety of disposal sites, even for those events, which are not overseen completely today. This would require independently acting barriers, which are based on different properties (see above).

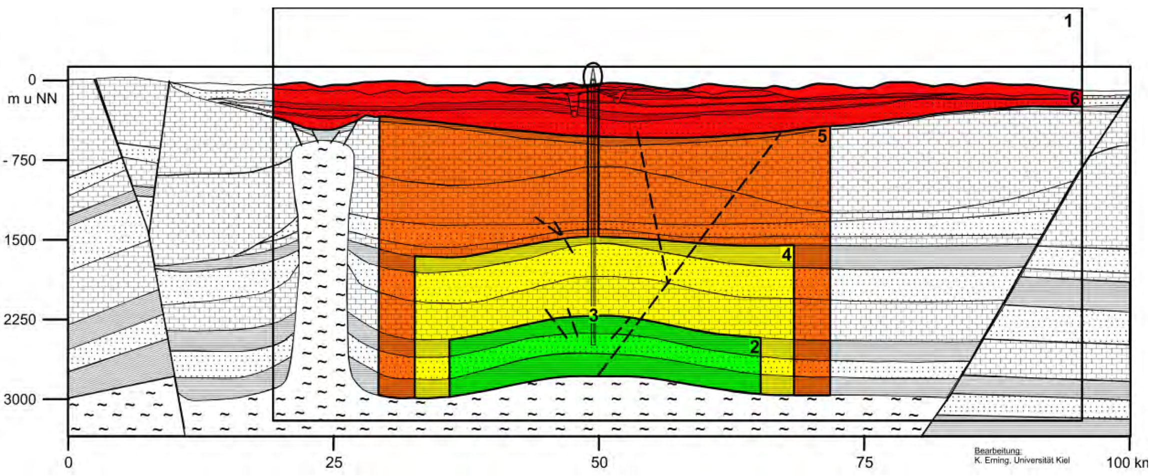


Fig. 3.4.1 Concept behind multi barrier systems (simplified /GRO 11/). Green: effective containment (storage) zone, yellow: (secondary) retaining formation (cap rocks), orange: transfer-zone consisting of layered permeable and low permeable rocks, red: protected good. Here, an example for a CO_2 storage site is drawn, whereas the CO_2 is deposited within a sandstone.

Multi-barrier approaches are a prerequisite in geological CO_2-storage (e.g. European Legislation on CCS) and implicit for fracking operations (actual “Fracking law”). CO_2 storage is foreseen either in given up oil and gas reservoirs or in porous aquifers at depths greater than 1200 m. If we follow the argumentation of an effective containment zone, all waste has to remain within the defined area of the rock (green colour in Fig. 3.4.1). In CO_2 storage one takes into account that over a long time-span (e.g. one Mio. years) geological effects may lead to a (partly) destruction of the containment zone.

Therefore, a second barrier system is taken into consideration, which may consist of a higher permeable layer and a second low permeable cap rock (yellow colour in Fig. 3.4.1). As long as contaminated material has not penetrated the second barrier, no risks exist for the protected goods. This is not the operation, which is anticipated – but the protected goods are still well protected.

A portion of the material may have migrated into the second barrier system (Fig. 3.4.1, yellow section – retaining formation) – in our analogue, a safety valve has released a small fraction of the fluid from the pressure vessel into a tank (predefined fluid-path). For the radioactive waste this would mean, that nearly all the material remains in the effective containment zone, the small portion (e.g. gases), which left the area, are still under non-critical conditions. No further action would be required, but one might more intensely monitor the retaining formation.

Further barriers (orange area in Fig. 3.4.1: transfer-zone) would act as an additional effective risk mitigation by absorbing and retarding ascending waste (interlayered low and higher permeable rocks). Even if some material would have left the retaining formation – this additional barrier system of more than 1 000 m would effectively hinder the pollution of drinking water and contamination of the upper biosphere. In our analogue, a paved floor with spill over channel.

3.4.3.4 Conceptual Multi-Barrier Deep Borehole Disposal (DBD)

The conceptual multi-barrier Deep Borehole Disposal (DBD) consists of multiple geological barriers with different petrophysical properties, in combination with technical barriers and an additional independent physical barrier. The barriers act horizontally but most important vertically towards the protected goods. The presented conceptual model does not concentrate on one rock type such as in many mined repositories (Fig. 3.4.2, Tab. 3.4.3). The focus of the DBD multi-barrier concept is to shield the protected good from nuclear waste, e.g. to protect against radionuclides within upward moving gases or upward migration of radionuclides into groundwater (driven by *e.g.* the heat developed during radioactive decay or diffusion processes). Direct radiation damage of protected goods from nuclear waste is seen rather unlikely in DBD due to the great distance between waste and protected good.

All geological barriers of the DBD need to fulfil the requirements of a secure containment alone. If we would find a location where different barriers with various retarding and containment properties can be combined in an ideal way, a much lower risk – even for not foreseen hazardous events – would result.

The general procedure to implement DBD requires, similar to the mined repositories, a detailed investigation of potential locations by geological, geochemical, hydrological and geophysical methods (exploration). At an appropriate location, several wide-diameter boreholes will be drilled to ca. 5 000 m depth from a well pad. The designated disposal depths could range from 3 000 to 5 000 m (Fig. 3.4.2). This enables to store approximately 100 canisters per well. The diameters of the wells could be in the range of 100 cm, however during the learning curve, the diameters should be increased stepwise from 35 cm (standard technology)[4] to the anticipated diameter. Further technical seals require proper borehole completion with enhanced heat resistant cementation and appropriate sealing infill to avoid circulation. This will efficiently eliminate the upward migration of e.g. heavy metals and radon.

[4] Even though bigger diameters have been successfully drilled (see *Röckel in this volume*; /BES 08/; /ALL 76/; /ALL 76/) in the past, a stepwise increase of standard diameters towards the planned diameter over a timespan of ca. 10 years seems to be a cost efficient and secure path to reach the goal.

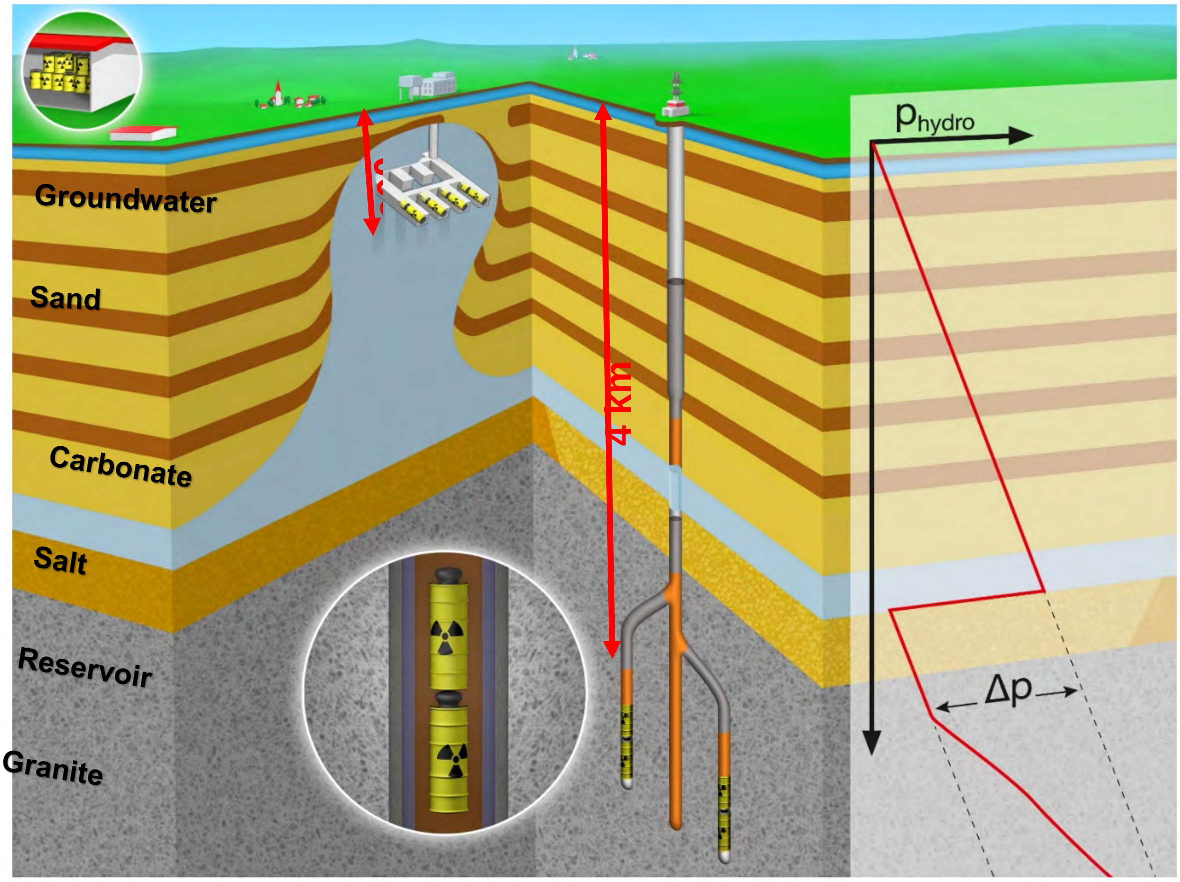


Fig. 3.4.2 Concept of a multi-barrier deep borehole disposal in comparison to interim storage at the surface (left) and mined repositories (centre)

Here we do not focus on the surface handling and canister technologies nor on the drilling and completion process (please refer e.g. to contributions by Röckel, Reich, Prevedel within this volume) but on the general barrier concept. All technical barriers are seen for short term only, namely during emplacement of the canisters and for the first years of surveillance (monitoring). The long-term consideration is based on natural barriers and naturally self-sealing of the borehole. Additionally, an appropriate abandonment of the wells is foreseen.

3.4.4 Functionality of Geological Barriers

The multi barrier concept requires drilling through alternating layers of porous rocks (e.g. sandstone) and impermeable rocks (e.g. clay, shales, evaporites) and at least one thick layer of salt to combine the advantages (see above and table 2) of the different petrophysical properties. In the following we present the conceptual model in the sequence of barriers which would have to be passed by nuclear waste on its passage towards the surface:

11. The lowermost part, the repository of the waste, will be in a crystalline rock. In a first approximation metamorphic, low quartz containing rocks may be favoured – but they can be hardly identified during exploration. Hence, not ideal crystalline rocks with a higher fracture porosity are assumed for the risk assessment. Due to the great depth, and as the formation is beneath a massive salt formation, the fluids in permeable fractures can be treated as highly saline[5]. However, due to the great pressure at depth the fracture porosity and permeability will be rather low (but will be much higher than in salt!). The crystalline rocks are not treated as impermeable. However, in a highly saline brine under low permeability conditions, no advection will form – even if the casks act as heat sources (FEBEX-Experiment «Full-Scale Engineered Barriers Experiment» /HUE 00/. The required combination of a high saline brine in fractures and a crystalline host rock act together as an effective containment zone.

12. Above the crystalline rock, a sedimentary formation with higher porosities in comparison to the crystalline rock should follow. The ideal rock would be a porous rock, which is often found in many locations beneath "Zechstein salt" layers e.g. in the North German Basin. The fluid in the pores should have a lower pressure than the expected hydrostatic pressure (details see below).

13. A thick salt layer act as high performance seal above the reservoir. Here, the low permeability and self-sealing capabilities of salt form an independent barrier system and act, together with the underlying porous rock, as an independent retaining formation.

14. Above the "Zechstein-salt" various layers of nearly impermeable shale, sandstone, carbonates, and evaporates (e.g. anhydrite) follow. As closer we approach to the surface, as lower the temperature will be. The clay-content at shallower depth could therefore fulfil the task of a radionuclide retardation layer. As at least one prominent shale layer will act as barrier, in addition to the salt layer, an additional natural, low permeable, ductile (self-sealing) material will be in place securing the site. The mechanisms and time-constant of the viscoelastic materials shale and salt vary significantly. From a systematic risk-reduction strategy, a much higher confidence is obtained – especially for not foreseen events – as different barriers with different processes are emplaced.

The presented multi-barrier concept would furthermore allow for a combination of abandonment technologies to improve the sealing through the man made distortion (well). A combi-

[5] A main difference between a repository in a mine (through a shaft) and in a deep well is, that in mines one would try to have dry conditions, as in deep wells fluids are present and used in the deposition process..

nation of self-sealing (salt), cemented paths (e.g. in sandstones), heavy drill mud on a bentonite basis e.g. in shales significantly reduces the pathways for fluid migration and/or diffusion and hence, reduces the risk. Over a length of several kilometres, a multi-barrier seal would be emplaced, whereas the different layers act on the basis of different physical and chemical mechanisms and processes. In other words, the risk of an abandoned opening (independent if it is a shaft, a tunnel or a well) is reduced by increasing the length of the abandoned path and the decrease in diameter which needs to be sealed.

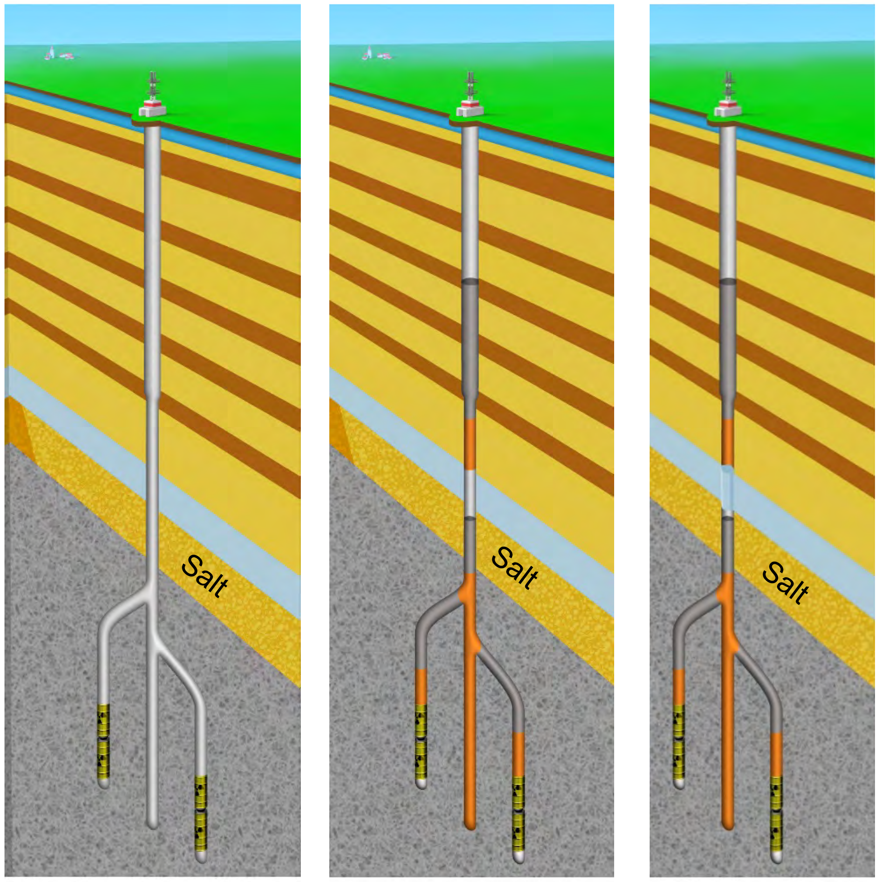
For DBD the man-made distortion (which seems to be one of the biggest risks in repositories) is minimized, as the length of the abandonment is maximized and the diameter is minimized. A combination of different abandonment strategies can help to abandon with a very high quality and thus high security.

3.4.4.1 Open-hole salt wellbore sealing

The use of drilling through a thick layer of layered salt enables a further option to borehole sealing. From numerous cases in salt basins around the world, such as in the Gulf of Mexico, Angola, Brazil the mobility of salt caused closure of open wellbores. It could be shown that for thick salt intervals, the rate of creep increases with depth. This is one reason why salt mining by “dry” mines is limited in depth. After having completed the wells and emplaced the nuclear waste, the space between waste and borehole casing will be filled by bentonite at depths between 3000 to 5000 m, with a cemented plug on top or by a combination of bentonite, heavy drill mud, salt and cement. Within the salt layer itself, the casing of the wells should be milled away across a depths interval of at least 50 m to guarantee the development of a long natural barrier by self-sealing (Fig. 3.4.3).

At the borehole wall, the lithologic state of stress within the salt is modified. E.g. in a vertical well, the circumferential stress at the borehole wall doubles the vertical stress and may significantly exceed the radial stress which is given by the drilling mud pressure. Salt cannot sustain such deviatoric conditions if the mud pressure is lower than the lithostatic stress. Already deviatoric stresses in the order of 10 - 20 MPa cause a fast creep of salt /LIT 08/ which results in borehole deformation and leads to a closure of the borehole at greater depth. This well-known phenomenon is well documented due to field measurement when borehole closure occurred /KIM 13/.

The type of salt, the stress state and the temperature mainly influences this creep behaviour. According to /POI 06/ chloride and sulfate salts are the most mobile, followed by halite which is rather slowly moving and anhydrite which is more or less immobile. Therefore, the rates of borehole closure range from days and weeks to months and years, depending on the pressure of the mud in the wellbore and the temperature /WEI 14/. Localized heating, reduction of bentonite in the drilling mud and mud pressure reduction will accelerate the process of salt mobilization. A thick salt layer is therefore seen as a nearly perfect seal for DBD wells.



a) b) c)

Fig. 3.4.3 a) emplacement of the nuclear waste in wellbores, which have been cased and cemented, the drill-holes will be filled back with

b) bentonite material and cement bridges to seal the protected goods against potential influence of leaking nuclear waste material.

c) Within the salt layer, an interval of the wellbore will be reamed to remove the casing in that interval. The high lithostatic pressure and enhanced temperatures will lead to a self sealing of the bore-hole within days to months due to the ductile behaviour of the salt. This will form a natural, nearly impermeable layer, which self-sustains low permeability, even if fractures (e.g. due to earthquakes) occur. Above that interval the classical abandonment with bentonite and cement bridges will be continued.

3.4.4.2 Hydrostatically Under-Pressurized Reservoir Barrier

In addition to the technical and geological multi-barriers, a physical barrier for gases and low density fluids is suggested. When the technical barrier is damaged or rotten, radionuclide-laden gases can escape through the bentonite or if casing failure would occur along the boundaries between casing and cementation, through the casing or along the boundary between host rock and casing cementation. All these leakage paths would create vertical flow mainly along the wellbore. Horizontal flow through fractures in the rock is less likely but has to be considered too. For these leakage pathways, a physical barrier would help to independently shield the radioactive waste at depth and to better control the flow direction.

The suggested physical barrier is a depleted gas reservoir or a naturally underpressured reservoir underneath the salt layer (under hydrostatic pressure conditions), but above the waste disposal zone. An underpressured reservoir or reservoir compartment is characterized by a pore pressure which is below the normal hydrostatic pressure for that depth interval. Underpressured reservoirs are isolated from their surrounding by low permeability rocks (dynamic seals, /JOL 10/) and thus sealing formations such as shales or evaporites. The existence of gas reservoirs or naturally underpressured reservoirs is the best proof for a functional cap rock, which inhibits pressure equilibration with the normally pressured hydrostatic environment and thus is an effective seal between differently pressurized layers or compartments for millions of years.

Underpressured reservoirs are attractive for carbon dioxide storage or wastewater injection and according to /JIA 97/ are considered as safer repositories for toxic liquid wastes than normally pressured or overpressured reservoirs /PUC 03/. Such an underpressured section would act as a sink for any radionuclide-laden gas or fluid rising from the higher pressured zones at greater depth and it would be difficult for gases or fluids to escape. Even if a leakage would occur in the cap rock or surrounding seals, the fugitive radionuclides have no tendency to escape against the pressure gradient into shallower sections (Fig. 3.4.1). To the contrary, if any seal breach would occur, it would lead to an inflow of normally pressured fluids from the surrounding strata into the underpressured reservoir, instead of an outflow. Thus, according to /PUC 03/ underpressured reservoirs fulfil two critical criteria: a) non- migration and b) isolation from surficial environment.

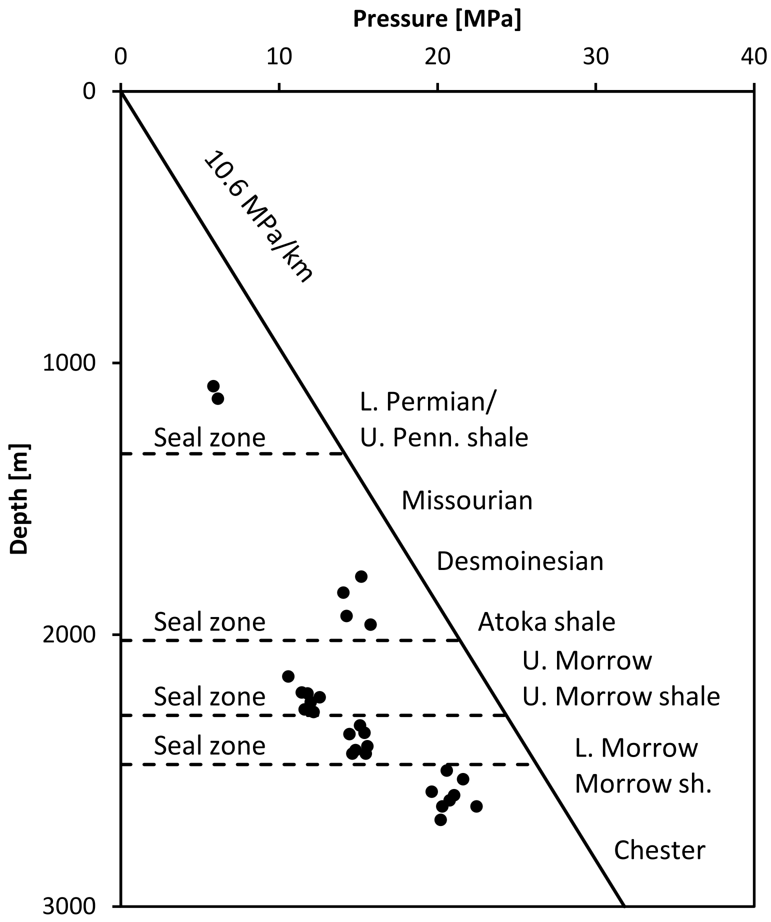


Fig. 3.4.4 Natural pressures are sealed against each other for millions of years vertically. The example shows a pressure-depth profile from Beaver County (Oklahoma) that illustrates numerous differently underpressured compartments. Redrawn after /PUC 03/

There are numerous examples for under-pressured and over-pressured reservoirs worldwide (e.g. Anadarko Basin in the U.S.). According to /FRE 15/ reservoirs with pressure gradients less than hydrostatic can exist onshore or offshore. Over 3000 out of more than 25000 screened reservoirs in the database of Nehring Associates Inc. 2012 version are considered as underpressured reservoirs. An old gas field could act as an artificial under-pressurized layer. Even over a long time-span, residual gas trapping would keep the released gases within the pore-space of the reservoir if water would flow back into the under-pressurized strata.

3.4.5 Discussion and Conclusion

The concept of deep borehole disposal is applicable to different combinations of geological barrier systems and has the advantage that it can be established in various places, even in countries without large accessible volumes of salt, shale or crystalline rock. For developing or border countries, DBD is internationally discussed as an option, which could allow a secure disposal where international trained operating rig and emplacement teams can secure the quality of the emplacement.

Deep borehole storage can be monitored through e.g. the central part of the well as long as the well remains open. But for security reasons no permanent monitoring or surveillance seems necessary; therefore, deep disposal fulfil the requirements of passive safety.

Deep borehole disposal requires to solve a number of technical challenges. To deposit a huge volume of spent nuclear fuels, wellbore diameters should be enlarged in comparison to the typical diameters used in oil and gas industry. This requires e.g. to build larger drilling rigs and drilling tools (upscaling). Furthermore, an adequate deployment technology need to be developed, as it seems that standard deployment procedures of e.g. monitoring tools do not qualify for the measures of radioactive waste.

With the experience of hydrocarbon industry in drilling, directional drilling, wellbore completion and deep borehole logging, sufficient knowledge and technology seems available to develop the last steps of DBD technology. The authors consider the development as being performable as a joint effort within one or two decades, especially if the wellbore diameter is increased in moderate steps.

For nuclear waste disposal, potential failure scenarios that might occur even 100 000 years after disposal have to be considered. This includes earthquakes and glaciation. These known events may lead to fault reactivation and glacial flexure or change of flexure due to deglaciation. All potential sites for waste disposal require a careful site investigation before starting waste disposal. One type of consideration is that the deposit site remains stable throughout the considered time frame of several radioactive half-times.

A prognosis on risk is difficult in view of the long term, where not only societal, political but also geological boundary conditions will change. Prognoses longer than 10 to 100 times of the overseen timespan may miss a process or mechanism which might become relevant over longer time spans. Thus, a different approach is presented here, to consider the effects if failure of technical and geological barriers occurs. The presented DBD would also include an additional safety for known upcoming events such as glaciation effects or larger magnitude earthquakes.

The actual legislation in Germany for CCS and fracking requests for geological multi-barrier system and minimum depths of 1 000 m and geological multi-barrier system and a depth of > 3 000 m, respectively. A more sophisticated multi-barrier system is presented here for even greater depth. Deep borehole disposal using a multi-barrier system could be regarded as an option, even if some modification in drilling and completion, as well as the recovery of casks need to be tested for the special requirements of nuclear waste treatment. The multiple barrier approach poses the opportunity for taking advantage of the different beneficial characteristics of each of the different petrophysical properties of the possible host rock for nuclear waste, crystalline, clay, and salt.

Last but not least, the size, the distance between the protected good and the waste can make a difference in risk mitigation. Sometimes, size matters.

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4 Deep Drilling / Shaft building (Bohren / Schachtbau)

4.1 Reich P.: Stand der Tiefbohrtechnik – wie werden Bohrungen nach Öl und Gas hergestellt?

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Die meisten Menschen gehen davon aus, dass eine Tiefbohrung einfach nur ein tiefes Loch in der Erde ist. Aber das eine sehr falsche Vorstellung, denn so ein offenes Loch in der Erde könnte keinesfalls die hohen Anforderungen an die Bohrlochintegrität erfüllen. Unter dem Schlagwort Bohrlochintegrität versteht man alle Aspekte einer Bohrung, die damit zu tun haben, dass weder Menschen, noch Tiere, Gebäude oder Gegenstände durch die Anlage oder den Betrieb der Bohrung gefährdet werden.

Eine moderne Tiefbohrung ist ein komplexes Gebilde aus Stahlrohren und Zement, welches verhindert, dass Gase, Flüssigkeiten oder Feststoffe unkontrolliert aus- oder eintreten können. Im folgenden Verlauf wird in groben Zügen beschrieben, wie eine Tiefbohrung nach Öl oder Gas hergestellt wird. Das Ziel dieser Darstellung ist nicht die technisch detaillierte Beschreibung aller Arbeitsschritte, sondern nur eine grobe und stark vereinfachte Beschreibung der wichtigsten Aspekte für bohrtechnische Laien.

Trinkwasser, welches ja ein äußerst schützenswertes Gut darstellt, darf nicht durch den Bohrprozess verunreinigt werden. Deshalb beginnt eine Tiefbohrung zunächst einmal damit, ein sogenanntes Standrohr in den Boden einzubringen, das bis mindestens so tief in den Untergrund hinunter reichen muss, dass die Trinkwasserhorizonte von den späteren Bohrarbeiten abgeschirmt werden. Weiterhin hat das Standrohr auch die Aufgabe, ein Nachfallen der lockeren oberflächennahen Erdschichten in das Bohrloch zu verhindern und auf diese Weise einen sicheren Ansatzpunkt für die Bohrung zu gewährleisten (Abb. 4.1.1 links).

Wenn das Standrohr gesetzt ist, kann um es herum der Bohrplatz angelegt werden. Der Mutterboden wird dazu zunächst abgetragen und für die späteren Rekultivierungsmaßnahmen aufbewahrt. Anschließend wird der gesamte Bohrplatz großflächig mit Beton und Asphalt versiegelt. Um das Standrohr herum wird ein Bohrkeller angelegt (Abb. 4.1.1 rechts).

Wenn der Bohrplatz vorbereitet ist, kann der Bohrturm mit allen Zusatzkomponenten angeliefert und aufgebaut werden (Abb. 4.1.2).

Abb. 4.1.1 links: Standrohr (Quelle: Geothermische Kraftwerksgesellschaft Traunreuth)
rechts: Bohrkeller mit Standrohr (Quelle: Geothermie Pullach)

Abb. 4.1.2 Bohrplatz (Quelle: Exxon Mobil)

Nun kann mit den Bohrarbeiten begonnen werden. Der erste Bohrmeißel wird durch das Standrohr auf die Sohle gefahren und beginnt zu bohren. Das gelöste Bohrklein wird durch eine spezielle Flüssigkeit, die Bohrspülung, kontinuierlich aus dem Bohrloch ausgetragen. Die Spülung gelangt durch das hohle Bohrgestänge zur Bohrlochsohle, nimmt dort das Bohrklein auf und spült es im Ringraum zwischen der Bohrlochwand und dem Bohrgestänge zur Oberfläche. Gleichzeitig stützt die Bohrspülung die Bohrlochwand und verhindert ein Nachfallen von Gestein. Im Gegensatz zu Bergwerken ist eine Tiefbohrung also immer mit Flüssigkeit gefüllt und somit niemals trocken.

Wenn der Meißel die lockeren oberen Gesteinsschichten durchbohrt hat und in die darunter liegenden, tragfähigen und massiven Gesteinsformationen vorgedrungen ist, ist der erste Bohrungsabschnitt abgeschlossen und die **Ankerrohrtour** kann gesetzt werden. Eine Rohrtour ist ein Strang aus aneinandergeschraubten oder verschweißten Stahlrohren, der in das Bohrloch eingefahren und dort im Gebirge festzementiert wird. Durch das Setzen einer Rohrtour wird also das bis dahin hergestellte Bohrloch dauerhaft stabilisiert und von der Umgebung isoliert.

Im Verlauf der Herstellung einer Tiefbohrung kann es jederzeit passieren, dass man unerwartet auf Gas oder Öl trifft. Insbesondere Gas, das in die Bohrung eintritt, stellt eine Gefahrensituation dar. Deshalb wird auf die Ankerrohrtour ein ***Blowout Preventer*** aufgeschraubt, mit dem die Bohrung im Fall einer drohenden Gefahr jederzeit sicher verschlossen werden kann. In Abb. 4.1.3 ist ein Modul des Blowout Preventers bei der Montage zu sehen.

Abb. 4.1.3 Montage eines Elementes des Blowout Preventers unter der Arbeitsbühne (Foto: Finenko)

Der nächste Bohrmeißel muss durch den geöffneten Blowout Preventer und die gesetzte Ankerrohrtour hindurch passen, deshalb entsteht unterhalb der Ankerrohrtour ein Bohrloch mit einem etwas kleineren Durchmesser.

Auf dem Weg in Richtung Lagerstätte durchbohrt der Meißel verschiedene Gesteinsformationen. Einige lassen sich problemlos durchörtern, aber es gibt immer wieder auch solche, die als problematisch eingestuft werden müssen. Zu den schwierig zu bohrenden Formationen gehören beispielsweise die Salze und Tone, instabile Gesteine oder Verlust- und Zuflusszonen. Die einzige Möglichkeit, solche problematischen Horizonte nachhaltig unter Kontrolle zu bekommen, besteht oft darin, weitere Rohrtouren einzubauen und zu zementieren. Das bohrtechnische Problem wird auf diese Weise „hinter das Rohr“ gebracht und kann somit den Bohrprozess nicht weiter beeinträchtigen. Rohrtouren, die auf dem Weg hinunter zur Lagerstätte eingebaut werden, um problematische Horizonte zu isolieren, nennt man ***Technische Rohrtouren***.

Zum Weiterbohren aus einer Technischen Rohrtour muss wieder ein etwas kleinerer Bohrmeißel verwendet werden. Und da im Verlauf einer Tiefbohrung meist mehrere technische Rohrtouren eingebaut werden müssen, bezeichnet man diese als die zweite oder dritte Technische Rohrtour und so weiter.

Schließlich wird die Lagerstätte erreicht. Um sicherzustellen, dass die erzielte Verbindung der Lagerstätte mit der Erdoberfläche dauerhaft gesichert ist, wird üblicherweise nach dem Durchbohren der abdichtenden Deckschicht der Lagerstätte, dem „Caprock“, eine letzte Technische Rohrtour abgesetzt und einzementiert.

Der weitere Verlauf der Bohrung verläuft in dem porösen und permeablen Gestein der Lagerstätte. Wenn die Endteufe der Bohrung erreicht ist, wird in diese Sektion eine Produktionsrohrtour eingebaut. Da in der Produktionsphase durch die Produktionsrohrtour hindurch Öl, Gas oder Wasser in die Bohrung eintreten soll, werden perforierte Rohre verwendet.

Die fertig gebohrte Tiefbohrung besitzt also einen teleskopartigen Aufbau, bei dem der Bohrungsdurchmesser mit zunehmender Tiefe immer kleiner wird (Abb. 4.1.4). Öffnungen gibt es nur ganz unten in der Lagerstätte und ganz oben am Turm.

Rechts in Abb. 4.1.5 rechts sieht man einen Schnitt durch den oberen Teil einer Tiefbohrung mit ihren ineinander verschachtelten Rohrtouren und den kompakt mit Zement verfüllten Ringräumen. Man erkennt sehr deutlich, dass der innere Kern der Bohrung durch mehrere Stahl- und Zementbarrieren von der Umgebung isoliert ist. Insofern kann bei einer ordnungsgemäß ausgeführten Tiefbohrung tatsächlich ausgeschlossen werden, dass zwischen der Lagerstätte und der Erdoberfläche ein seitlicher Ein- oder Austritt von Gasen oder Flüssigkeiten nicht möglich ist.

Links in Abb. 4.1.5 sind die Elemente einer Rohrtour vor dem Einbau auf dem Bohrplatz zu sehen.

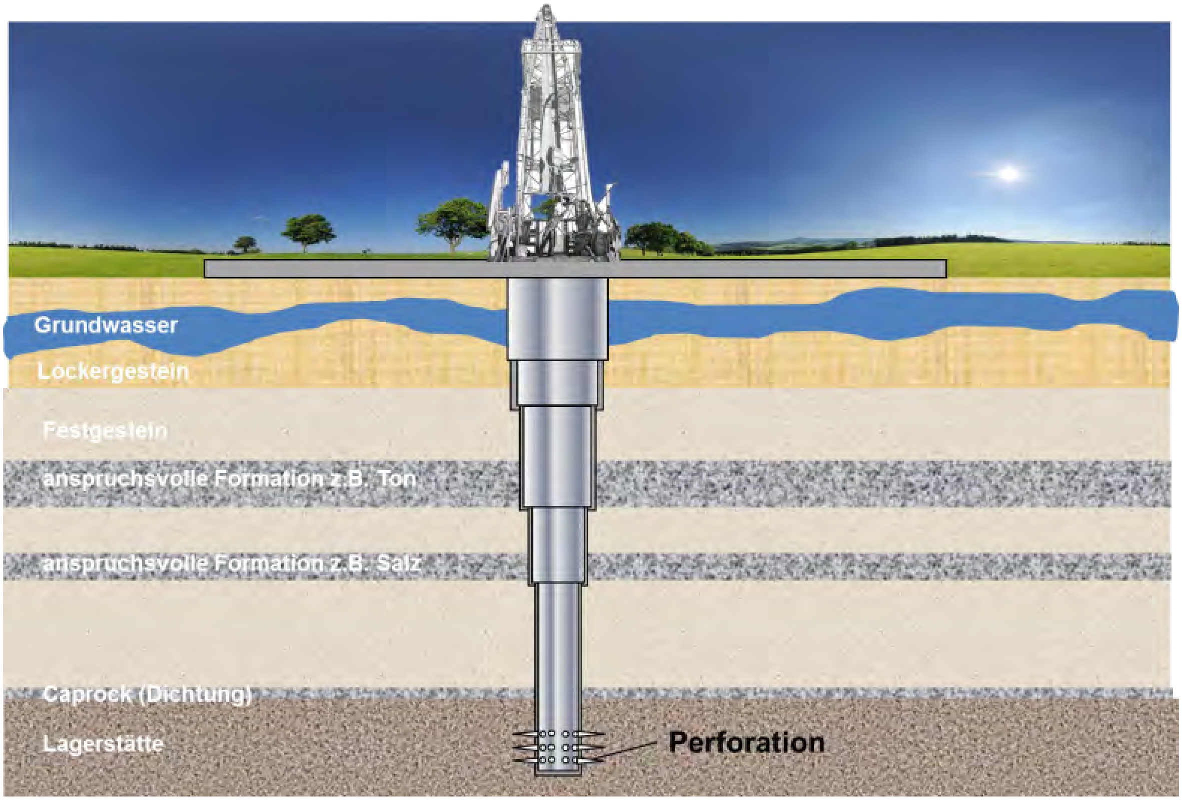


Abb. 4.1.4 fertig verrohrte Bohrung (Quelle: Reich)

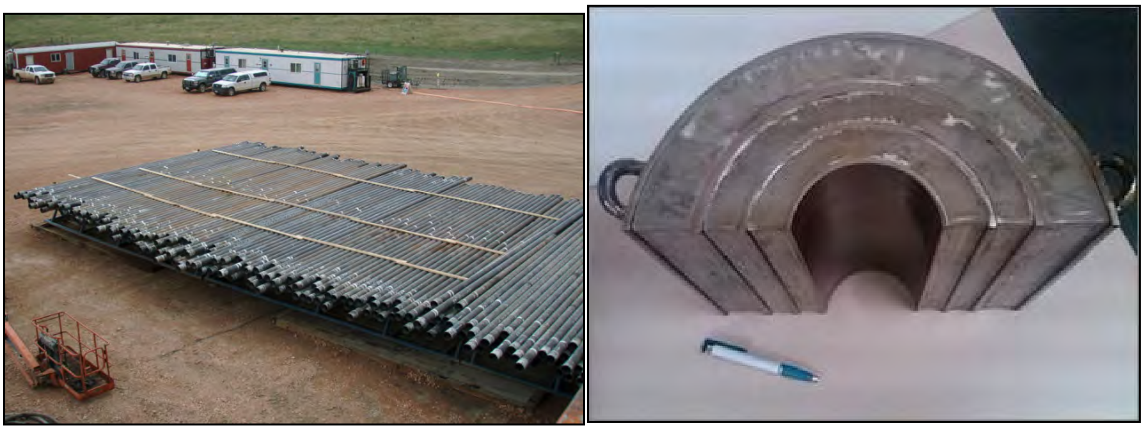


Abb. 4.1.5 Casingrohre vor dem Einbau und Schnitt durch einen Bohrungsabschnitt

Das Gesamtgebilde aus Rohren und Zement, das eine Tiefbohrung umschließt, nennt man eine ***Bohrlochkonstruktion***. Sie muss so dimensioniert werden, dass sie alle auftretenden Belastungen während der Bohrphase und des Förderbetriebs sicher ertragen kann.

Tiefbohrungen werden von unten nach oben geplant. Der Planungs-Ingenieur legt als Allererstes die Endtiefe der Bohrung und den Durchmesser der letzten Produktionsrohrtour fest.

Dieser ergibt sich aus der angestrebten Förderrate der Bohrung. Dann werden anhand eines geologischen Profils eventuelle problematische Formationen und Zonen identifiziert. Je nachdem, wie viele Rohrtouren aufgrund der geologischen Gegebenheiten als erforderlich erachtet werden, werden die technischen Rohrtouren, die Ankerrohrtour und ganz zum Schluss auch das Standrohr außen um den Produktionsstrang herum geplant. Schließlich ergibt sich daraus der Durchmesser des Standrohres, mit dem die Bohrung an der Oberfläche begonnen werden muss.

Die Durchmesser der gebohrten Strecken und der darin zementierten Rohre sind genormt und folgen der in Abb. 4.1.6 dargestellten Durchmesserreihe nach API (American Petroleum Institute). Im gezeigten Beispiel (gelb markierte Kreise) sollen die Bohrarbeiten aus einem 24“ Standrohr heraus stattfinden. Dazu wird ein 20“ Meißel eingesetzt (ein Zoll entspricht 25,4 mm). Die Ankerrohrtour, die in der 20“ Sektion gesetzt wird hat einen Außendurchmesser von 16“. Der folgende Bohrmeißel besitzt einen Durchmesser von 14 ¾“ usw.

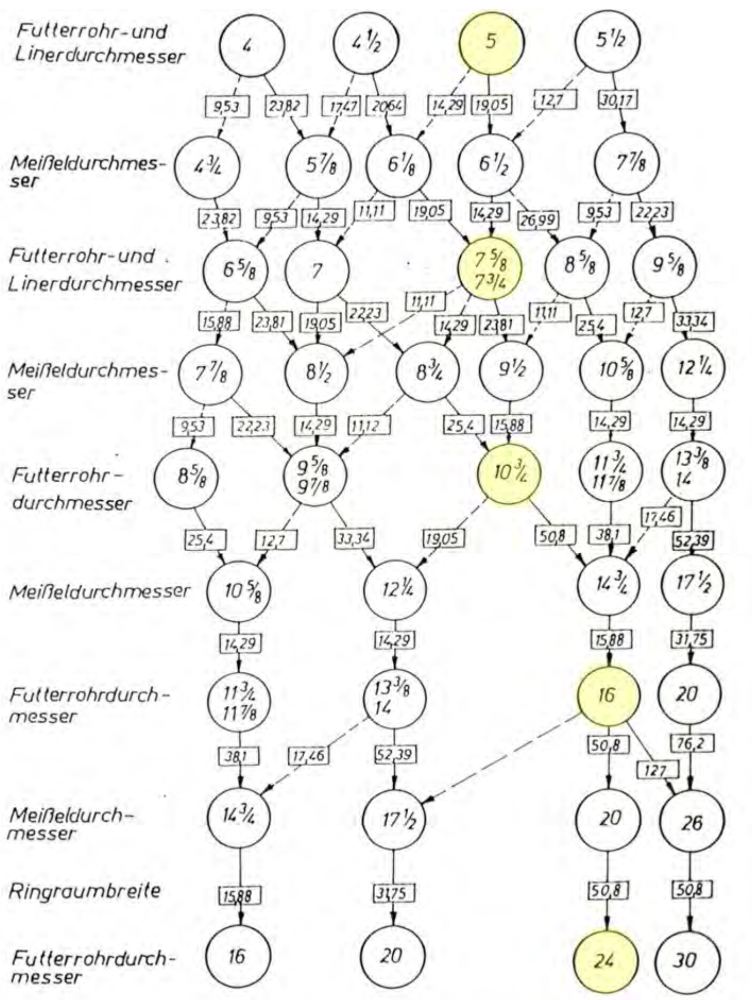


Abb. 4.1.6 API-Durchmesserreihe für Rohre und Meißel

Die Zahlen in den Feldern zwischen den Kreisen geben an, wieviel Spielraum zwischen dem Rohr und dem Bohrloch vorhanden ist. Bei der Zementation müssen diese Ringräume bis zur gewünschten Zementkopfhöhe vollständig ausgefüllt werden. Wenn der Zement Spülungstaschen enthält oder nicht am Rohr und am Gebirge anhaftet, können sich Wegsamkeiten für das Gas und Öl zur Oberfläche bilden. Die Qualität der Zementation muss also unbedingt nachgewiesen werden. Tatsächlich gibt es dafür verschiedene Messverfahren.

Zunächst wird festgestellt, wie hoch der Zement im Ringraum steht. Das ist relativ einfach mit einer Temperaturmessung, einem ***Temperatur-Log***, durchzuführen. Normalerweise steigt die Temperatur im Untergrund ja alle 100 Meter vertikaler Tiefe um etwa 3 °C an. Das Temperatur-Log einer ungestörten Bohrung zeigt also einen etwa linearen Verlauf. Da der Abbindevorgang des Zementes eine exotherme chemische Reaktion darstellt, wird beim Abbinden Wärme abgegeben, die das natürliche Temperaturprofil verändert. Wo Zement aushärtet, ist es also wärmer als an Stellen, wo kein Zement aushärtet. Und deshalb lassen sich aus dem Temperatur-Log Rückschlüsse über die Qualität der Zementation ziehen. Der Zementkopf, also die Oberkante der Zementierung, ist im Temperatur-Log als Temperatursprung zu erkennen.

Die nächste Kontrollmessung, die man durchführt, ist ein ***Cement Bond Log*** (CBL). Diese Messung basiert auf einer Schallgeschwindigkeitsmessung. Im Prinzip „klopft" das Gerät die innere Wand der Verrohrung ab und registriert dabei das entstehende Geräusch. Stellen, die mit massivem Zement verfüllt sind, klingen beim Abklopfen anders als Hohlräume! Und diesen Effekt nutzt man im Bohrloch aus, um zu prüfen, ob der Zement sicher am Rohr anhaftet oder ob sich Spülungstaschen hinter dem Rohr gebildet haben. Das Ergebnis dieser Messung wird meist als Abbild der Rohr-Innenoberfläche ausgegeben, in dem die Stellen mit besserer oder schlechterer Zementanbindung durch verschiedene Farben wiedergegeben werden.

Weiterhin wird vom eingesetzten Zement eine Probe genommen, die in einem speziellen Labor unter genau dieselben Drücken und Temperaturen abbinden gelassen wird, wie sie auch im Bohrloch herrschen. Die Proben werden nach dem Aushärten im Labor untersucht. Insbesondere wird die Härte des Zements bestimmt. Sie muss immer oberhalb der Härte des Gesteins liegen, damit der Zement nie die Schwachstelle im Gesamtsystem ist.

Die Zementfestigkeit wird aber nicht nur im Labor überwacht, sondern auch in der eigentlichen Bohrung. Dazu wird nach dem Aushärten ein ***Leak off Test*** (LOT) gemacht. Mit diesem Test wird getestet, ob das frisch verrohrte und zementierte Bohrloch wirklich dicht im

Gestein versiegelt ist. Für den Test wird oben am Blowout Preventer das Bohrloch so verschlossen, dass nichts mehr aus dem Ringraum hinaus fließen kann. Gleichzeitig wird aber durch das Bohrgestänge mit geringer, konstanter Rate Spülung in die Bohrung hinein gepumpt. Dadurch steigt der Druck in der Bohrung linear an. Natürlich kann der Druck in der Bohrung nicht beliebig weit gesteigert werden, sondern bei Erreichen der Gesteinsfestigkeit beginnt das Gestein aufzureißen. Übertage erkennt man diesen Effekt an einer Abflachung der Druckkurve. Die Pumpen werden nun sofort abgeschaltet, um zu verhindern, dass sich größere Risse bilden Dann wird der Druck in der Bohrung beobachtet. Wenn sich der in der Bohrung eingeschlossene Druck hält, ist die Bohrung dicht. Fällt der eingeschlossene Druck dagegen ab, ist die Zementierung undicht und der Leak-off Test ist nicht bestanden.

Grundsätzlich kann man eine schadhafte Zementation nachträglich noch reparieren, aber das ist aufwendig, dauert lange und ist somit sehr teuer.

- Typische vertikale Teufen: 3 – 6 km
- Bohrungslängen bis zu 12 km

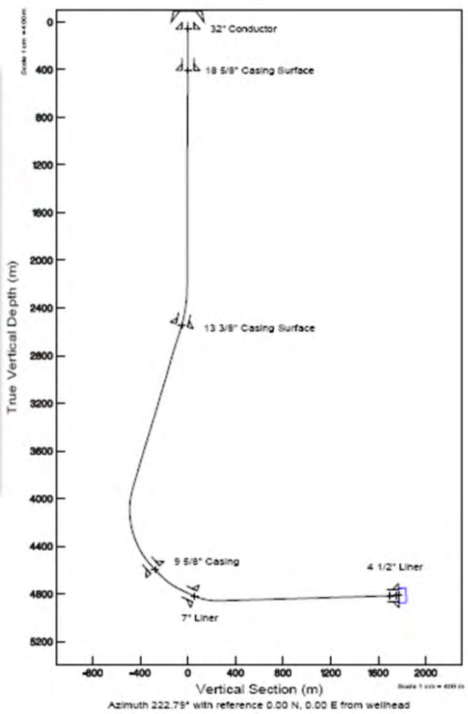


Abb. 4.1.7 Dimensionen typischer Öl- und Gasbohrungen

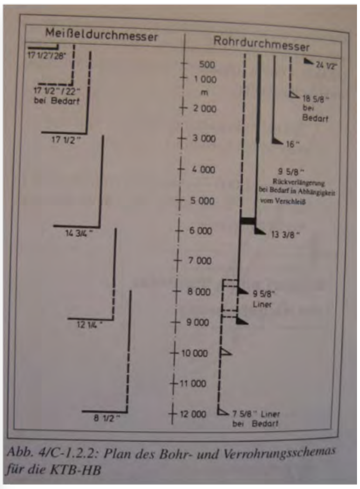
In Abb. 4.1.7 sieht man die Dimension einer typischen Öl- oder Gasbohrung. Dabei drängt sich ein Vergleich mit einem Inlandsflug in einer Höhe von 5 bis 6 km auf. Der Durchmesser der Bohrung entspricht etwa dem des Fensters im Flugzeug. Von dort aus verliefe die Bohrung senkrecht hinunter bis zur Erdoberfläche und würde dort waagerecht noch mehrere Kilometer weit führen.

Der Bohrturm muss in der Lage sein, alle einzusetzenden Bohrstränge und Rohrtouren sicher zu handhaben und muss also über eine entsprechende ***Hakenlast*** verfügen.

„Normale“ Tiefbohranlagen verfügen über Hakenlasten von 250 bis 350 Tonnen, „große“ Tiefbohranlagen für Landbohrungen verfügen über Hakenlasten von ca. 500 t.

Die KTB-Forschungsbohrung mit 9101 Metern Tiefe ist die tiefste Bohrung Deutschlands. In 5 000 Metern Tiefe (diese Tiefen stehen im Rahmen der Endlagerung zur Diskussion) besitzt sie einen Durchmesser von 13 3/8“ (340 mm) und ist damit im Rahmen der üblichen Tiefbohrtechnik durchaus als „sehr groß“ zu bezeichnen. Die Bohranlage besaß eine entsprechend große Hakenlast von 850 t (Abb. 4.1.8).

Mit steigender Hakenlast einer Bohranlage steigen die Tagesraten überproportional an – eine Verdoppelung der Hakenlast hat eher eine Vervierfachung der Mietkosten zur Folge. Auch die Materialkosten für Rohre, Zemente usw. steigen mit größerem Bohrungsdurchmesser stark an. Deshalb ist man in der Tiefbohrtechnik immer bestrebt, den Bohrlochdurchmesser so klein wie möglich zu halten. Die Frage nach dem maximal möglichen Durchmesser einer Tiefbohrung, die im Rahmen der Diskussion über eine Endlagerung radioaktiver Abfälle oft gestellt wird, ist in der Tiefbohrtechnik nicht zielführend und kann entsprechend nicht beantwortet werden.



24 ½“ Standrohr (622 mm)
7 5/8“ Liner (193 mm)

Abb. 4.1.8 Bohranlage der tiefsten Bohrung Deutschlands (KTB)

Moderne Tiefbohrungen können sehr präzise in die Lagerstätte geführt werden. In Abb. 4.1.9 ist das untere Ende eines typischen Bohrstranges zu sehen. Hinter dem Bohrmeißel, der für die Gesteinszerstörung zuständig ist, folgt ein Steuerkopf, mit dem die Richtungskontrolle erfolgt. „MWD-Systeme“ (measuring while drilling) vermessen den Bohrpfad ohne die Bohrarbeiten zu unterbrechen, „LWD-Systeme“ vermessen die Eigenschaften des durchbohrten Gesteins während des Bohrprozesses. Dabei sind alle Messungen interessant, die auf das Vorhandensein von Kohlenwasserstoffen in der Lagerstätte hinweisen. Insbesondere handelt es sich hier um:

- Gamma-Sensoren, die zwischen dem porösen Gestein der Lagerstätte und der undurchlässigen Deckschicht darüber unterscheiden können
- Resisitivity Sensoren, die feststellen, ob sich die Bohrung im Öl oder Gas befindet, oder ob sie sich bereits dem darunter befindlichen Wasser nähert
- Porositätsmessungen
- Permeabilitätsmessungen

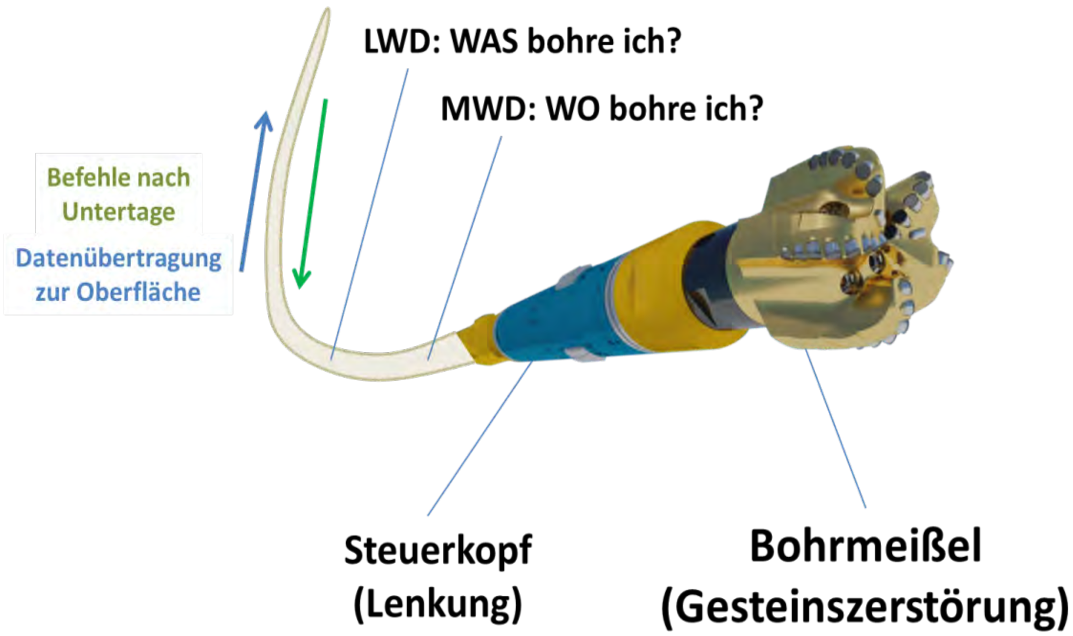


Abb. 4.1.9 unteres Ende einer Bohrgarnitur

Die Bohrgarnitur steht in ständigem Kontakt mit der Oberfläche, es können sowohl Befehle nach Untertage wie auch Daten nach Übertage übertragen werden.

Die Bohrungen werden so im Untergrund platziert, dass eine maximale Förderung der Rohstoffe garantiert wird – es werde also in der Regel die porösesten und durchlässigsten Stellen des Gesteins angesteuert. Gleichzeitig muss bei Clusterbohrungen sichergestellt werden, dass es keine Kollisionen mit anderen Bohrungen gibt. Abb. 4.1.10 zeigt einige der üblichen Messungen, die zur Navigation eingesetzt werden.

Typische Messungen:

Directional	WO bohren wir? Himmelsrichtung, Neigung, …
Druck	Bohrlochkontrolle, Bohrlochstabilität
Dynamik	Meißelandruck, Drehmoment, Vibrationen, …
Gamma	Erkennung von Tonschichten (Oberkante Lagerstätte)
Resistivity	Unterscheidung zwischen Wasser und Öl (Unterkante)
Neutron Porosity	Porosität des Gesteins
Formation Density	Porosität des Gesteins, Poreninhalt
Ultrasonic Caliper	Bohrlochqualität
Acoustic	Gesteinsfestigkeit
Imaging Tools	Klüfte, Risse im Gestein
Seismic while drilling	Erkundung des Bereichs VOR dem Bohrmeißel
NMR (nuclear magnetic resonance)	Porenvolumen, bewegliche und gebundene Fluide

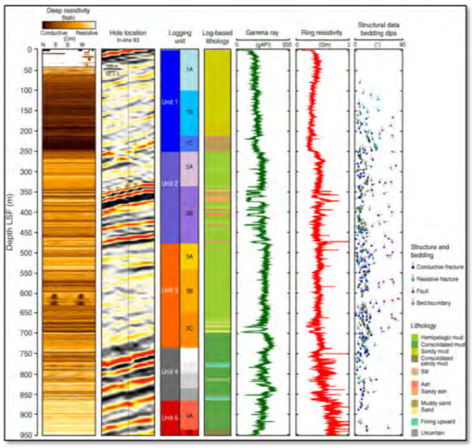


Abb. 4.1.10 Beispiele für untertägige Messungen

Im Gegensatz zur Fliegerei wird in der Tiefbohrtechnik immer mit dem Auftreten von Problemen gerechnet. Die daraus resultierenden Ausfallzeiten („non productive time“, NPT) betragen meist ca. 30% und sind auf Werkzeugausfälle oder unerwartete geologische Besonderheiten zurückzuführen. Die NPT wird in die Kostenkalkulation immer mit einbezogen.

Weitere Faktoren, die die Projektkosten beeinflussen, sind:

1. Endteufe der Bohrung
   - Anlagengrösse
   - Bohrplatzbau
   - Havariegefahren
2. Lebensdauer der Bohrung
   - Verrohrungsausbau
   - Zutage Rohrtouren
   - Bohrlochkopf

   - Bohrlochkomplettierung

3. Durchmesser der Bohrung
   - Materialkosten
   - Anlagengröße
4. Exploration
   - Geophys. Loggingprogramm
   - Teste
   - Minimaler Kerndurchmesser
   - Länge der Kernstrecken
5. Marktpreise, Verfügbarkeit
   - Casingrohre, Material, etc.
   - Bohranlagen, Services
6. Bohrlokation, Umwelt & Genehmigungsverfahren

Eine tiefe Bohrung mit sehr großem Durchmesser, die sehr lange halten soll, ist somit besonders teuer. Beispiel: für eine 5000 Meter tiefe Geothermalbohrung mit einem Enddurchmesser von 12 ¼“, die ursprünglich 2014 im Granit des Erzgebirges gebohrt werden sollte, waren Kosten von ca. 20 Millionen Euro veranschlagt worden.

Ca. 60% der Projektkosten einer Tiefbohrung entfallen üblicherweise auf die Miete der Bohranlage, die Verrohrung, die Richtbohrtechnik und das Personal (Abb. 4.1.11).

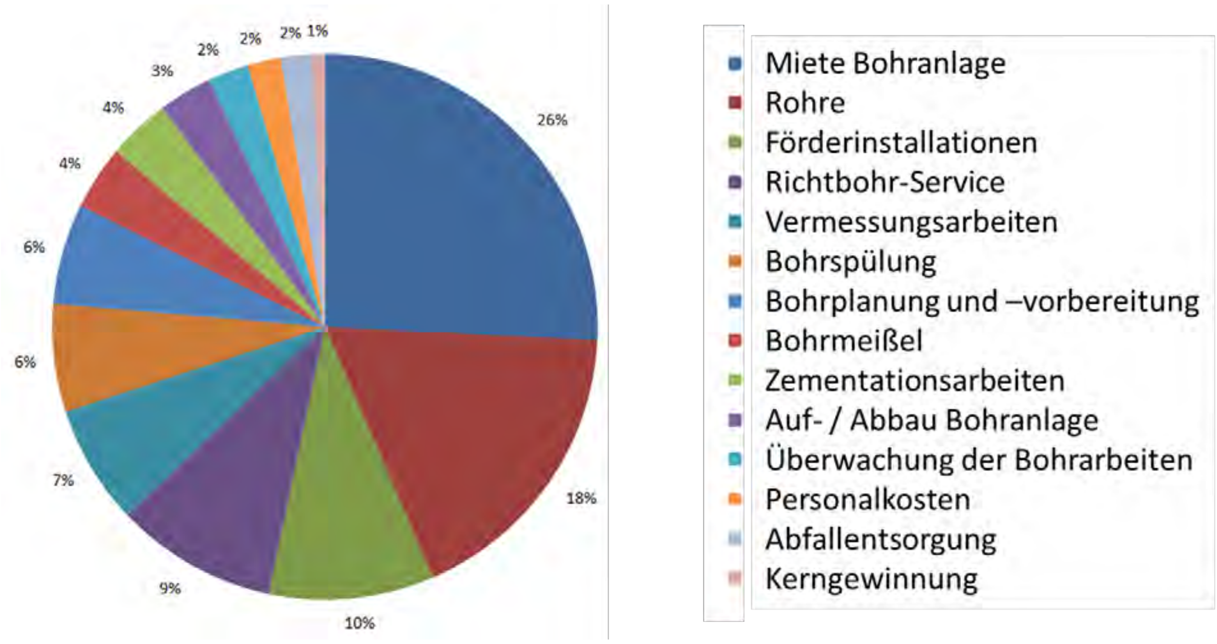


Abb. 4.1.11 typische Aufteilung der Projektkosten

In Abb. 4.1.12 sind zwei Bücher zu sehen, die als tieferer Einstieg in die Materie empfohlen werden:

- M. Reich: „Auf Jagd im Untergrund - Mit Hightech auf der Suche nach Öl, Gas und Erdwärme“, Springer Verlag, 2. Aufl. 2015.
- M. Reich, M. Amro: „Schätze aus dem Untergrund – wie Hightech das Öl- und Gaszeitalter verlängert“, Verlag add-books, 2015.

Das erste Buch befasst sich mit der Tiefbohrtechnik, das zweite behandelt die Fördertechnik.

Bohrtechnik

Fördertechnik

Abb. 4.1.12 Buchempfehlungen

4.2 Röckel T.: Drilling with large diameters in crystalline rocks – experience from KTB (Große Durchmesserbohrungen im Kristallin – Erfahrungen aus der KTB)

Thomas Röckel, Piewak & Partner GmbH, Jean-Paul-Straße 30, 95444 Bayreuth

4.2.1 Zusammenfassung

Zum sicheren Erreichen großer Teufen ist es notwendig einzelne Bohrlochabschnitte mit Verrohrungen abzusichern. Zum Schutz des Grundwassers und zur Beherrschung von Gasausbrüchen wird in der Regel eine Ankerrohrtour eingebaut. Im Kristallin können in großen Störungszonen starke Instabilitäten auftreten. Diese Abschnitte müssen mit Rohrtouren gesichert werden. In Sedimentgesteinen ist es auf Grund von sehr stark unterschiedlichen Druckverhältnissen notwendig Bereiche mit hohen Drücken (Salz) von Bereichen mit niedrigen Drücken zu trennen. Aus diesen Gründen ist es notwendig für größere Tiefen eine Mindestanzahl an Verrohrungen vorzusehen.

Bei KTB wurde die KTB-Vorbohrung als Pilotbohrung weitgehend gekernt und bis zu einer Tiefe von 4 000,1 m vermessen. Hierdurch lag eine exzellente Datenbasis für die KTB-Hauptbohrung vor.

Die KTB-Hauptbohrung war auf eine Teufe von 10 000 m konzipiert, mit der Möglichkeit einer Vertiefung auf 12.000 m. Da Kerne bis zu einer Teufe von 4 000 m aus der KTB-Vorbohrung vorhanden waren, wurden in der KTB-Hauptbohrung erst unterhalb von 4 000 m Kerne gezogen.

Zur Sicherung des Bohrlochs wurde bis zu einer Teufe von 290,5 m eine Verrohrung mit 711 mm Durchmesser eingebaut. Danach wurde bis zu einer Teufe von 3 003,5 m im Durchmesser von 444,5 mm (17 ½“) gebohrt das Bohrloch und bis zu einer Teufe von 3 000,5 m mit einer 16“-Verrohrung (406,4 mm) gesichert. Für instabile Bohrlochbereiche war noch eine Reserverohrtour vorgesehen. Der Bereich zwischen 290 m und 3 000 m hätte auf 22“ erweitert und mit einer $18^{5/8}$“-Verrohrung gesichert werden können.

Aus der 16“-Verrohrung heraus wurde bis zu einer Teufe von 6 018 m mit einem 14 ¾“-Durchmesser gebohrt und das Bohrloch bis zu einer Teufe von 6 013,5 m mit einer $13^{3/8}$“ bzw. $13^{5/8}$“-Verrohrung gesichert. Der Einbau dieser extrem langen und schweren Verrohrung von über 600 to (6 000 kN) Gewicht wurde bereits vor etwa 25 Jahren sicher beherrscht.

Eine wichtige Voraussetzung hierfür war, dass die Schleiflasten beim Rohreinbau und die Drehmomente beim Bohren auf Grund der eingesetzten Richtbohrtechnik sehr gering gehalten werden konnten.

Auf Grund der hohen Temperaturen (>200 °C) konnte die Richtbohrtechnik unterhalb von 7 500 m nicht mehr eingesetzt werden. Zusammen mit den zunehmenden Bohrlochinstabilitäten unterhalb von 7 000 m führte dies zu verstärkten bohrtechnischen Problemen mit großen Zeitverlusten.

Die Erfahrungen von KTB und anderen Kristallinbohrungen zeigen aber, dass Teufen von 5 000 m sicher beherrschbar sind. Im Gneisgebirge können größere Probleme auftreten. Im Granit ist ein Abteufen von Bohrungen bis etwa 5 000 m sicher möglich.

Ein Bohrungs- bzw. Verrohrungsdurchmesser von etwa 350 bis 400 mm in einer Teufe von etwa 5 000 m ist mit der damaligen Technik möglich.

Die wesentlichen Bohrlochmessungen sind für diese Teufen und Temperaturen vorhanden. Für größere Durchmesser ist sowohl beim Bohren, wie auch beim Messen, noch Entwicklungsbedarf vorhanden.

Die prinzipielle Machbarkeit von großkalibrigen Bohrungen im Kristallin kann durch das Beispiel von KTB als erbracht gelten.

4.2.2 The drilling concept

In an early stage of the KTB-project studies showed, that the drilling of two boreholes are the best way to reach the scientific targets. With a pilot hole the essential scientific and technical data should be gathered to plan the deep borehole. To obtain a maximum of information an intense borehole logging program was planned. Additionally it was considered as necessary to core nearly the complete section of the pilot hole.

Great depth can only be drilled with large diameters at the beginning, since several casings are needed to stabilize the borehole in unstable sections, to seal underpressured or overpressured sections or stabilize squeezing salt and clay formations. In large diameter boreholes coring operations are difficult. Therefore coring should be carried out in a small diameter pilot hole. Logging is also simpler in hole with small to medium diameter. For boreholes with big diameters at the end of the 1980 only a limited number of logging tools were available. For this reasons it was decided to drill a pilot hole. On the base of the knowledge the main hole should be designed finally.

Fig. 4.2.1 KTB Drill site. Aerial photograph with the drill rig for the KTB pilot hole in the foreground and drill site for the main hole in the background. The building on the left side is the KTB field laboratory

4.2.3 The KTB pilot hole

Borehole sections with fault zones and borehole stability problems, zones with fluid loss or overpressured zones should be already identified during the pilot phase to develop the adequate drilling strategy for the main hole. Build up of inclination anisotropic rocks was of specific interest to develop strategies for vertical drilling in the main hole. Another purpose of the pilot hole was to test new logging tools. For a scientific borehole a complete scientific profile was of great interest to study the earth crust. The analysis of the obtained data should be the base to develop the optimal drilling strategy for the KTB main hole.

A maximum depth of the KTB pilot hole of 3 000 m to 5 000 m was required. The analysis of the temperature for the Ultra deep hole was a major target. With this strategy it was possible to avoid an expensive operation of a heavy rig for drilling and logging in the upper section.

The drill side for the KTB pilot hole has a place of about 4 000 m^2. The length is 81.5 m and the width is about 50 m. the drill rig used for the pilot hole was a modified rotary drill rig combined with wireline coring technique.

Fig. 4.2.2 Drill rig GH 1400E for the KTB Pilot hole. Modified rotary drill rig for deep wire line coring operations

The KTB pilot hole was started on September 22, 1987, and was finished April 4, 1989 after 560 days at a final depth of 4 000.1 m. During 956 core runs a total of 3 593 m or 90 % of the hole were cored. With a $10^{5/8}$" roller cone core bit 451 m were cored and 3143 m were cored with 6" diamond core bit. The diameter of the cores were 101.6 mm (4") and 94 mm (Fig. 4.2.3a) respectively. The rate of penetration of the diamond core bits were 1.66 m/h. The average length of a core run was 3.5 m.

Twice the bottom hole assembly was lost and two side tracks had to be performed. The first time, at a depth of 1998 m the bottom hole assembly was lost and the second time at a depth of 3 767 m. The core recovery in the diamond cored section was 98 %. Even in fault zones core recovery was good. An open fracture was drilled at a depth of 3447 m (Fig. 4.2.3b).

The temperature a the bottom of the borehole at 4 000 m was 118 °C and the deviation was 190 m. this results were important for the technical planning of the KTB main hole.

After finishing the pilot hole the hole was extremely good logged and provided together with the drill cores a lot of important scientific data.

a)

b)

Fig. 4.2.3 a) 6"-Diamond Core Bit
b) Gneis from a depth of 3 447 m with an open joint (94 mm core diameter)

4.2.4 KTB main hole (KTB Hauptbohrung)

Based on the experience of the geological profile and the drilling experience from the KTB pilot hole the planning for the ultra-deep borehole was revised. Especially rock instabilities in fault zones, steeply dipping foliated rocks, which were responsible for the build up of inclination, breakouts and core disking made it necessary to modify the concept for the KTB Main

Hole. The KTB Main Hole was spudded 200 m east of the KTB Pilot hole. A temperature of 250 °C to 300 °C is critical for logging and drilling. It was expected, that this goal would be reached at a depth of about 10 000 m or less. The technical planning was based on a depth of 10 000 m including an option to continue drilling to a depth of 12.000 m, when lower temperatures were encountered.

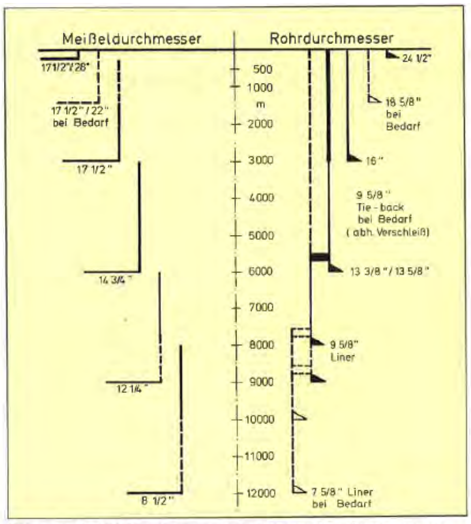


Abb. 3 Für die KTB-Hauptbohrung geplantes Bohr- und Verrohrungsprogramm

Fig. 4.2.4 Casing and bit size concept for the KTB Main hole /SPE 90/

From the experience with borehole stability problems in the KTB pilot hole, the open hole section in the KTB main hole were restricted to sections not longer than 3 000m.

At a final depth of about 10 000 m the borehole diameter was planned not smaller than $8^{1/2"}$ to make use of standard bits and equipment. In the upper sections of the borehole were vertical drilling systems were run, small clearances were planned. For the deeper sections problems with the vertical drilling systems were expected due to high temperatures in the borehole. In the lower section larger clearances were chosen. The casing and bit size concept for the KTB main hole is shown in Fig. 4.2.4.

4.2.5 Coring

Down to 4 000 m the crust at the KTB drill side was intensively cored during the Pilot Hole phase. Therefore coring in the KTB main hole was planned to start below 4 000 m. Also borehole logging was minimized in this section. To gather scientific information spot coring was planned. Before installing the casings, an intensive logging program was performed. Sampling of Cutting and gases was performed continuously. In the $14^{3/4"}$ phase coring was performed with a double tube core barrel with roller cone core bits with a diameter of 4” (101.6 mm,Fig. 4.2.5). The core recovery was between 0 % and 40 %. This lead to the decision to core the $12^{1/4"}$ section with large diameter coring system (LDCS). The drill cores had a diameter of 245 mm ($9^{5/8"}$) and a length of 6 m (Fig. 4.2.5). A core of one meter length has a weight of about 235 kg. The enormous rock volume let to high scientific acceptance of this coring system.

Fig. 4.2.5 Large diameter core (245 mm) and standard core (4”, 101,6 mm)

4.2.6 The vertical drilling concept

To minimize torque and drag forces between drill string and borehole, a vertical borehole with a straight trajectory is needed. Therefore the borehole has do vertical to a depth of at least 6 000 m. This was an important goal to set a 16”-casing in a $17^{1/2"}$borehole and a $13^{3/8"}$ casing in a $14^{3/4"}$ borehole. The use of downhole motors till final depth was also considered as an important fact. Limiting factors for the vertical drilling concept is the borehole stability because with increasing depth the stress concentrations at the borehole wall overcome the rock strength and the borehole wall fails. The borehole diameter at a depth of about 7 500 m increased from nominal 245 m to more than 700 mm (Fig. 4.2.6) In this situation the steering ribs (Fig. 4.2.7) of the vertical drilling systems become ineffective.

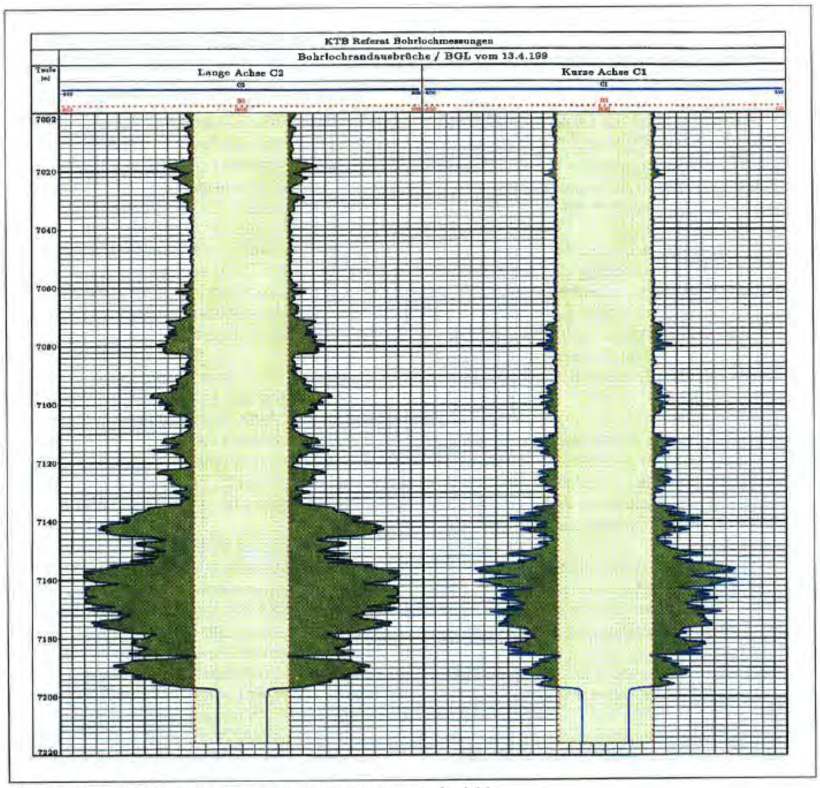


Abb. 11/C-3.12.2.4: Kalibersituation im Bereich der Störungszone des SE 1

Fig. 4.2.6 Caliper at a depth of about 7 150 m. The borehole has a nominal diameter of 121/4” (311 mm). The measured caliper reached about 700 mm in an instable zone

Fig. 4.2.7 Vertical drilling system with steering ribs (Photo: Nora Röckel)

4.2.7 The KTB Drilling Rig

Several studies showed the requirements to reach a depth of 10 000 m for a scientific borehole in crystalline rocks.

This studies lead to the decision to build a new rig with a hook retractor system and an automatic pipe handling system. The load capacity should be sufficient for at least 12 000 m of drill pipes. The KTB drilling rig was the highest and strongest onshore rigs (Fig. 4.2.8). This advanced rig has following characteristics:

- Height: 83 m
- Capacity: 12 000 m
- Max. hook load: 8.000 kN
- Rig floor: 13x13 m
- Height of the rig floor;: 11.75 m
- Mud pumps: 2 x x1 240 kW, 1 x 620 kW
- Working pressure: 350 bar

- Remote controlled gear driven draw works
- Advanced drilling instrumentation and data processing
- Electrified rig with reversal power generating break systems
- Central rig controls from the drillers cabin.

Fig. 4.2.8 Drill rig for the KTB Main Hole

4.2.8 Experience from the KTB Main hole

4.2.8.1 $17^{1/2"}$/28” diameter section 0-305 m

The borehole was spudded on October 6th 1990. The $17^{1/2"}$ (444.5 mm) section was opened to 28” (711.2 mm) and a $24^{1/2"}$ (622.3 mm) casing was set at a depth of 292 m and cemented to the surface. It was not necessary to take the option to drill an additional 22” (558.8 mm) section with a $18^{5/8}$” (473.1 mm) casing to a depth of about 1 500 m.

4.2.8.2 17$^{1/2}$" diameter section, 290.5 – 3 003.0 m

The 17$^{1/2"}$ section was drilled to a depth of about 3 000 m using Moineau downhole motors. A measuring while drilling technology was used to control the verticality of the borehole. During drilling an active vertical drilling system was used. At a depth of 3 000 m the horizontal distance from the vertical is just 12 m and the inclination of the hole is below 0.5°.

The 17$^{1/2"}$-borehole was cased with a 16" (406.4 mm) casing down to 3 000.5 m at the end of May 1991. The 3 000 kN (360 to) heavy casing could be lowered without problems to the bottom of the hole. During this operation the clearance between the borehole wall and the Hydril connectors was just 14 mm. The hole was cemented with a cement weight of 1.6 kg/l to the surface. At the bottom of the hole the pressure of the cement was just about 48 MPa and therefore a little bit lower than the fracture pressure, which was known from a hydrofrac experiment in the KTB Pilot Hole at a depth of 3 000 m.

4.2.8.3 14$^{3/4}$" diameter section, 3 000.5 – 6 018.0 m

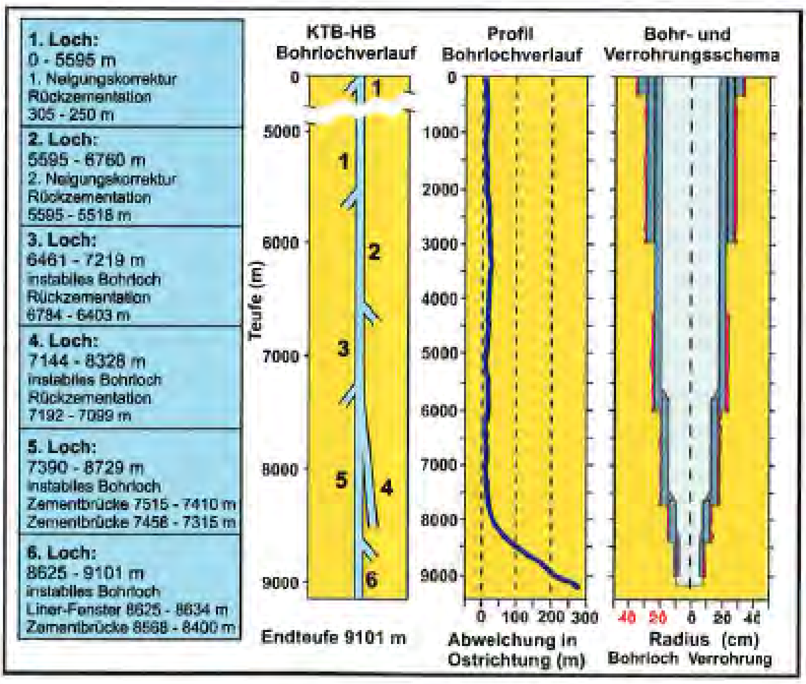
From 3 000 m to 6 018 m the KTB Main Hole was drilled with 14$^{3/4}$" diameter (374,7 mm). A depth of 6 018 m was reached in March 1992. The deviation at a depth of 6 018 m was below 10 m from vertical. Most of the section was drilled with vertical drilling systems. At a depth from 5 519 m to 5 596 m a packed hole assembly (PHA) run without steering system was run. In steeply dipping gneisses a high deviation was build up. After the cementation of the deviated section a sidetrack performed and a new hole was drilled with a vertical drilling system. The setting of the 6 000 m long 13$^{3/8}$" (339.7 mm) casing was very challenging. The weight of the casing was 7 000 kN (700 to) and the clearance between the 14$^{3/4}$" borehole and the 13$^{3/8}$" casing was just 13 mm between the bit size and the outer diameter of the casing. The casing could be lowered without any problems and was cemented to a depth of about 3 000 m.

4.2.8.4 12$^{1/4}$" diameter section, 6 013.5 – 8 328.2 m

In the following 12$^{1/4}$" section a hydraulic-fracturing experiment was performed. After drilling out the cement from the 13$^{3/8}$" casing the hydrofrac experiment was carried out in the open hole section between 6 013.5 m and 6 031 m. Drilling and coring continued to a depth of 6 760.5 m were the drill bit got stuck. A side track was successfully at a depth of 6 461.5 m using a motor steering system (MSS). This system pushes the bit to predetermined direction.

Drilling and coring continued in the $12^{1/4}$" section to a depth of 7 219.5 m. Several tests were performed at this depth in the KTB Main Hole. After a failure of the drill pipe the hole had to be cemented back to7 099 m. A new side track was drilled and finished at a depth of 7 225.1 m at the April 16, 1993. At September 7, 1993 a depth of 8 328.8 m was reached. Below 6 700 m increasing rock stresses and decreasing rock strength lead to an increase in borehole stability. Borehole breakouts caused a reduction of cleaning of the borehole. This increased the borehole problems additionally. Probably shear failure along preexisting planes of weakness (foliation planes and faults) increased the borehole stability problems further.

At a depth of 7 356.5 m the drill bit get stuck during reaming of the borehole. After cementing the hole, a whip stock was set at a depth of 7434.7 m and a new side track was drilled to a depth of 7 790 m. to stabilize the unstable borehole sections a $9^{5/8}$" liner was installed from 5 893 m to 7 784.8 m.



Der Bohrlochverlauf mit Neigungskorrekturen und Havarien, das Profil des Bohrlochverlaufs mit dem senkrechten Abschnitt und der starken Krümmung im unteren Teil sowie dem Verrohrungsschema der fertigen Hauptbohrung

Fig. 4.2.9 Borehole stability below 6 700 m was the most critical point and the limiting factor during deep drilling operations. The side tracks and borehole correction, the build up of inclination an the casing scheme are shown

4.2.8.5 $8^{1/2}$” diameter section, 7 784.8 – 8 729.7 m

The $8^{1/2}$”- section was drilled from December 18, 1993 to the 1st of February 1994 from 7790 m to 8 714.8 m. Borehole stability problems increased dramatically at that depth. Within the next two month the penetration of the borehole reached just 0.2 m.

After very severe problems at a borehole depth of 8 729.7 m a $7^{5/8}$”-liner was run into the borehole to a depth of 8 665.0 m. A whip stock was integrated in the liner at a depth of 8 625.2 m.

4.2.8.6 $6^{1/2}$” diameter section, 8 625.2 – 9 101 m

After cementing the $7^{5/8}$”-liner a side track at 8 625.2 m failed. A successful side track was achieved after more than one month. The final depth of 9 101 m was reached on October 10th 1994. This was the official end of the drilling operation.

4.2.8.7 Experiments and final works

Borehole logging could be performed to a maximum depth of 8 667 m in the open hole.

For the preparation of the final Hydrofrac/Seismic experiment a $5^{1/2}$” liner was set from 8 550.5 m to 9 031.0 m. Borehole logging was possible between the liner shoe at 9 031 m and 9 080 m. Between Dec. 6th and Dec. 2nd in 1994 the final Hydrofrac/Seismic experiment was carried out.

For the conservation of the borehole for a deep crustal laboratory the drill mud was exchanged for a soda mud. The operational works were finished at January 28th,1995.

4.2.9 Conclusions

More than 20 years ago KTB showed, that deep drilling operation even in hard rocks are possible with large bit and casing diameters to at least 6 km. At greater depth (more than 7 km), especially in foliated and anisotropic gneisses borehole stability is a major problem. Borehole correction and precise drilling were performed. The development for advanced drilling especially directional drilling and logging are based on KTB experience.

References

/SPE 90/ Sperber, A.: Das Verrohrungskonzept für die KTB-Hauptbohrung, Hamburg/Wien (1990) 12,. Erdöl Erdgas Kohle, No. 106, pp. 483–485, 1990.

5 Technical Barriers and Emplacement Technology for High P/T conditions (Technische Barrieren, Einbringungstechnologie bei hohen Temperaturen und hohen Drücken)

5.1 Vietor T.: Multiple barrier concept for high level waste repository in Switzerland. Scientific basis and demonstration (Multibarrierenkonzept für die Endlagerung hochradioaktiven Abfalls in der Schweiz - wiss. Grundlagen und Demovorhaben)

Tim Vietor, Lawrence Johnson, Piet Zuidema, NAGRA, Wettingen, Schweiz

Expert Workshop: Final Disposal in Deep Boreholes Using Multiple Geological Barriers

Berlin, 5-6 June, 2015

Multiple barrier concept for a high level waste repository in Switzerland -

Scientific basis and demonstration

Tim Vietor, Lawrence Johnson and Piet Zuidema

Nagra
Wettingen, Switzerland

nagra

Overview

- **Introduction to Swiss program**
  - multiple passive barriers, role of the geological barrier, site selection process and criteria
- **Basis for a safety-driven site selection**
  - Host rock properties
  - long-term stability
  - reliability of geological information
- **Process understanding: example URL experiments** for the phases of the repository live-cycle
  - Construction/Operation/Monitoring + Repository induced effects
  - Canister lifetime
  - Gas migration
  - Nuclide migration

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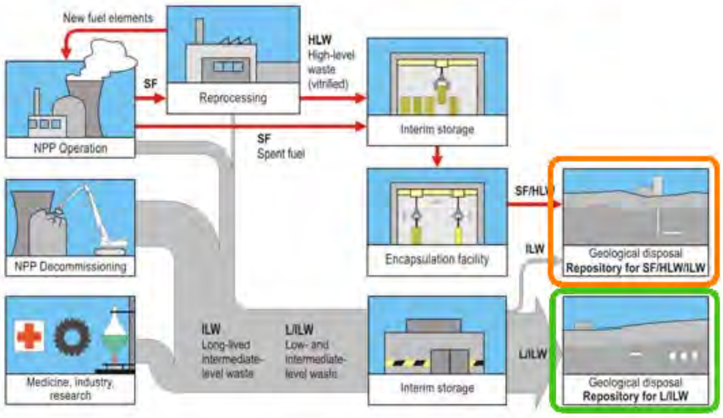
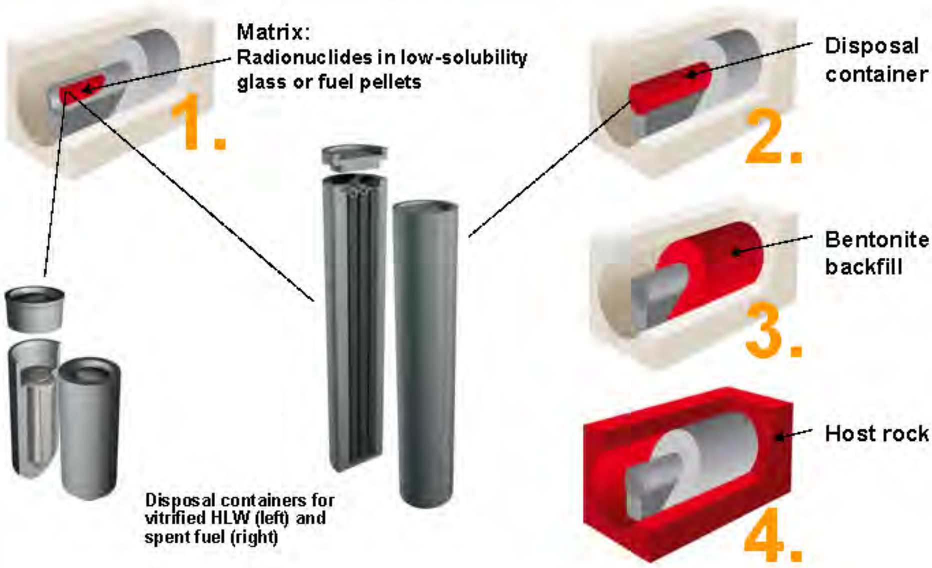
Swiss waste management concept



- Spent Fuel (SF) and vitrified high level waste (HLW) → HLW repository
- Long-lived intermediate waste (ILW) → HLW repository (co-disposal)
- Low and intermediate waste (L/ILW) → L/ILW repository

Concept with multiple passive barriers



Key requirements for deep geological repositories

Swiss legislation based on conclusions of EKRA commission in 2002 (incomplete list)

- **Geological disposal** for radioactive waste is the only viable option
- **Geological barrier** and **engineered barrier elements** both have to contribute to long-term safety
- **Pilot repository**: Monitoring of a small seperate but representative inventory allows to conclude towards development of repository and supports confidence building (geological barrier function must not be compromised by monitoring)
- **Retrievability** of the waste has to be technical feasible throughout monitoring phase

- site selection focus on contribution of the geological barrier over repository lifetime

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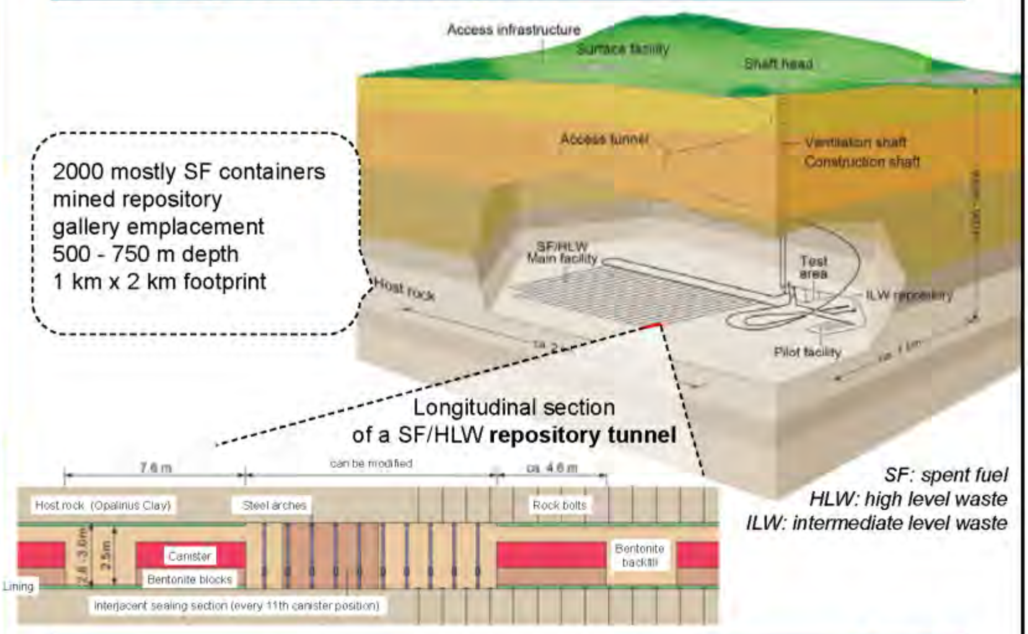
Swiss repository concept for SF/HLW



SF: spent fuel
HLW: high level waste
ILW: intermediate level waste

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Site selection: Safety criteria

Group of criteria	Criteria
1. Properties of host rock	1.1 Spatial extent 1.2 Hydraulic properties 1.3 Geochemical conditions 1.4 Migration paths
2. Long-term stability	2.1 Durability of properties 2.2 Erosion 2.3 Repository induced effects 2.4 Resource conflicts
3. Reliability of geological information	3.1 Characterisation of host rock 3.2 Spatial explorability 3.3 Temporal predictability
4. Suitability for construction	4.1 Rock mechanical properties 4.2 Underground access

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Identification of suitable geological situations for a SF/HLW repository (site selection)

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Clay rocks – the promise of a good repository

- Key arguments for safe isolation
  - clay rocks are generally impermeable
  - diffusion-controlled transport
  - strong sorption
  - self-sealing

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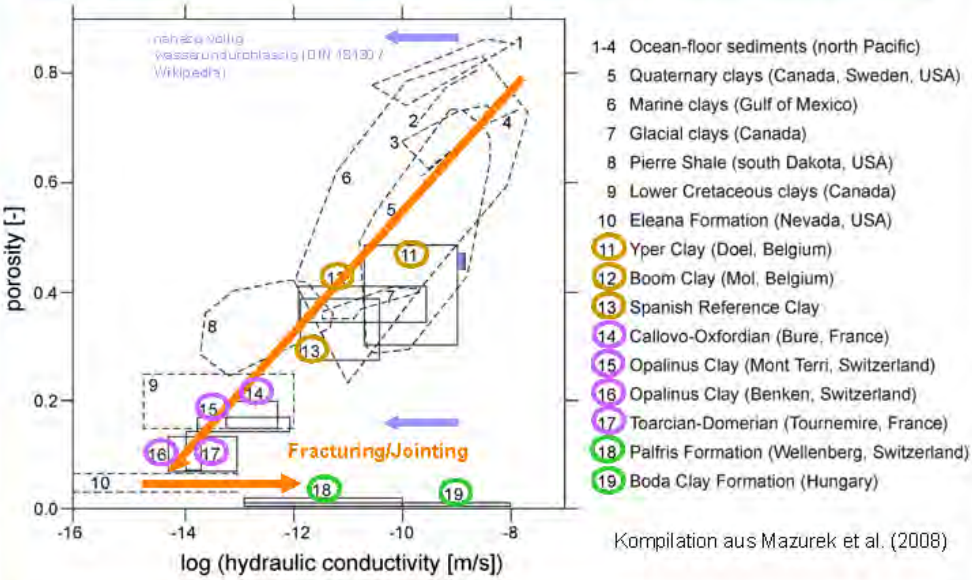
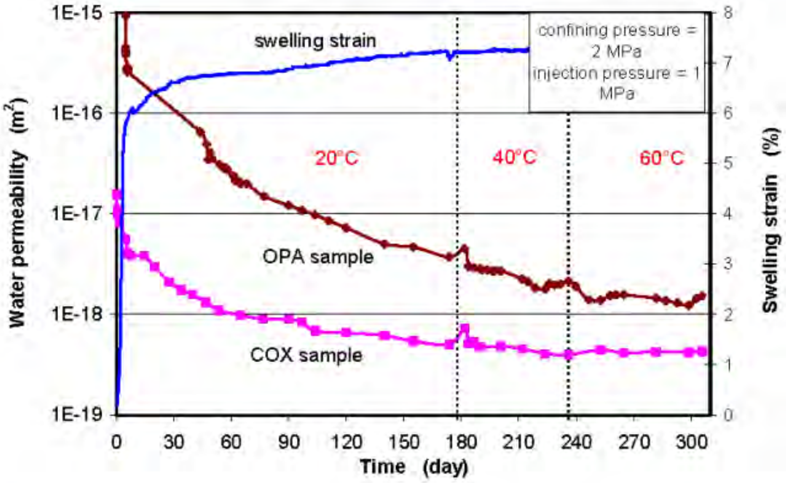
Rock properties – porosity / hydraulic conduct.



Kompilation aus Mazurek et al. (2008)

10 nagra

Long-term stability: Self-sealing of fractures



Zhang (GRS) (2009)

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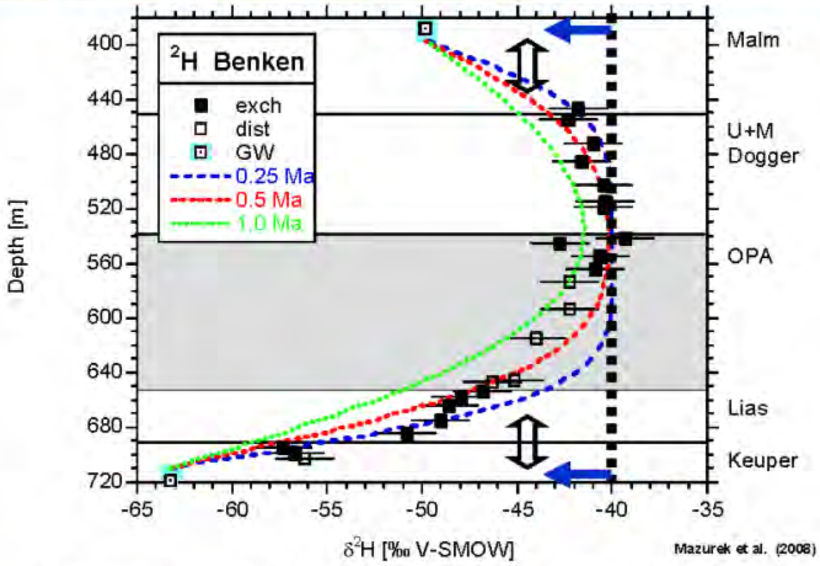
Diffusion-controlled transport



Mazurek et al. (2008)

Best fit simulations of profiles of δ^2H for the base case (pure diffusion, constant concentration at Keuper and Malm) and for a zero gradient upper boundary condition

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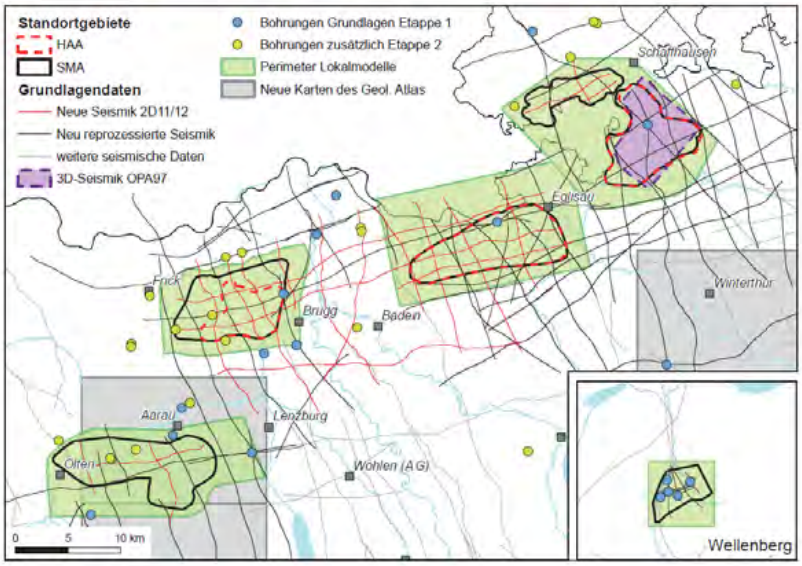
Reliability of geological information – data base



NTB 14-01

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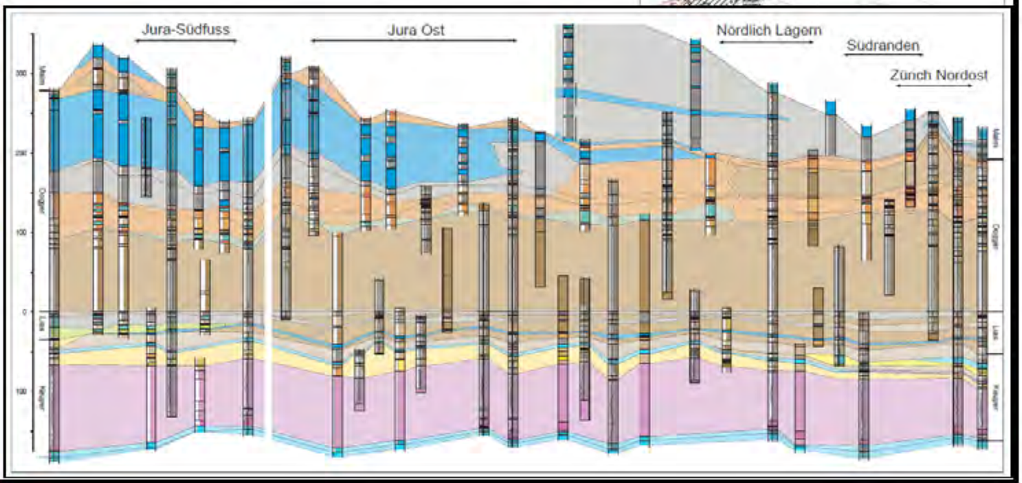
Reliability of geological information – borehole data

- rock profile (west – east);
- complete facies overview along 70 km section



Reliability of geological information – spatial explorability

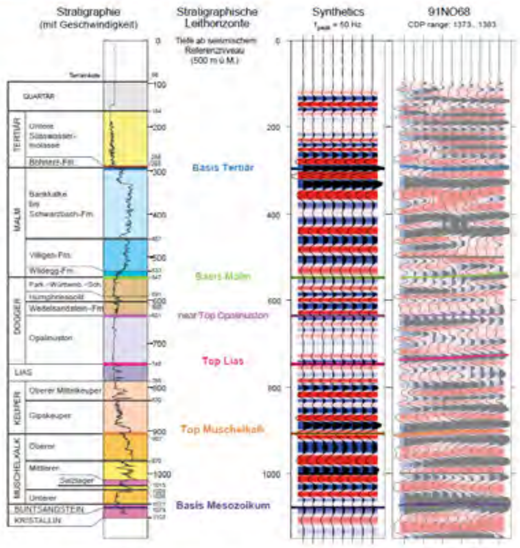


Fig. 3.3-2: Reflexionsbild des mesozoischen Schichtstapels am Beispiel der Sondierbohrung Benken (aus Meier et al. 2014).

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Available underground space ← seismic data

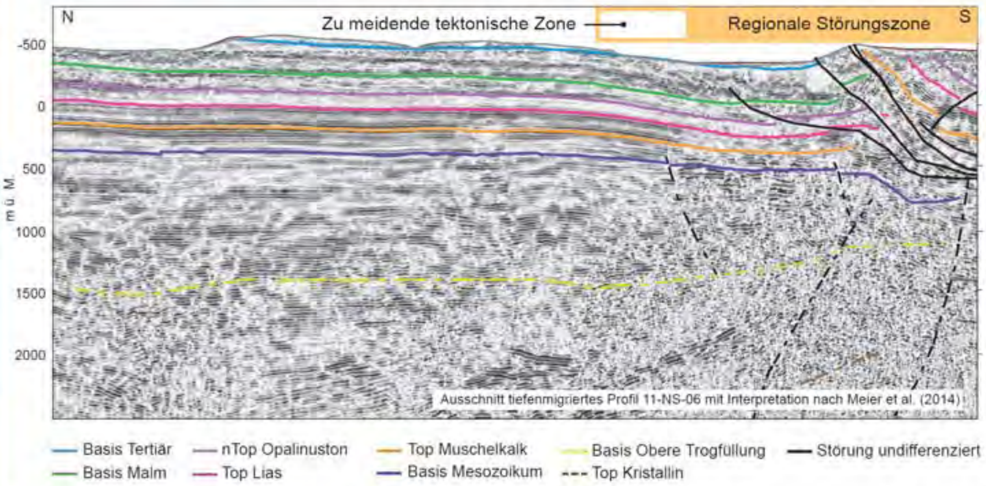

Fig. 4.4-6: Illustration der zu meidenden tektonischen Zone im Süden des geologischen Standortgebiets Jura Ost anhand von Schwere- und 2D-Seismikdaten.

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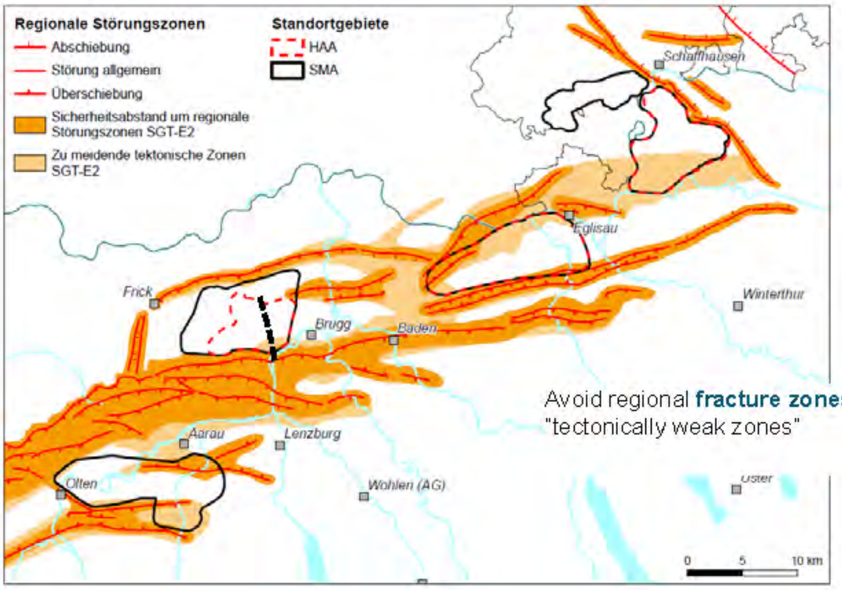
Available underground space ← tectonic zones



Avoid regional **fracture zones** & "tectonically weak zones"

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Available underground space ← final delination

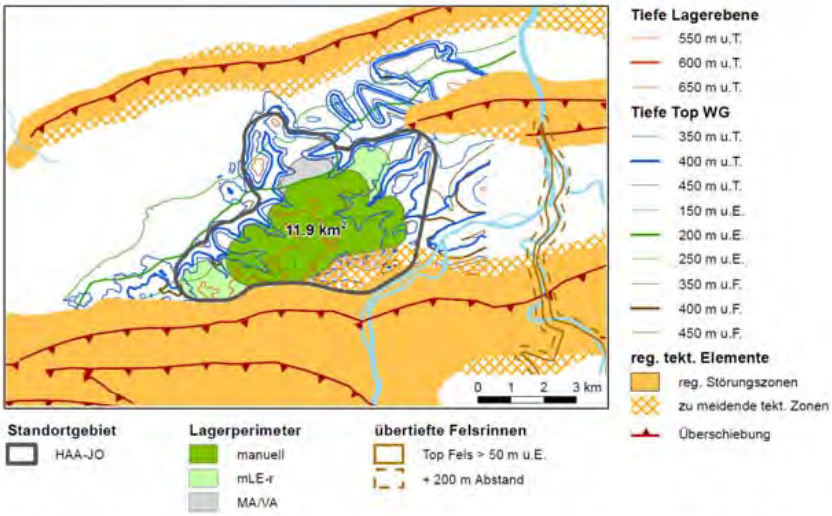

Fig. B.9-4: Lagerperimeter Jura Ost: Fall HAA-JO-mLE-r-manuell (massgebender Lagerperimeter für die Einengung, mLE), manuell optimiert.

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(Clay host rock and) site selection summary

- Clay rich formations such as the Opalinus Clay can contain radioactive waste for a long time due to:
  - Low hydraulic conductivity
  - Strong sorption
  - Self-sealing
  - Diffusion controlled transport
- Long-term stable siting perimeters can be delineated due to the good explorability of sedimentary basins in general and the Opalinus Clay specifically
  - The structure of the subsurface and the location of faults can be detected using normal 3D-seismic land surveys
  - Standard drilling technology allows depth control of seismic horizons and measurement of relevant properties as well as sample collection
- → data relevant for the siting process focussed on the geological barrier function can be collected with available standard technology
  - → reduces technological and financial risks
  - → supports acceptance

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Clay rocks – the other side of the coin

Barrier effectiveness provided by

- Low permeability
- Self-sealing
- Sorption
- Lateral und vertical homogeneneity

Side effects of high clay content

- Limited strength
- Anisotropy
- Limited thermal conductivity
- Low gas permeability
- Coupled processes

➢ **Preservation of favourable properties of the geological properties to be considered by layout and EBS**

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Demonstration of key processes and elements

URL testing

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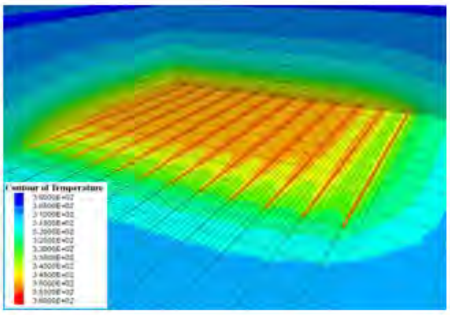
RIE* – identifying the critical constraints

- THM – managing thermal load – avoiding excessively high temperatures and pore water pressures
- H(Gas)M – ensuring that gas production rate is acceptably low relative to dissipation
- HM - controlled excavation and rock support
- HC – limiting chemical impacts – concrete (high pH)



*Repository Induced Effects

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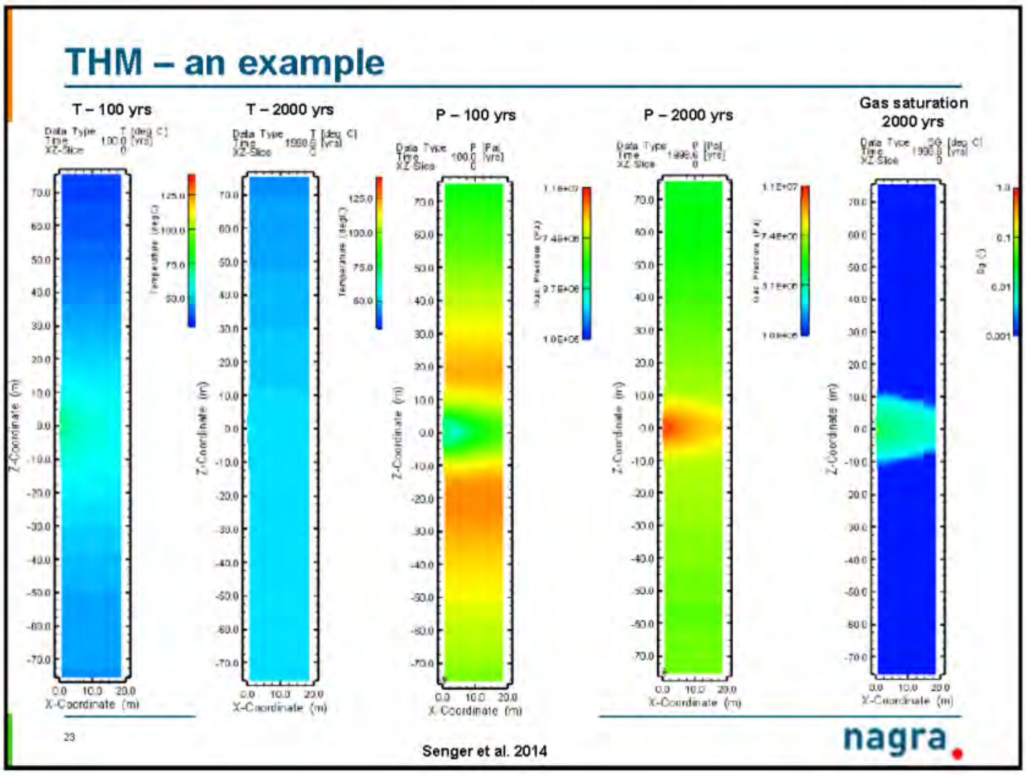
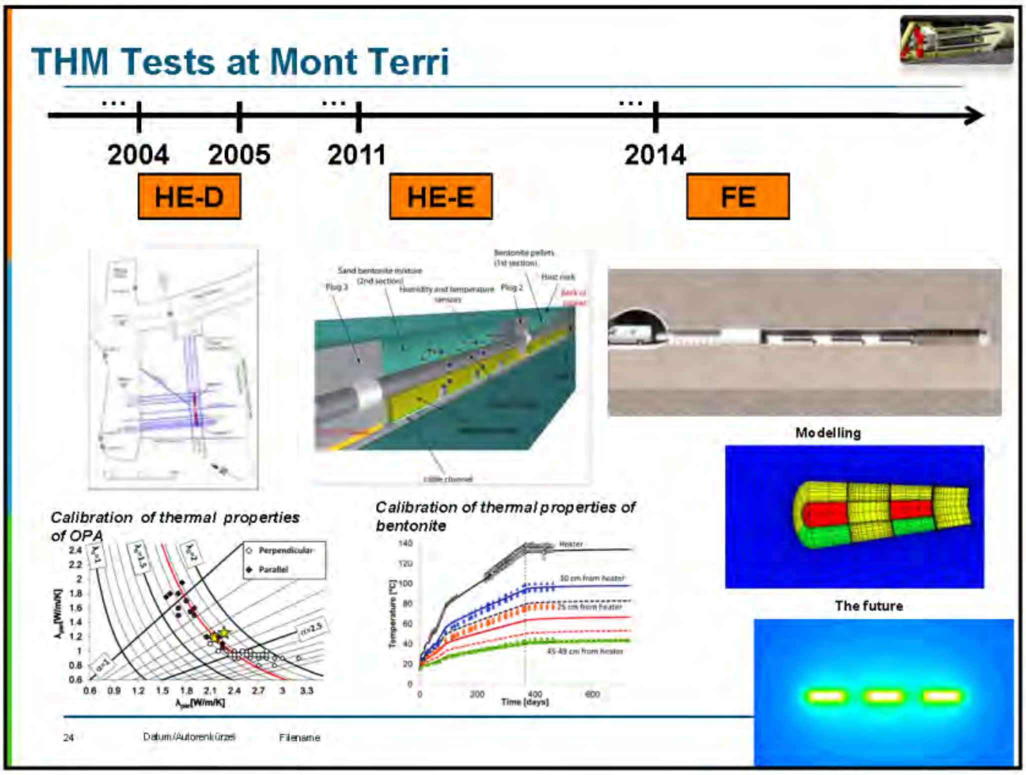
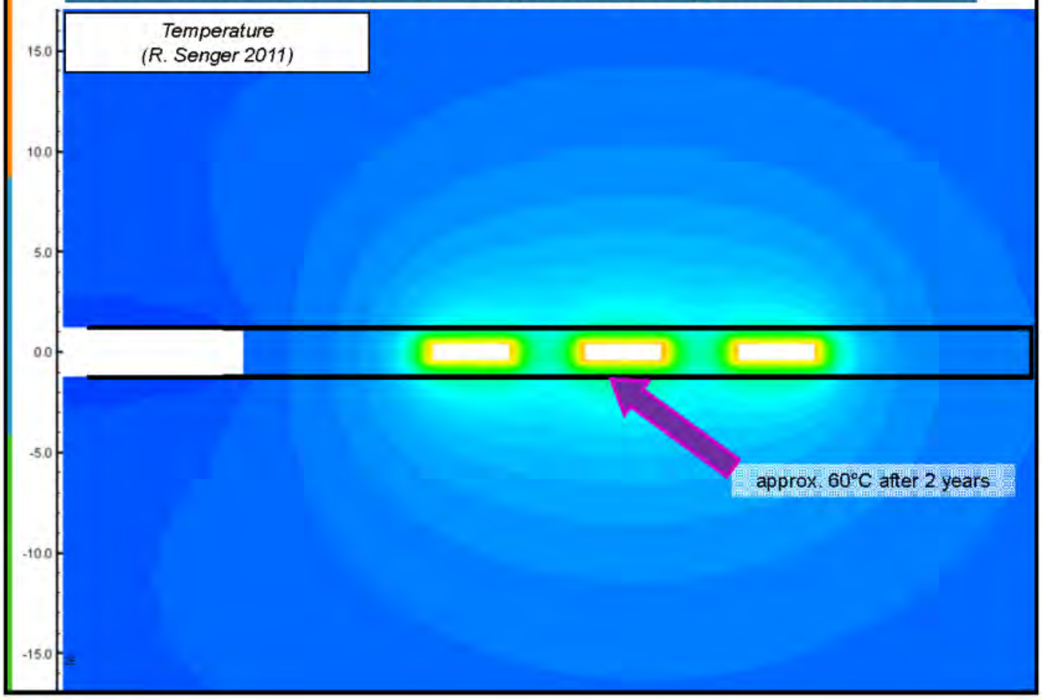

THM – an example
T – 100 yrs
T – 2000 yrs
P – 100 yrs
P – 2000 yrs
Gas saturation 2000 yrs
Z-Coordinate (m)
X-Coordinate (m)
23
Senger et al. 2014
nagra


THM Tests at Mont Terri
2004
2005
2011
2014
HE-D
HE-E
FE
Modelling
The future
Calibration of thermal properties of OPA
Perpendicular
Parallel
Calibration of thermal properties of bentonite
Heater
Time [days]
24
Datum/Autorenkürzel
Filename

Full-scale FE demonstrator aims

- **Full-Scale Emplacement (FE) Experiment** is a 1:1 full-scale heater experiment according to the Swiss concept for a spent fuel (SF) / high level waste (HLW) repository in a shale (Opalinus Clay)
  - FE aim: Investigation of repository induced thermo-hydro-mechanical (THM) coupled effects on the host rock and the bentonite backfill material
  - Tunnel construction
  - Bentonite material production
  - (Canister &) bentonite emplacement into a horizontal tunnel

Predictions for the FE Experiment @ Mont Terri



FE tunnel excavation

- FE tunnel: 50m long, ca. 3m diameter
- Pneumatic hammer and road-header
- Progress about 1m / day
- Detailed geological mappings (daily)
- Panoptic scans (ShapeMetrix)
- IR 3D scans (Kinect)

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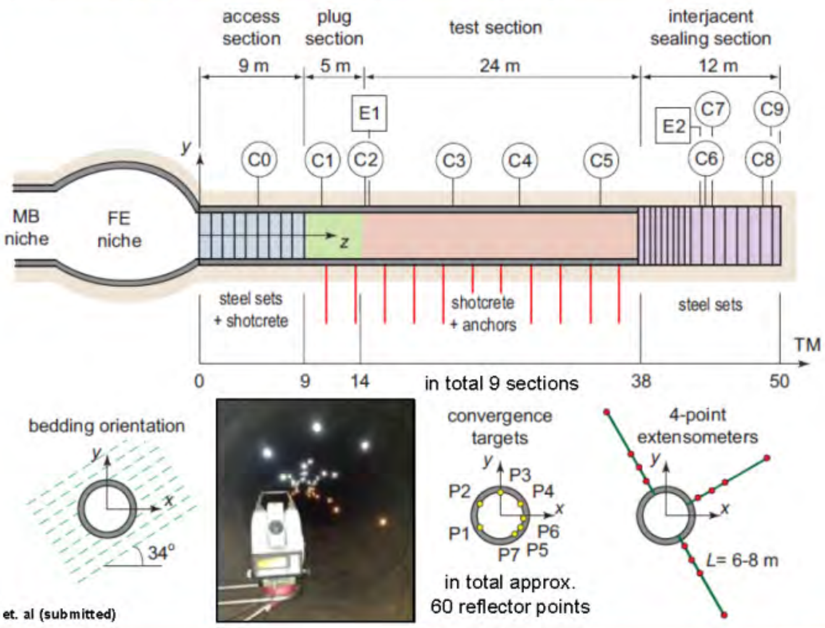
Monitoring «within» the FE tunnel



Lisjak et. al (submitted)

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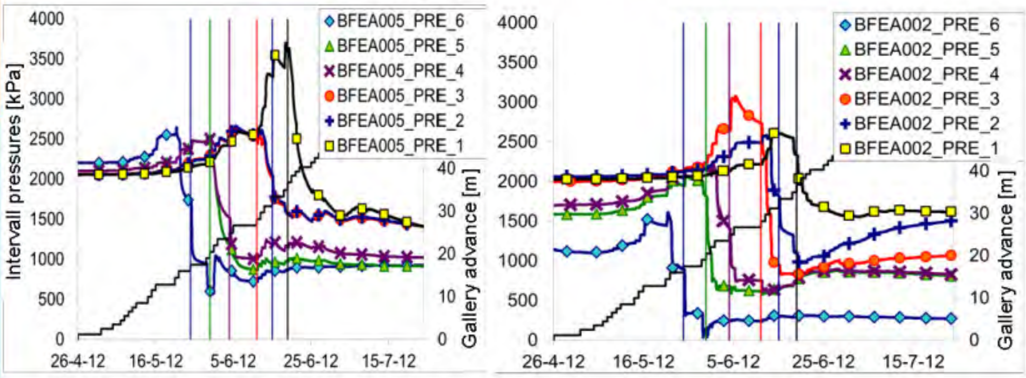
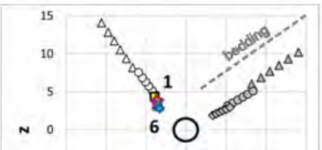
(Far-field) pore pressure evolution during excavation

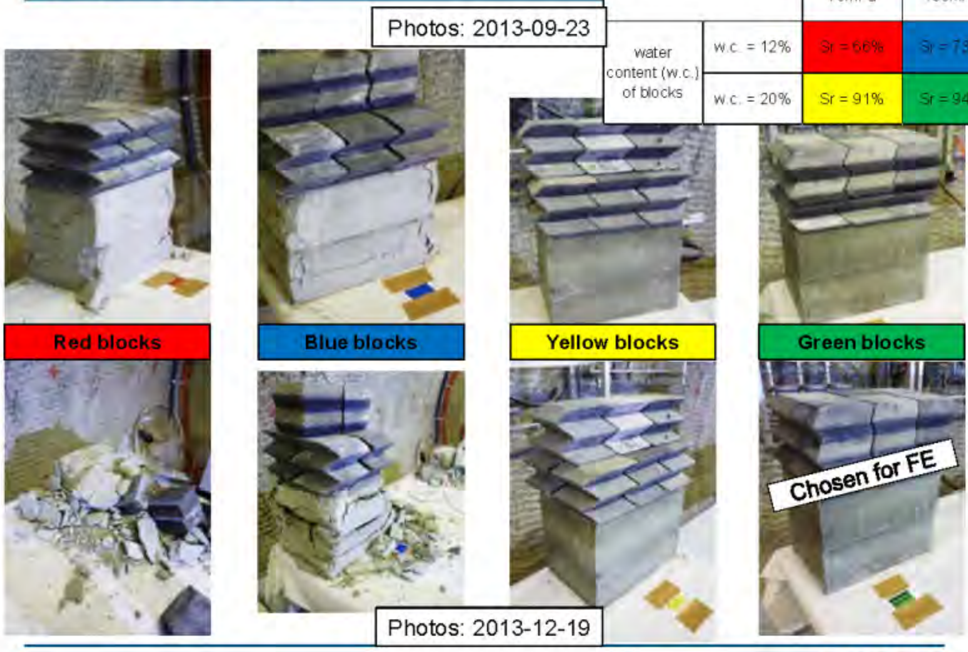




Cross section showing intervall positions; radial distance to gallery wall 2.3 – 4.4 m

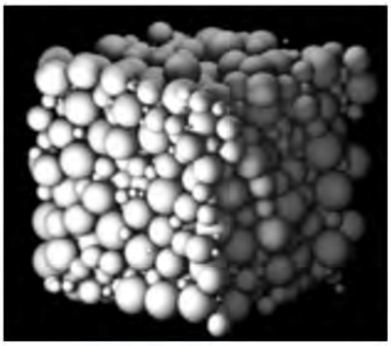
Bentonit-Blöcke

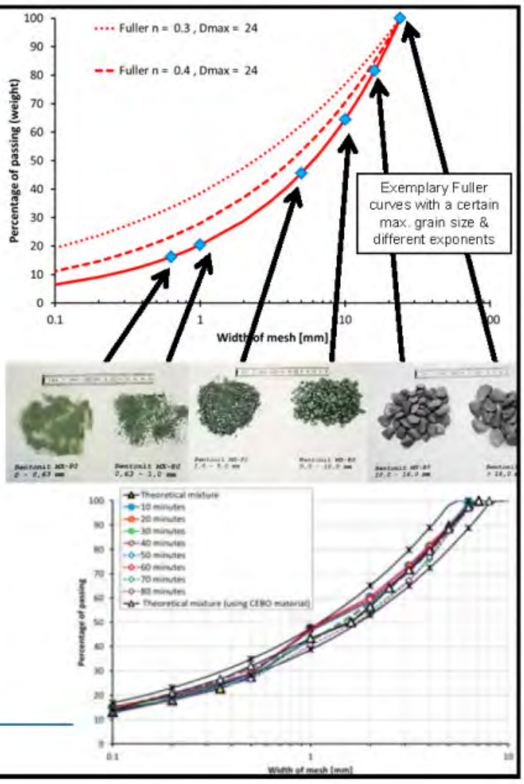
initial conditions (Sr = degree of saturation)		compaction pressure during block production	
		70MPa	130MPa
water content (w.c.) of blocks	w.c. = 12%	Sr = 66%	Sr = 73%
	w.c. = 20%	Sr = 91%	Sr = 94%



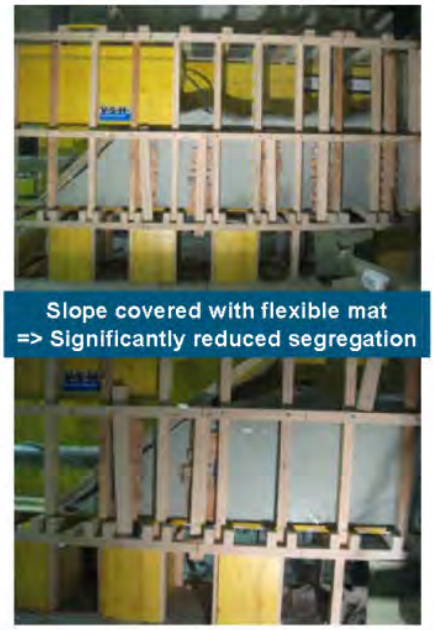
Granular Bentonite

- (highly compacted &) granulated bentonite mixture = (hc)GBM





Homogenity



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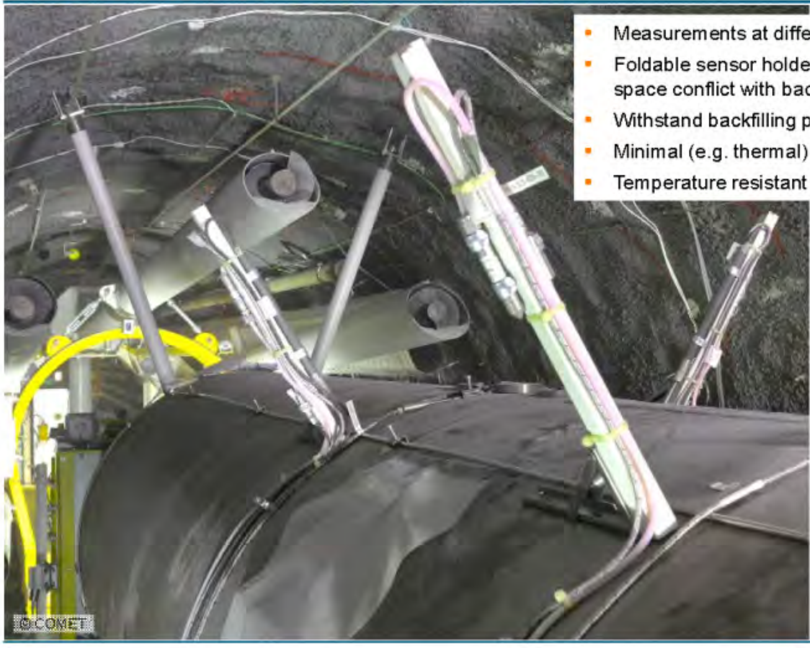
Instrumentation on the heaters



- Measurements at different depths
- Foldable sensor holders to avoid space conflict with backfilling machine
- Withstand backfilling pressure
- Minimal (e.g. thermal) disturbance
- Temperature resistant

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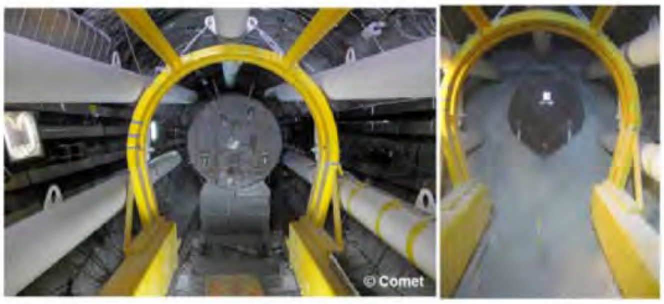
Backfilling operation

Backfilling machine passing under the gantry crane in the FE-A niche at Mont Terri

Front view of the backfilling machine in the FE emplacement tunnel



Backfilling machine with screw conveyors driving over the heater and its pedestal (left) and during backfilling operation (right)

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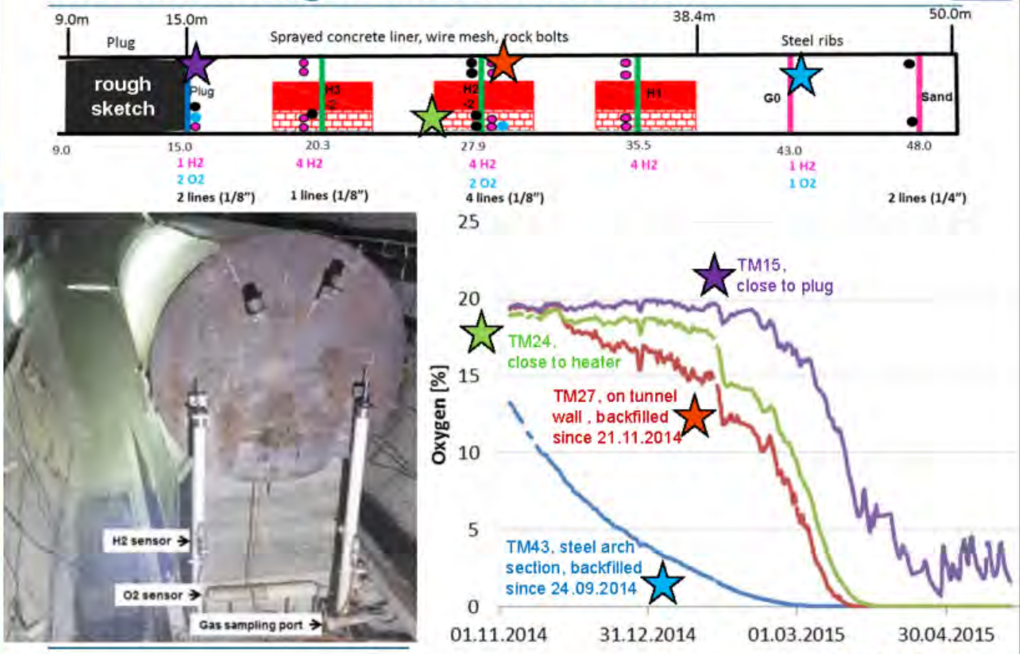
Gas monitoring in backfilled FE tunnel



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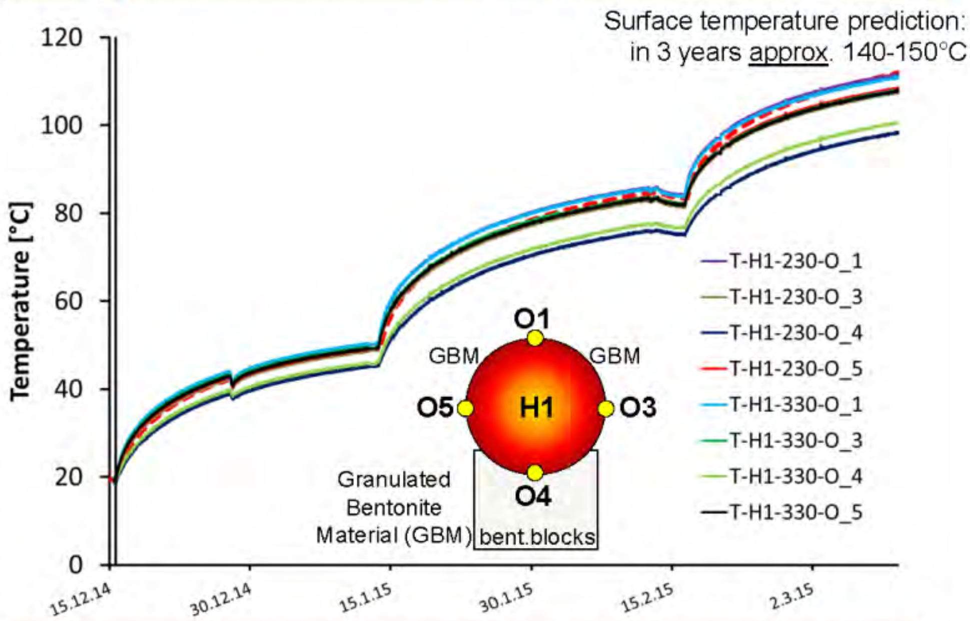
Heating started in December 2014



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Conclusions repository design

- Safety & system behaviour
  - clay rocks will confine waste for a long time
  - RIE need to be taken into account while designing the repository
- URL work allows to deepen understanding and demonstrate functionallity of repository elements under realistic conditions e.g.
- → the research and demonstration of repository design elements in a URL can be done using current technology
  - → reduces technological and financial risks
  - → supports acceptance

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Summary

- Significant progress made in site selection process over the last 7 years (since start of "sectoral plan")
- "Priority to safety" is broadly accepted (common denominator)
- Involvement of society through regional conferences & working groups successful (active co-operation)
- Key factors
  - Clearly defined stepwise process & criteria defined before start of site selection with
  - Stakeholders in general prepared to engage and work together (and to accept basic rules defined beforehand)
  - Importance of strong process owner to keep project on track
  - Broadly accepted technological excellence of implementor
  - Sufficient time available for the process

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5.2 Graf R.: Status of Cask Concepts for Disposal of Spent Fuel in Germany

Reinhold Graf*, Dr. Astrid Jussofie, GNS Gesellschaft für Nuklear-Service mbH,
*now: BKW Energie AG (CH) as of 1 October 2015

Wolfgang Filbert
DBE TECHNOLOGY GmbH

5.2.1 Basic Concept for Disposal of SF

Internationally, there is a consensus that radioactive waste, especially spent fuel (SF), is to be disposed of in deep geologic underground formations always relying on conventional mining solutions. The first steps to prepare a concept for a repository for radioactive waste were already taken in the 1950s. In Germany, salt was preferred as host rock from the very beginning. So, the technical developments concerning treatment and packaging of SF and site exploration focused mainly on salt as host rock, but clay is still being investigated as an alternative and has been taken into account in various aspects. The main principle of a disposal mine is shown in Fig. 5.2.1. With salt as host rock, the waste would be disposed of at depths of about 800 – 900 m; with clay as host rock, it would be disposed of at depths of about 300 – 500 m.

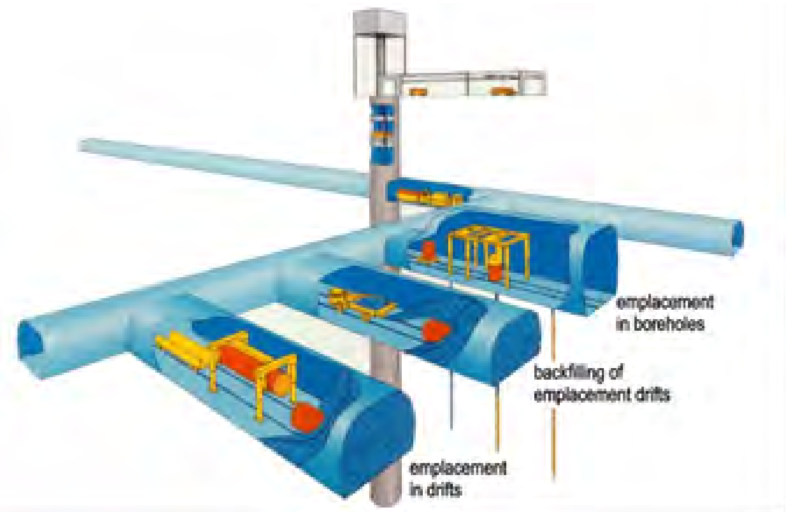

Fig. 5.2.1 Basic repository concept

The casks have to be loaded in an aboveground treatment facility with radioactive waste or spent fuel, transported to the shaft, hoisted down in the shaft (alternatively via a ramp) and transferred underground in drifts to the exact locations of emplacement. These may be drifts or purpose-made boreholes. This basic emplacement process is the result of the mining experience gained over centuries. The conventional mining solution allows to put very heavy mechanical loads onto hoisting and transport systems. Although this shaft hoisting technology has been available for a while, it had to be improved further for the handling of heavy casks.

So far, three concepts have been developed in Germany for salt as host rock (Fig. 5.2.2). Two of them – the so-called reference concept POLLUX® and the BSK3 concept have already been tested aboveground in extensive full-scale handling testing programs. The third – called DIREGT concept – has been developed on a conceptual basis. It comprises the hoisting, transport, and emplacement of very large and heavy CASTOR® casks. The further investigation of this concept could be started with full-scale aboveground handling tests.

In the meantime, all concepts have been checked conceptually for retrievability, as it has recently been required in Germany. The following chapters concentrate on the cask concepts instead of describing handling concepts and requirements for aboveground and underground conditions. To gain more insight into the whole disposal systems see /GRA 09/ /GRA 10/ /BOL 11/ /GRA 12b/ /GRA 12a/ /BOL 13/.

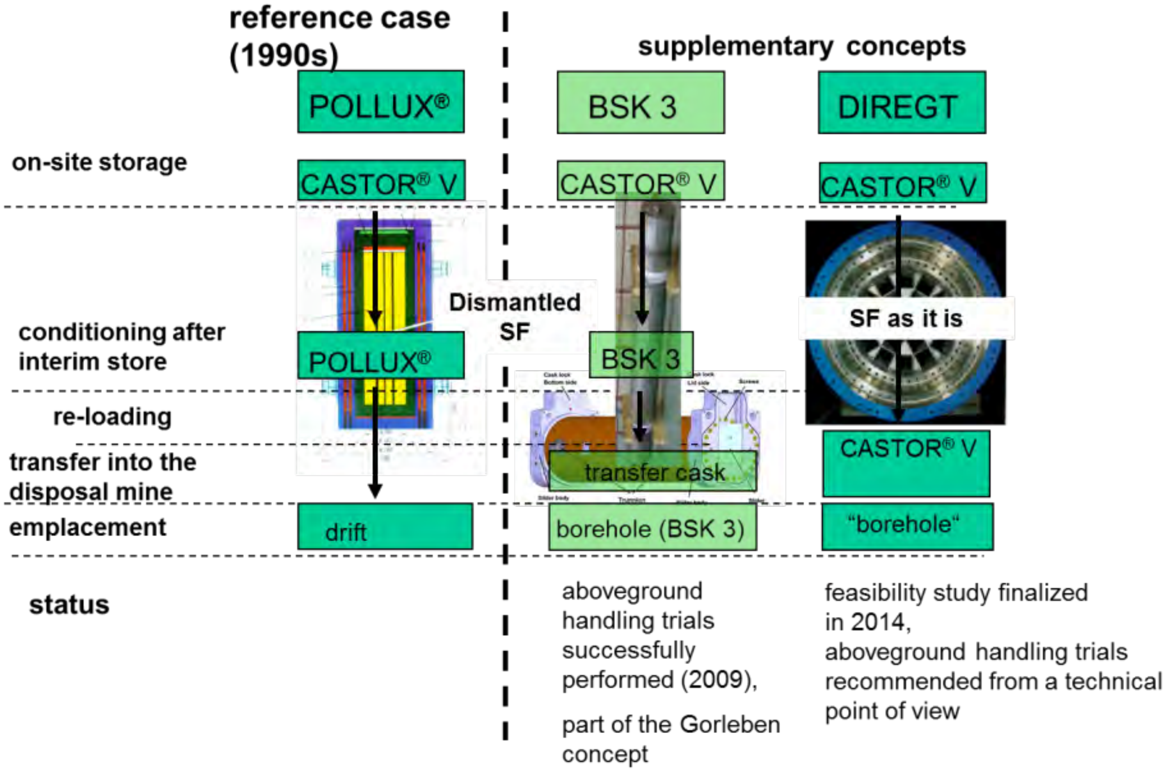

Fig. 5.2.2 Concepts for the disposal of SF in Germany

5.2.2 Spent Fuel Arisings in Germany and Casks Used for Transport and Storage

According to the Atomic Energy Act, nuclear power plants will be operated until 2022 at the latest. Currently, reprocessing of SF is no option so that at the end about 10 000 MgHM, representing about 13 000 SFA from PWR and about 17.000 SFA from BWR, will have to be disposed of. Until their emplacement into a repository, they are stored aboveground in about 1 000 casks of the CASTOR® type.

Reprocessing of SF was allowed until 2005 and will result in about 8 000 canisters filled with various categories of waste that will be stored in about 290 casks of the CASTOR® type (see Fig. 5.2.3).

Additionally, smaller casks with SF from smaller plants and from research reactors have to be taken into account, i.e. up to about 460 casks of the CASTOR® THTR/AVR type and approx. 50 casks of the CASTOR® MTR type (see Fig. 3).

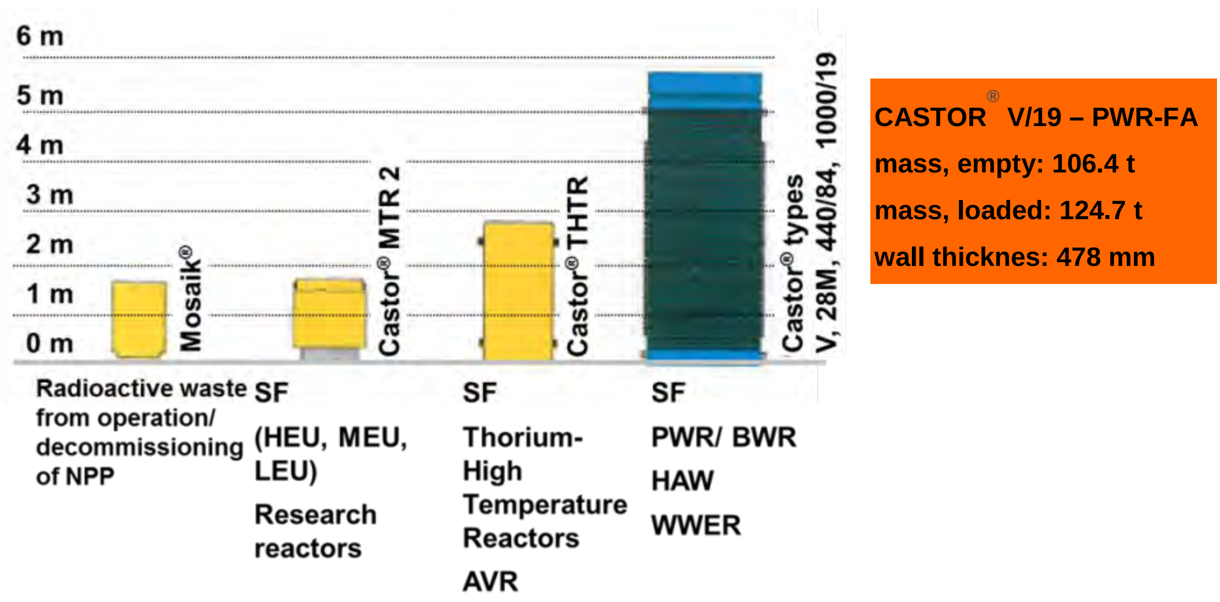

Fig. 5.2.3 Typical casks for radioactive waste and SF

5.2.3 POLLUX® concept for spent fuel

The current POLLUX® reference concept for the final disposal of irradiated fuel assemblies is based on the dense packaging of fuel rods in a POLLUX® cask. Therefore, it requires a conditioning facility where the fuel rods can be separated from the structural parts of the fuel assembly. A POLLUX® cask would include the fuel rods from 10 SFA from a PWR (in total about 5 Mg HM). Its total weight is up to 65 Mg (Fig. 5.2.4), the height about 5.5 m and the diameter (with trunnions) about 2 m. For the disposal of 10 000 Mg HM, about 2 000 POLLUX® casks would be needed.

There are also concepts from the 1980s to use POLLUX® casks for canisters from reprocessing. About 900 – 1 000 POLLUX® casks would then be needed additionally.

POLLUX® casks are to be emplaced in the drifts of the disposal mine and directly afterwards, the drifts will be backfilled with crushed salt.

The licensing documents according to the regulations of the Atomic Energy Act and the transport regulations (type B(U)F) were submitted to the competent authority at that time but later withdrawn because reliable design requirements could not be identified. The reason was that the exploration of the Gorleben site was interrupted so that waste acceptance criteria were not available. As a consequence, POLLUX® casks neither have an approval certificate nor a storage license.

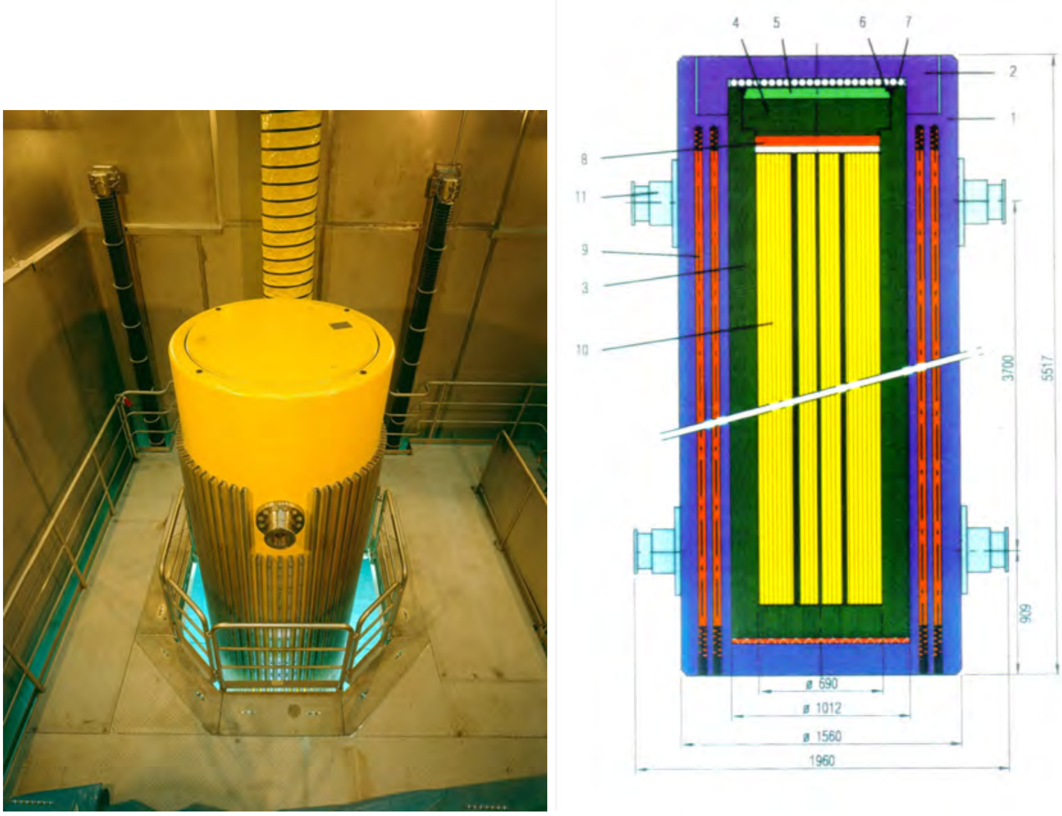

Fig. 5.2.4 POLLUX® cask

5.2.4 BSK3 concept

Supplementary to the POLLUX® concept, it was planned to stack waste from the reprocessing of SF into vertical boreholes drilled from the repository galleries. Vitrified HLW and other waste from reprocessing (Fig. 5.2.5) are to be disposed of in up to 300-m deep, unlined vertical boreholes with a diameter of 0.6 m. The diameter of these boreholes is slightly larger than the diameter of the waste canisters (43 cm). Up to about 150 - 200 canisters (height about 1.35 m) could be stacked into one borehole.

This concept was further extended for the disposal of BSK3 canisters and tested at full scale to reach the same degree of technical maturity as gained with the POLLUX® concept. Each BSK3 canister (Fig. 5.2.5, Fig. 5.2.6, Fig. 5.2.7) would contain about 0.6 Mg HM and weigh up to 5 Mg in total. The SF arisings would result in a total number of 7 000 BSK3 canisters. The dimensions of the BSK3 canister would enable the loading of three waste canisters from the reprocessing of SF.

The concept – for SF as well as for waste canisters from reprocessing – would require shielded transfer casks, with dimensions and masses in the range of the POLLUX® cask. Thus, about 10 000 transfer cycles would be needed to transfer SF and canisters with reprocessed waste from aboveground to the borehole for emplacement.

The concept needs a strong focus on radiation protection aspects because the canister itself must be shielded in each handling step.

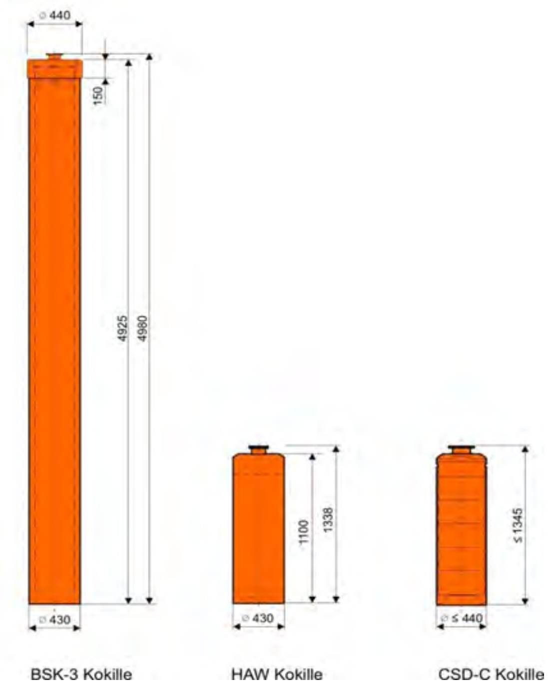

Fig. 5.2.5 Dimensions of canisters for borehole emplacement

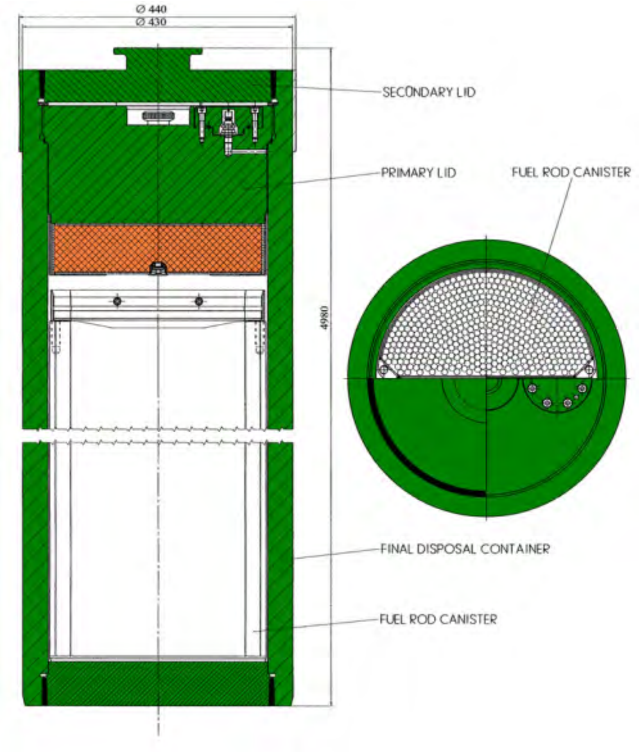

Fig. 5.2.6 Conceptual scheme of the BSK3 canister

Fig. 5.2.7 Mock-up of the BSK3 canister as used in the full-scale handling tests

Fig. 5.2.8 Full-scale handling test equipment for the BSK3 concept

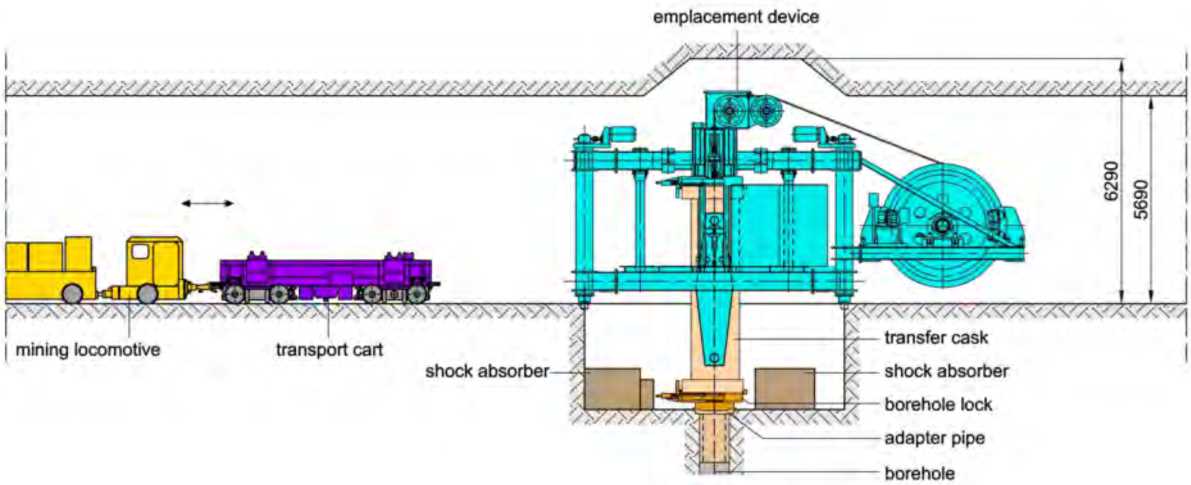

Fig. 5.2.9 Scheme of the full-scale test equipment for the BSK3 concept

5.2.5 DIREGT concept

Just recently, GNS and DBE TEC have successfully concluded a concept for the direct disposal of large transport and storage casks (DIREGT concept). It allows the direct transfer of CASTOR® casks (Fig. 5.2.10) from the surface to underground. With this concept, SF could be disposed as it is without any disassembling actions as required in the POLLUX® reference concept. It minimizes the number of transfers from the surface and the number of handling procedures in the disposal mine. In case of the DIREGT concept, the evidence of criticality safety has to be provided for the assembled fuel bundles as a whole due to the requirement that the criticality safety has to be guaranteed for 1 Mio. years (for any repository/disposal concept) as stipulated in the safety requirements /BMU 10/. For a generic proof of subcriticality, the loaded CASTOR® casks have to be filled with inert materials, e.g. magnetite /CHE 12/. Consequently, the deployment of a hot cell will also be necessary for that purpose. However, the hot cell design for the DIREGT concept will be less complex compared with those of the POLLUX® or BSK3 concepts, where disassembling actions are unavoidable. From a technical point of view, the DIREGT concept is ready for full-scale testing above-ground.

Fig. 5.2.10 CASTOR® V/19-cask

Each cask loaded with SF assemblies contains about 10 MgHM; the cask height is about 5.5 m and the diameter (with trunnions) about 2.5 m. Due to additional mass from the filling material, the cask mass would be in the range of 160 Mg if the casks are intended for the disposal of SF assemblies.

In total, about 1 300 casks of the CASTOR® type would be needed for the disposal of SF and waste from reprocessing.

5.2.6 Concepts for host rocks other than salt (clay, granite)

Some basic aspects are summarized in Fig. 5.2.11, compared with salt as host rock. With clay or granite, the content per waste package in terms of heat and waste mass has to be lower than with salt. In principle, this condition can be met by using smaller packages with lower content or extended cooling times prior to disposal.

- Clay (compared with salt):
  - Less heat output per waste package allowed, may be reached by
    - longer cooling times aboveground
    - less inventory per waste package, resulting in more transfer packages/disposal casks and more transfer actions
  - Cross sections of drifts smaller than in salt
    - POLLUX® concept, BSK3 borehole concepts: seem to be manageable in principle (see DBE TEC), adaptations needed (e.g. depth of boreholes, inventory)
    - DIREGT concept: to be checked whether technically feasible
  - Inventories that might be possible for clay
    - POLLUX: up to 4 PWR-FA
    - BSK3: up to 3 PWR-FA (or fuel rods)
- Granite (compared with salt): nearfield of the cask with “clay“
  POLLUX® range; CASTOR® technically feasible, probably more mining efforts

Fig. 5.2.11 Basic aspects for a repository in salt compared with clay and granite

5.2.7 Summary

Cask concepts for the disposal of SF – as complete SF assemblies or after disassembly into SF rod and structural parts – have been developed in Germany with a focus on salt as host rock. The casks are mechanically and chemically stable for several hundreds of years and bridge the time until the host rock ensures the safe enclosure of the waste. Aspects of retrievability and recovery as recently under discussion are taken into account.

The safe handling of casks or containers of any size (from 5 Mg up to 65 Mg) have been shown in full-scale test programs. For larger casks (up to about 160 Mg), a very promising concept has recently been developed, which is ready for full-scale testing from a technical point of view.

Based on a mining approach, borehole technology has been tested for waste packages with masses of about 5 Mg and boreholes with a diameter of about 60 cm – 100 cm, drilled from the repository gallery. The borehole depth would range up to 300 m. Drilling and emplacement itself would be operated in a fully dry manner.

Reducing "net loads" of waste packages would result in an extremely increasing number of handling and transfer steps so that efforts have been made to minimize the handling and transfer cycles.

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6 Recovery (Rückholung/Bergung)

6.1 Prevedel P.: Fishing & Retrieval Technology

Bernhard Prevedel, GFZ-Potsdam

6.1.1 Deployment

6.1.1.1 Applications of deployment

In the majority of the borehole applications, the temporary down-hole deployment of equipment happens after finishing the drilling or at completion of a borehole to a production well. Such installations could include production hardware, i.e. flow restriction valves, packers or sieves or on the other hand also measurement instrumentation for the monitoring of the down-hole conditions during a limited production period. They are designed to be recovered after a certain time period from the borehole for scheduled replacement, repair, data retrieval or power re-charge.

The size, complexity and value of the installed equipment are typically the driving factor for their mode of deployment and such an operation can vary from few hours duration to a several days lasting well intervention /JOH 12/.

6.1.1.2 Methods of conveyance

A deployment or conveyance system is the means to transport a down-hole tool or measurement instrumentation in and out of a borehole. It also serves as its power supply and data umbilical to the surface. The most common and versatile way to deploy borehole instrumentation is by means of a cable or wire line coming off a winch. The benefit of a wire line operation lies in its independency from any rig or special surface installation. It requires typically only a tripod over the wellhead or sometimes a crane if long tool strings have to be handled (Fig. 6.1.1).

Wire ropes and slick line cables are the simplest well servicing devices and come in sizes from truck mounted winches with several 1 000 m cable length to small hand portable winches with a few hundred meters. But they do not have any electric conductor and were used in the past primarily for the installation of mechanical measurement devices or memory gages.

Complex surface powered electronic arrays or fiber-optic sensors systems could also be deployed via a wire rope by clamping their non-armoured Polyurethane data cables to the rope line. Rigid clamping needs to occur in discrete intervals minimum every 15 m in order to sufficiently support the weight of the Polyurethane cables and avoid slippage along the line and to prevent cable tear /PRE 15/. Careful planning and calculation of weight, buoyancy and cable tension, combined with frequent selection of clamping intervals and enough installation time is a good basis for achieving best results.

Armored electric cables were originally developed for electric wire line logging under very harsh conditions in the oil & gas drilling industry. Their design typically consists of two components, the mechanical outer armor and the electrical core. The armor consists of two layers of counter-helically twisted steel wires. Inside is a core of individually insulated conductors (copper lines) wrapped in a plastic coating. For special sensors, armoured electric cable can also be augmented by a small metal tube containing typically 3 or 4 fibre-optic leads /THO 85/.

To relief expensive drill rigs from production well work-over the oil & gas industry supported the development of a steel material suitable as endless production tubing stored on a reel, called coiled tubing (CT). This tubing is made from a highly ductile steel alloy that recovers its initial strength even after being plastically deformed beyond yield. But it is also a material that has a greatly reduced breaking stress level at very much reduced fatigue cycles compared to high graded steels. Therefore the number of cycles (off/on reel motion), combined with the additional stress in the material from axial loads and internal/external pressure needs to be carefully monitored for each CT unit in the field to avoid material fatigue and failure in the hole. Hence, a CT well intervention is also a heavy and expensive operation equivalent to a mid-sized drill rig /ROD 98/ (Fig. 6.1.1).

In horizontal and highly deviated wells greater than 60 degrees from vertical borehole instrumentation cannot be deployed on a standard wireline any longer and special pipe conveyed techniques are necessary to deploy tools down-hole. In long high angle and horizontal open-hole sections even the CT has a tendency to helically lock, if the friction force exceeds downward thrust and the CT then behaves under loss of compressive strength like a wire rope. In such conditions, the only further option is conveyance on drill pipe or production tubing. Especially when there is risk of stuck in hole, then this rig assisted mode of conveyance should be selected (Fig. 6.1.1).

Fig. 6.1.1 Wireline unit for logging or fishing on cable (left, a coil-tubing unit for well work-over and fishing with CT pipe (center) and a 1 million pound hook load capacity „heavy“ oilfield drill rig for drilling deep boreholes and fishing with pipe (right)

6.1.2 Retrieval

6.1.2.1 Fishing applications, conditions and techniques

It does not make a difference for a retrieval operation if a piece of lost hardware – a Fish – is deliberately or accidentally brought into that borehole position. To bring him safely back to the surface is in any event a critical operation and requires careful planning and development of contingency plans if one rescue avenue may not work.

Tools that are planned to be deployed in a borehole have to be exactly measured and documented for their shapes and dimensions before such equipment goes into a borehole. In addition they have to be designed with a suitable latch-on catching device, or best with several such systems, if one mode of catching does not work.

Likewise, service equipment lowered into a borehole, like drill pipe, service tools or wireline sondes, have also to be designed and build in a way, that in the event of an unplanned stuck in hole situation, those devices part at a predefined location and that the tool body as such offers at top fish a long enough freely accessible and defined pipe section for the grabbing on with catching tools (Fig. 6.1.2).

Fig. 6.1.2 Overshot catcher with spring supported mechanical claws for deployed instrumentation in cased borehole sections (left), Overshot bell with spiral catching springs (center) and taper taps (richt both for openhole fishing

Fishing tools differentiate themselves between those which catch the fish on the outside (overshots) or in the inside (taper taps). Overshots carry inside their bell a special designed latch-on device and/or a catcher spiral that moves over a catching surface in downward motion and tighten around the fish when pulled upwards. Taper taps and grapples are another choice if overshots will not work. They represent big thread cutters which cut into the inner diameter of the fish body with right-hand pipe rotation from surface so that a firm connection between the fish and the fishing string can be established. Both types of catchers support mud circulation through the fish, if this is required to free the fish. There are further specialized fishing tools like darts for the fishing of lost cable or wash-over pipes for freeing differentially stuck pipe from the borehole wall /SCH 12/.

Knowledge about the location as well as position of the fish vis a vis the borehole axis is of critical importance with respect to retrievability. Fishing in a cased borehole environment is usually good defined and results in most of the cases in a successful borehole operation. Fishing in open-hole conditions is always an emergency operation and a race with time, as the geology will have a tendency to close in on the fish with time, hence probability of success will diminish rapidly.

The anticipated and needed degrees of freedom of movement down-hole for the latch-on and freeing of a fish will drive the selection of the surface equipment to be employed for the operation. Cables and CT offer only one freedom of movement and pipe offers two, axial and rotational. Deliberately down-hole deployed tools in a cased-hole section are most often successfully latched-on and retrieved to surface with a custom made catcher run on a wireline. Their catching sequence requires typically only one degree of freedom in the axial direction, - up and down. Electric power supply to positively lock the catcher for the out-run or confirmation of positive catch is desirable, but not mandatory.

Accidentally lost tools down-hole may likely have their designed latch-on device damaged and might also have lost their centric position in regard to the borehole axis. Such fishes need to be inspected by a reconnaissance wireline logging prior to the start of the fishing operation. Depending on this logging result a decision will be taken which mode of fishing operation is best to be selected. In many cases a first fishing attempt will be performed with a wireline run. If this is not successful, then coil tubing or a work over rig will have to be mobilized to catch the fish with a pipe string.

Loss of equipment in an open-hole section is frequently associated with a drilling or a completion operation and represents always a repair situation, which will require the employment of a drill rig with drill pipe and mud circulation in order to assure best success in this fishing operation /JOH 12/, /SCH 12/.

6.1.2.2 Emergencies and risk management during fishing operations

The procedure of catching and retrieval of a fish can generate a substantial strain on the borehole, e.g. in the form of a pressure surge that can trigger an unexpected reaction in the borehole construction or the formation. Such events are always highly undesirable, as they can change the plan of operation significantly up to the point that they could disqualify the selected fishing mode and reduce the chances of success significantly.

In particular for gas bearing formations, pressure imbalances during a fishing operation can suddenly bring pressure neutral wells back to life. Therefore in gas provinces, special attention has to be given to borehole blow-out hazards during any borehole fishing operation. Specialized pressure control equipment is available for any kind of well intervention, like for wireline, CT and pipe and has to be considered already in the planning phase.

Fishing in particular with drill pipe can also create damage to the other installed equipment in a borehole and to the casing itself. If not run very careful the sheer weight of the fishing string can very easily break components down-hole or rupture the casing wall.

If planning time permits a detailed risk assessment matrix (RAM) combined with a risk management (RM) process, as well as an operational work flow diagram with contingencies have to be developed and adhered for every fishing operation in a borehole.

The RAM identifies all the operational steps for which a certain risk category can be identified in the form of the probability for an event and its severity of impact. The RM process asks for each of the unacceptable risk categories an avoidance action plan, incl. the associated cost for the individual mitigation efforts. After mitigation a residual risk exposure can be defined, which should avoid for the entire planned operation any non-acceptable risk conditions /WEA 01/.

The RAM has further to be extended to a variety of alternative operational approaches and contingencies, because the initially planned procedure can change during a fishing operation at any time. Fishing crews will need to be open and flexible to “alternative” operational approaches and have to have the freedom to switch procedures without having to scarify work safety.

6.1.2.3 Hazards during fishing

As with any well intervention, there is the potential of hazards arising during a retrieval operation, which could require the employment of additional services and technology. The most common things which can “go wrong” during fishing are the inability to access the top of fish, the risk of getting stuck with the catcher, hence having two fishes in the hole, the hole collapsing on the fishing assembly, therefore being unable to return with the fish to surface and the risk of losing the fish on its way out of the hole /SCH 12/, /WEA 01/.

Losing a catch on the way out is one of the most critical hazards that can happen during a fishing operation, as it is always followed by a crash of the fish to the bottom of the hole, resulting inevitably with the loss of its mechanical integrity. Consequently the fish is then often not fishable any longer and abandonment procedures will have to step in.

Therefore, greatest care and all effort needs to go into the direction, that when the fish is “on the hook”, there is no thinkable way that the fishing assembly could be losing this cargo, except by active intervention from surface.

6.1.2.4 Cost of fishing

The condition of the borehole and the confirmed integrity of the fish down-hole will drive the mode and type of fishing equipment contracted on location and the daily cost involved.

Wire line and cable operations involve only a limited amount of personnel on location and do usually not require any special legal permit to perform that work; hence it represents the least expensive of all available fishing methods.

CT and a work-over rig is a full 24 hours per day and 7 days a week (24/7) well intervention with significant costs involved. Such an operation can cost between € 50k and € 100k per day. For that reason, drilling operators usually entertain the effort to recover a fish only for a limited time period, before they reach a point of no return, where the cost of fishing is exceeding the value of the lost equipment down-hole. Therefore, the time available for fishing will not be endless, unless the value or the danger arising from the fish is infinite. There will usually be a cut-off point for fishing set before such an operation starts, at which it is better to abandon this operation and proceed with an alternative plan.

It follows the formula $D_f = (V_f + C_s) / (C_f + C_d)$, where D_f is the number of days allocated for fishing, V_f the value of the fish, C_s the estimated cost for sidetracking the well, C_f the daily fishing tool rental and personnel charges and C_d the daily rig operating cost /JOH 12/.

The potential alternative exit scenarios are the controlled fishing abandonment by back cementation or destruction of the fish down-hole and recovery of the borehole in its original condition.

6.1.3 Fishing Abandonment

6.1.3.1 Regular or unplanned abandonment

When a fishing operation is abandoned for financial reasons as the cost of the operation is exceeding the value of the fish, then this is often considered as a routine decision point and widely accepted by the mining authorities, provided that there is no potential thread arising from the fish. Then the obstructed borehole section will be cemented off and side-tracked above the fish and the lost section past the fish re-drilled and continued for further deepening.

When a fishing operation has to be abandoned and stopped for technical reasons, then this usually represents a major change in plans. In particular in the case of a hazardous fish or risk of underground blow-out conditions causing from the stuck in-hole incident, authorities could refuse the fishing abandonment and instruct the operator to continue with the fishing and well repair.

A fishing operation could on the other hand also be terminated and abandoned by order of authorities for reasons of endangerment to the environment or thread to public safety. In such an event authorities could enforce borehole abandonment procedures that will have to be followed by strict order and under supervision of a representative from the mining authority. Likely will the borehole also have to be equipped with permanent monitoring instrumentation and the wellhead installation, well site and the downhole measurement readings monitored round the clock on a 24/7 basis.

6.1.3.2 Control of hazardous borehole stray

Especially some measurement-while-drilling (MWD) and wire-line logging tools can carry in their instrument housing radio-active sources as part of their geophysical evaluation set. In case one of these nuclear logging tools gets lost down-hole, then the mining authorities need to be notified immediately and a recovery plan proposed by the operator how to recover this chemical out of the hole. The authorities will set the duration and mode of the fishing efforts until it is deemed not to be further technically feasible. At failure to recover the source, a well abandonment plan will be set up by the authorities which the operator has to adhere and follow. In special severe cases authorities can order the drilling of a relief well in order to re-establish contact with a potentially hazardous fish and resume its recovery activities via this newly drilled relief borehole. Unfortunately, all risks and cost for consequential damage in such a case could go to the account of the holder of the mining rights, the owner of the hazardous borehole.

6.1.3.3 Emergency response

Prior to any fishing operation, the owner of the borehole has to inform and in some cases file a work plan with the mining authorities. Part of this notification are technical details about the fish, like: type, condition, position and date of loss, as well as an emergency response plan that contains all relevant information about all parties to be notified in case an emergency situation emerges during the planned fishing operation. Names, addresses, email and telephone contact information has to be part of this plan as well as instructions for medical support and guidelines who has to behave how in case of an emergency. This plan is made open to the public and has to be posted in every container room on the wellsite.

Basis of this emergency response procedure is the general health and work safety system of the operating company that includes further regular training and detailed work instructions to the field crews.

6.1.4 Relief Drilling

This paragraph is discussing a potential solution for accessing and retrieving a fish based on a technology that was developed and successfully practised many times by the oil & gas industry for controlling and killing wild eruption wells /BAI 00/.

6.1.4.1 Type, location and condition of the buried fish

There could be situations when buried equipment is not accessible through their original borehole anymore and have to be revisited at depth and excavated to the surface. The reason for such an extraordinary scenario may be many folds, one of them being that the legal situation could have changed over time or that a rising market value or a growing thread to the public could have developed from the fish.

The location of such a tomb is independent from depth. It may be accidentally in a certain location because of a past drilling or work-over hazard or it may be intentionally at a point of depth because of a disposal activity in the past. But its position in 3D space may also have changed with time due to geologic and tectonic movements in the earth crust over very long time periods. Also, this buried and potentially roving fish may also have changed it shape because of physical and chemical attack from geology over a long time span. So in deviation to conventional fishing in the geothermal and oil industry, one might be looking here at a completely new quality of buried, potentially roving and corroding fish situation.

6.1.4.2 Position uncertainty of fish

As there are no ranging methods like GPS positioning possible in the subsurface of the earth the position of bottom-hole borehole locations has to be determined geodetically from sequential measurement stations following classic surveying techniques. Laser surveying technology is also not applicable as the boreholes are typically filled with a liquid, which reduces the number of available variables to the earth gravity and magnetic and/or geometric north vectors. This way inclination and directional heading readings have to be taken with classic type of surveying instruments at each survey station resulting in varying measurement accuracies, borehole misalignments and depth errors.

Therefore, every computed borehole location is attributed with an error margin that will translate cumulatively to a position of uncertainty for a particular fish location. Considering all possible error sources, this position of uncertainty is contained in a volume of a three dimensional Ellipsoid-of-Uncertainty, which determines the location of the fish within an e.g. 90 % probability. The size of that ellipsoid can be reduced by the number and type of different surveying techniques run in a hole, but it can also be significantly enlarged by applying the wrong surveying strategy, running non calibrated surveying tools or contracting poor service contractors /HIC 12/.

There are high-precision optical or mechanical inertial navigation and north-seeking gyro systems both on electric logging wireline and pipe string available on the market. They can keep the probability of a bottom hole location over several kilometre length even in high deviated sections within a volume of 1 m^3, but bottom-hole temperature acting on the downhole instrument is clearly working against this performance /WOL 81/.

Standard pendulum tilt-meters or accelerometers in combination with flux magnetometers are reliable and temperature resistant directional sensors up to 200 °C and higher, but their measurement can be severely biased in the presence of ferro-magnetic material in the geology or the borehole construction itself.

6.1.4.3 Relief well drilling planning and retrieving strategy

To access a buried fish, either the original old borehole could be worked over and attempted to be reopened, if this is at all possible, or a new borehole to be drilled towards the fish in order to establish contact at depth.

6.1.4.3.1 Final drilling approach and surveying strategy

If the decision is for a newly drilled relief well, then the new borehole’s surface location need to be selected in at least a few hundred meter distance from the old well, so that any risk of borehole collision during drilling can be positively excluded. The newly drilled borehole should be kept naturally vertical as long as possible. Upon reaching a suitable geologic casing setting point, the hole will then be deviated deeper on towards the trajectory of the target well following an S-shape profile. For final approach it will be turned towards the orientation of the borehole in that section until an approximate 10m parallel distance is established in a few hundred meters above the fish location /NG 10/. Casing is run and cemented at this point in order to secure the relief borehole. Acoustic, electric or radar based homing-in surveying instruments are then run on wire line into the open hole section below this casing shoe in order to identify and image with highest accuracy the exact 3D location of the target well. This logging sequence can be quite extensive and some instruments may even require for their measurements a non-conductive fluid like Diesel or natural oil to be temporarily placed in the open-hole section.

6.1.4.3.2 Re-entry, reconnaissance logging and fish integrity

A strategy for the contact procedure with a drilling assembly will then have to be derived from these high precision image log results. Contact with the target borehole is usually identified at this stage by observing cement traces or metal shavings over the mud shakers. At this indication a milling assembly will be run down-hole to cut a window from the outside into the casing of the target well. When this window is finally established and dressed for safe entry, a flush pipe string with a drill bit will be threaded into this well and carefully flushed and lowered towards top fish /NG 10/. After reaching with the bit a proximity of a few meters distance from the fish or a dedicated gate to the fish chamber, casing has to be run and threaded into the target well which finally establishes a secure conduit to the top fish. For reasons of cleanliness in the section above the fish, this casing will not be cemented but rather packed-off with external casing packers inside the abandoned well. The drilling mud will then have to be fully replaced by a clear fluid for visibility reasons for the now to be performed down-hole cameras runs towards top fish position (Fig. 6.1.3).

6.1.4.3.3 Safe connection with fish and pull-free procedures

After positive confirmation of the fish's integrity from reconnaissance logging a fishing assembly can be run into the relief well and first contact established with the fish itself and consequently its pull-free conditions tested. At confirmation of a free fish, it can be slowly pulled up provided the surface conditions allow its recovery to surface. At failure to pull free a controlled destruction of the fish by down-hole milling and circulation of its piece parts to surface could be considered if the environmental conditions at surface do allow such an operation. However, it is unlikely that all of the milled fish material will make it to surface. Some amount will remain on bottom or somewhere along the well path of the relief borehole, which may create a problem for later well abandonment procedures.

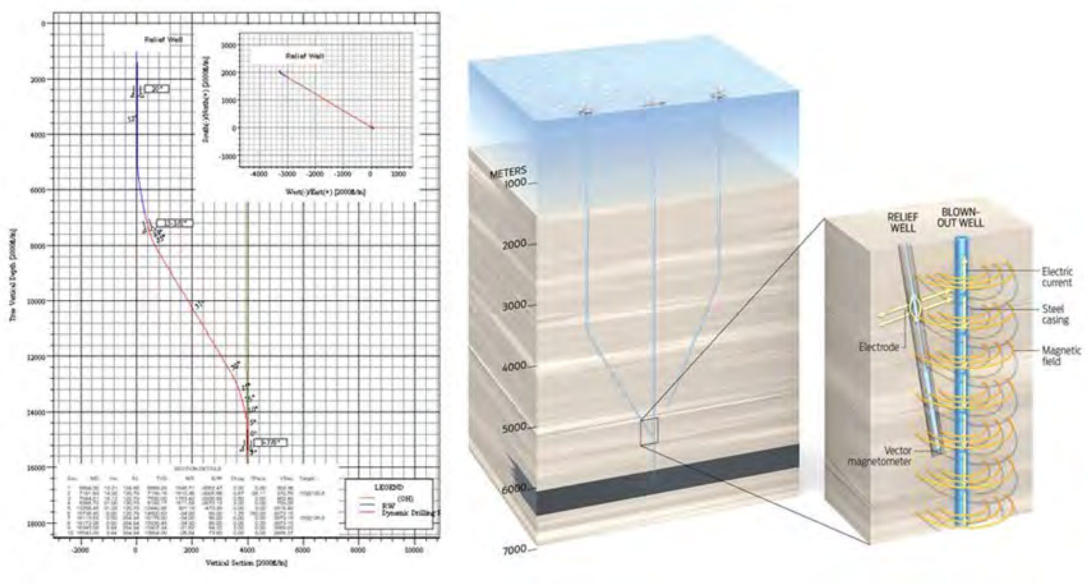

Fig. 6.1.3 Directional drilling planning of a relief well in the vertical projection (left) and 3-dimensional position towards the target well (center) with the final approach section with home-in wire-line logging (right)

6.1.4.4 Abandonment of relief borehole

In the event when all identified fish equipment is successfully fished out of the ground both the old well with the fish chamber and the relief well will have to be secured and plugged back mechanically for borehole abandonment.

6.1.4.4.1 Securing/back-filling of fish chamber

A flush pipe sting will be lowered into the fish chamber, the clear water replaced with drilling mud and the string proceeded to the anticipated bottom of the chamber or the final end depth of the abandoned old well. There may actually be damage at the bottom of that chamber which will only be visible after the fish has been removed from its location which could also have been a cause of the stuck fish or the reason for its recovery demand.

The damage will have to be assessed with wireline logging and camera runs and a plan developed how to repair it, so that a safe back-filling of the chamber can be assured and left safely in the ground with no potential for future hazard conditions.

After repair, a slick cementing string will be lowered to the bottom of the chamber and cement slurry pumped from surface under continuous retracing of the cementing string. Reaching with the cement the top of the chamber the cementing operation will be interrupted and the cement column rested for hardening. Integrity of the cement plug is typically checked after 36 to 48 hours of setting time by applying the cement head with compressive load from the weight of the cementing string and pressurization of the mud column for a given time period.

After confirmation of cement head tightness a mechanical plug is usually set above the cement plug in the old well section and the next plug will be cemented from this mechanical plug through the window up into the next casing section of the relief well.

6.1.4.4.2 Back-filling of relief borehole

The back-filling of the remaining relief borehole will be performed as for any other well in that area. Authorities may request to delay this abandonment steps for a given observation period and may also request to perform the back-filling of this section by leaving permanent down-hole monitoring sensors and cables in the ground, so that any possible future activity from the chamber can be recognized early at depth. All surface site installation may be back constructed at this stage.

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6.2 Travis P.: Deep Borehole Disposal Research at the University of Sheffield

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6.2.1 Introduction

Deep Borehole Disposal (DBD) has a long association with the University of Sheffield, commencing in the early 1990s, when it generated interest and initial support from the former British Nuclear Fuels Ltd (BNFL). Two papers by Fergus Gibb /GIB 00/, /GIB 99/ laid the foundations for further research and another by Chapman and Gibb /CHA 03/ merged this work with other borehole concepts, e.g. /WOO 83/, and brought the potential of DBD to the wider attention of the international nuclear industry.

Three main DBD concepts were developed**:** high temperature very deep disposal (HTVDD) and two low temperature variants**;** LTVDD1 and LTVDD2 (Fig. 6.2.1). The main difference between LTVDD 1 and LTVDD 2 lies in the material used to fill the two annuli between the waste packages and casing and between the casing and wall rock. LTVVD 1 is designed for wasteforms which have relatively low decay heat outputs and a cementitious grout is used. LTVDD2 is for slightly hotter wastes and uses a high density support matrix (HDSM) and represents the optimum choice for filling material. In HTVDD, the radiogenic heat from the waste would be sufficient to partially melt the surrounding rock which upon subsequent recrystallization would completely encapsulate the waste packages in solid granite. This variant would only be suitable for the disposal of young, hot spent fuel which could generate the temperatures required to melt crystalline rock under the conditions in the DZ. HTVDD would necessitate the use of a refractory material as a basal plug (preventing a scenario involving self-sinking containers) and possibly withdrawal of the DZ casing before significant decay heating has got underway to maximise melting Of the three disposal concepts, this is potentially the best in terms of long-term safety.

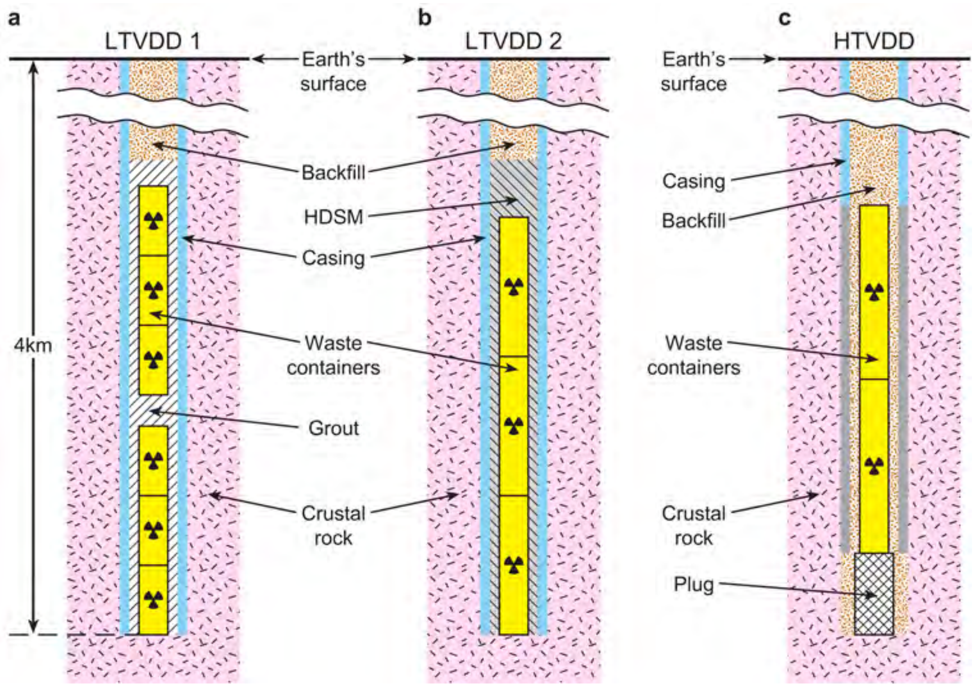

Fig. 6.2.1 Three design concepts for DBD: HTVDD, LTVDD1 and LTVDD2. (Note – the outer annulus between the casing and host rock is not shown.)

A series of papers published throughout the following decade further expanded and underpinned the concept by utilizing numerical heat flow modeling, the mathematical details which were set out in detail in /GIB 08d/. Modelling has confirmed the feasibility of all three of the above concepts as well as indicating which sealing and support matrix is most appropriate for a given waste /GIB 08b/, /GIB 08a/, /GIB 12/. Beswick *et al*. /BES 14/ have recently reviewed the state of the art in deep borehole disposal, discussing drilling capabilities, deployment methods and other engineering issues in addition to the topics already mentioned.

With the decision by the US Department of Energy (DOE) to begin construction of a Deep Borehole Field Test (DBFT) in 2016, a successful outcome of which could encourage the implementation of DBD in and beyond the US, it is timely to review some of the options available for the concept. In this article we review some of the research currently underway within the Deep Borehole Disposal Research Group at the University of Sheffield. These topics include sealing and support matrices (SSMs), borehole sealing by rock welding, and the use of mathematical heat flow models to determine the feasibility of, and optimize, DBD for various candidate waste types, including MOX, higher burn-up spent fuels and smaller waste packages such as the Hanford Cs and Sr capsules /TRA 15/.

6.2.2 Numerical Heat Flow Modelling

In the absence of an actual borehole, either a test hole similar to the one planned by the DOE, or one containing heat generating waste containers, modelling data provide the only guide to the feasibility or otherwise of any particular DBD scheme.

At the University of Sheffield we have concentrated our modeling efforts to date on heat flow, preferring to decouple the thermal conduction effects from fluid mechanics for reasons of simplicity and efficiency. A similar approach was taken by Hodgkinson /HOD 77/. In a typical DBD scenario, conduction can be expected to dominate over both convection and radiation as the mechanism of thermal transport. Within this approximation, the temperature (near- or far-field) is given as the solution of the heat conduction equation:

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot \left(\kappa \frac{\partial T}{\partial \mathbf{r}} \right) + \sigma \tag{6.1}$$

where ρ is the density, c the specific heat, T is the temperature, $\boldsymbol{r}$ is the spatial position, κ is the thermal conductivity and σ is the source term. Except in a few special cases, this equation cannot be solved analytically. Hodgkinson /HOD 77/ derived a semi-analytical solution for the case of a cylindrical heat source (the 'waste') with a simple exponential time dependence, embedded within an infinite mass of material having the properties of a typical granite. Solutions such as this are extremely useful, both for pedagogical reasons and for validating more sophisticated models.

At Sheffield, we have developed an in-house finite difference code for solving the above equation. This code, named "*GRANITE*", has enabled us to predict the spatial and temporal variations of temperature for a large variety of DBD scenarios and configurations /GIB 08d/, /GIB 12/, /TRA 15/. Using the *GRANITE* code we have been able to develop our concepts and resolve options such as the choice of SSM and evaluating the advantages of consolidated fuel pin disposal versus complete assembly disposal. We have also investigated the potential for disposal of higher burn-up fuels and MOX (anticipating future fuel cycles), the feasibility of rock welding and disposal of the Hanford Cs/Sr capsules within a single borehole. The code is sufficiently general that multiple barriers can be simulated, each with its own set of temperature-dependent thermophysical properties. In addition, it is able to account for latent heat effects (particularly important in rock welding and HTVDD) as well as allowing for time dependent disposal with canisters disposed of singly, in small batches or long strings over a period of days, weeks or months.

Numerical heat flow modeling underpins much of our research and examples of these applications are described in more detail below. Additionally, we are also using meshless methods (Smooth Particle Applied Mechanics /HOO 06/) to investigate the sinking rates (in free fall) of canisters in a fluid-filled borehole and estimating upward particle transport by convection (resulting from strong thermal gradients in the borehole fluid) as well as attempting to answer some fundamental questions such as: how long it will take for the pressure in the hole to return to the hydrostatic value in the surrounding rock following final sealing of a borehole?

6.2.3 Sealing and Support Matrices

When setting out the advantages of disposal of HLW and SNFs in deep boreholes against emplacement in a mined, engineered repository, it is usually considered that at the proposed depths of the DZ, lateral flow of groundwater is slow enough to be disregarded while vertical transport is effectively prevented by the density stratification of the brines present in the crystalline basement. However, in a borehole, two annuli provide a potential route for leachates back to the surface via advection: the annulus between the casing and the borehole wall, and the annulus between the casing and the waste containers. These annuli should ideally be filled with an impermeable sealing material to eliminate this effect although some DBD design concepts *e.g.,* /ARN 11/ simply leave the annuli in the DZ filled with water, drilling mud or deployment fluid.

The approach we have taken at the Sheffield is to use what we term “sealing and support matrices” or SSMs. We define these as materials whose primary function is to prevent the access of groundwater to the casing and disposal containers for as long as possible, so preventing or delaying any corrosion and closing a possible escape route for any gaseous corrosion products or released radionuclides back to the surface. Their secondary function is to provide mechanical support against the hydrostatic pressure in the DZ and axial load stresses from the overlying waste containers, especially in the period before the borehole is sealed. In the longer term an SSM could help to counteract any tectonic stress on the casing and waste packages.

6.2.3.1 High Density Support Matrix

Our preferred type of SSM is the HDSM. It is a fine, lead alloy shot which can be emplaced easily via drill string or coiled tubing. The optimum size of the shot particles is currently being refined but an average diameter of a few millimeters is appropriate. Particles of this size and density will flow easily down the sides of the containers to fill the inner annulus and, if perforated casing is used, also into the outer annulus, filling any irregularities and some of the larger fractures in the rock wall. Radioactive decay heat from the waste would result in melting of the alloy. A typical Pb-Sn alloy with a composition close to the binary eutectic will melt around 185 ˚C at one atmosphere (and only a few ˚C higher at DZ pressures) to give a dense liquid in which steel containers filled with spent fuel rods would be only slightly negatively buoyant /GIB 08c/.

Once molten, the liquid alloy will penetrate even smaller cracks and voids, and when the decay heat subsides and the temperature reaches the solidus, the molten metal will re-solidify, essentially soldering the waste containers into the borehole. The use of lead has two additional advantages: 1) it could reduce the stockpiles of contaminated lead held by nuclear operators and 2) it would provide an additional level of radiation shielding to facilitate handling operations. Potentially suitable alloying metals such as Sn, Sb and Bi are expensive and our on-going research will look at ways of optimizing the cost of the HDSM, including minimizing the volumes of the annuli.

The HDSM would be ideal for heavier waste containers, requiring greater mechanical support but having a relatively high heat output. For example, the disposal of spent fuel especially in a consolidated form (removal of fuel pins from an assembly followed by efficient packing in the waste container with a suitable infill). It is expected that nuclear reactors will in the near future need to operate more efficiently and extract more energy from the fuel through either a second cycle (e. g., as MOX) or higher burn-ups (or both). Such increased efficiency is required to meet the twin demands of greater energy usage and meeting ambitious targets for lowering greenhouse gas emissions (which could be achieved by increasing the nuclear contribution to the baseload). LTVDD 2 would be ideally suited to the disposal of waste packages containing SNF from LWRs (which could include MOX) operating at burn-ups of 55 GWd/t or greater /GIB 12/ provided their heat output is sufficient to melt the HDSM.

6.2.3.2 Choice of SSM

Numerical heat flow modeling enables a systematic study of the thermal footprint arising from disposal of SNFs with different combinations of**:** type of waste (UO_2/MOX), burn up, post reactor age and number of fuel pins per waste package /GIB 12/.

Fig. 6.2.2 shows temperature-time curves for a single container of consolidated SNF with 1 000 fuel pins. Each curve represents the temperature at one point on a radius extending outwards from the centerline. Radii level with the top, middle and bottom the container are shown in different colours. Two points are taken on each radius representing the surface of the container and the borehole wall. For HDSM to be used as an SSM, we ideally require the temperature at the borehole wall to exceed the solidus of the alloy along the whole length of the container. For those cases in which the temperature does not reach the solidus (predicted to be 192 ˚C at DZ pressures) at the middle and bottom of the container, the HDSM could not be used and a lower temperature alternative (cement) would be needed.

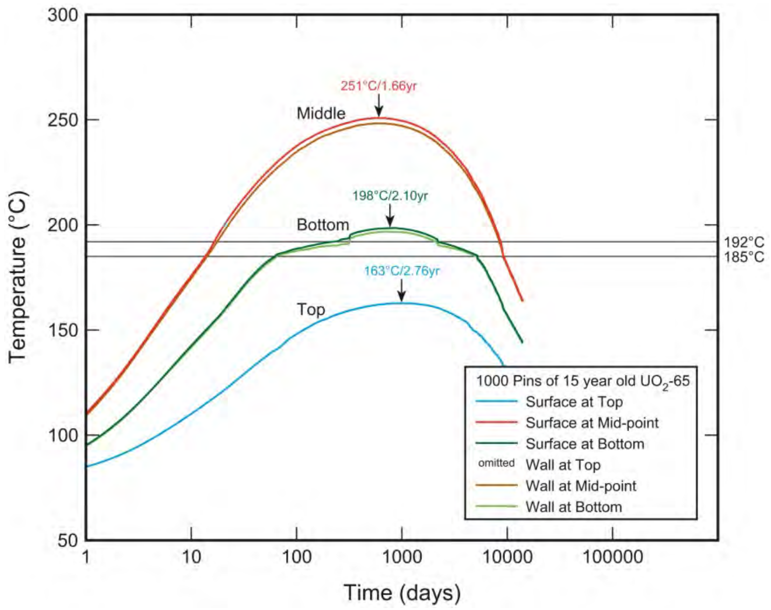

Fig. 6.2.2 Variation of temperature with time at the outer edge of the waste package and at the borehole wall for three levels (top, middle and bottom) for a single container of consolidated spent UO_2 (65 GWD/t burn-up). Horizontal lines show the solidus for the HDSM at 1 atmosphere and 50 MPa (projected)

The heat conduction modelling can be used to construct optimization field diagrams such as Fig. 6.2.3 in which the combinations of variables for which a given SSM (either cement or HDSM) would be appropriate can be demarcated.

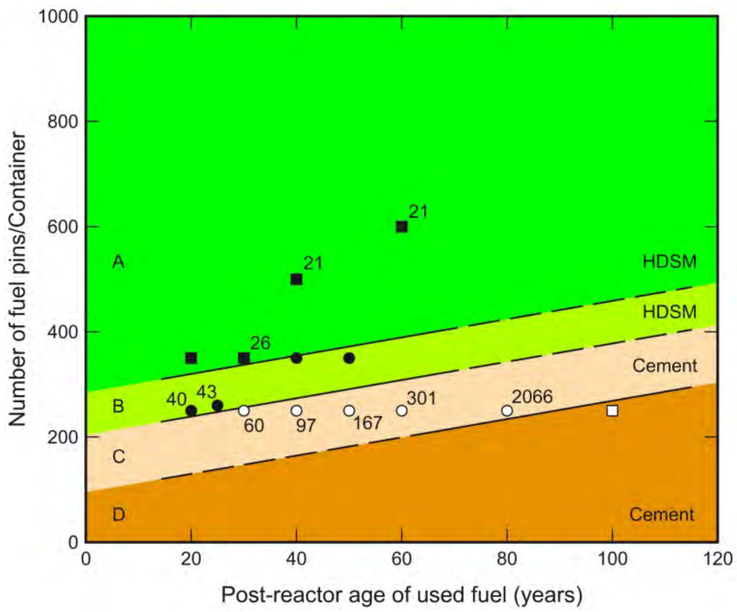

Fig. 6.2.3 SSM Optimization diagram for a single container of consolidated spent MOX at 65 GWd/t burn-up from the outcomes of heat flow modeling

The numerals on the plot are the number of days from initial disposal to the onset of melting of the HDSM (if used). The lines serve to demarcate the optimum choice of SSM for a given combination of number of fuel pins against age of the fuel. We are exploring more flexible disposal options using this same thermal model, including disposal of mixed wastes. Among the scenarios being explored are mixing fuel pins of different ages, burn-ups and types (UO_2 or MOX) within individual packages and using packages of different heat outputs to manage the temperature profile along a stack of packages, e.g. adding packages containing high burn-up MOX to a stack of mostly lower heat output waste content. These scenarios could greatly expand the flexibility of LTVDD 2 and other borehole disposal concepts. For those cases in which insufficient heat is generated to use the HDSM a high temperature cementing system is needed.

6.2.3.3 Cementitious grouts

Cement is widely used in the oil and gas industry to seal boreholes mainly because of its low cost and relative ease of deployment. However, the nature of DBD imposes new scientific and engineering challenges for a cement-based SSM.

Elevated temperature and pressure both influence the properties of cementitious grouts, and cause a reduction in grout thickening and setting times /SCH 10/, /JUP 08/. Because of the grout deployment time likely to be required, grout thickening needs to be retarded to facilitate its flow around the waste packages, and then the grout must set and develop sufficient strength before emplacement of subsequent packages. Additionally, the grout must have wet paste properties that facilitate deployment through the borehole fluid. Grouting systems based on Portland cement have been investigated, and a range of retarding additives has been assessed.

Class G oil well cement /BRI 09/ partially replaced with silica flour was used to make a grout which also contained a water proofing additive. The influence of organic retarding additives (sodium gluconate and commercially available products based on polycarboxylate, sulphonate and phosphonate compounds) and inorganic compounds of phosphate and borate have been investigated. Wet paste properties (consistency, 24 hour set, isothermal conduction calorimetry, viscosity and flow) and hardened paste composition were investigated in the short term (over 14 days curing). Where possible all laboratory investigations were carried out at elevated temperature and pressure in order to approximate DZ conditions as closely as possible.

The addition of each product caused a retardation in grout thickening time, but only sodium gluconate and the polycarboxylate product were able to delay thickening sufficiently for this application at each testing temperature up to 140 °C. The presence of all additives delays the reaction between the cement powders and the mix water. The delay in the times at which the main heat flow events occurred in the samples containing either sodium gluconate or the polycarboxylate additive was readily observed, but this was much less obvious for the grouts containing the other additives. Investigation of other wet paste properties showed that the presence of each organic additive, except the phosphonate product, increased paste workability and reduced viscosity, and as testing temperature was increased from ambient (22 °C) to 70 °C the viscosities of all grouts containing the organic additives were less than the control grout. It was difficult to identify any trends in viscosity using the inorganic additives. Compositional analysis of each hardened cement paste demonstrated that the cement hydrate phases formed in all samples were typical of those present in oilwell cement grouts cured at a representative downhole temperature (120 °C). There was no detectable difference in the compositions of the hardened cement pastes due to the presence of any additive and the phase formation is in line with that reported in the literature /NEL 06/.

This work has demonstrated that some of the available oilwell additives will provide the necessary level of retardation required for this DBD application, but only sodium gluconate and the polycarboxylate product offer the potential to retard at temperatures up to, and possibly over, 140 °C. No additive appears to affect the composition of the hardened cement pastes after 14 days curing, and all phases formed have demonstrated durability at temperatures and pressures similar to that in this application. Further work will be undertaken to a) enable reduction of grout water content and assess porosity and permeability, b) investigate long-term durability characteristics, c) study the effect of radiation on grout performance, and d) investigate the influence of near-field conditions on grout performance in terms of the reactions between the grout and the groundwater, the waste container, the borehole casing and the host rock.

6.2.4 Sealing the Disposal Zone (DZ)

The SSMs described in the previous section provide only a sealing of the annulus inside the disturbed rock zone (DRZ) created by the drilling of the borehole. A permanent (or at least > 100 000 year) sealing of the borehole above the DZ that also closes off or eliminates the DRZ is required for attainment of complete isolation of the waste packages. Only rock complete with density-stratified brines could provide such a seal. At Sheffield we have an active research programme aimed at developing such a seal by 'rock welding'. In outline this concept consists of the following stages: (1) A section of borehole casing is removed close to where the seal will be situated; (2) crushed host rock is emplaced in the hole; (3) a sacrificial heating device is lowered into the crushed rock with power supplied from the surface through an umbilical cord inside coiled tubing; (4) more crushed rock is emplaced to completely bury the heater, (5) a pressure seal is set above the backfill, (6) heat from the electrical elements raises the temperature of the rock above its solidus for a set period before power is reduced leaving the rock magma to slowly cool and recrystallize, forming a permanent seal which extends beyond the annulus through the DRZ, hence eliminating it. We have successfully demonstrated on a laboratory scale that small samples of granite can be partially melted under water pressures of 150 MPa at temperatures over 700 ˚C and that when cooled slowly and allowed to crystallise, develop a microstructure essentially indistinguishable from the original rock /ATT 03b/, /ATT 03a/. Current research is focused on further quantifying the melting relations and recrystallization under conditions more appropriate to sealing a DBD, optimizing the operating conditions, design of suitable down-hole heaters and scale-up, with actual field trials a longer term goal.

6.2.5 Other Candidate Wastes

Efficient disposal calls for larger waste containers capable of holding up to 1 000 consolidated fuel pins. However, large containers require relatively wide diameter boreholes with the added cost associated with drilling to a depth of 4-5 km. In the USA, much spent fuel is already packaged in containers too large to fit into boreholes within the current and near-future drilling envelopes. However, certain waste packages are quite small in diameter and well-suited to DBD. One example of this is the Hanford Cs/Sr capsules.

The Hanford site in Washington State - possibly the most radioactive contaminated site in the USA, has a total of around 2 000 sealed capsules containing halides of strontium and caesium which account for almost 40 % of the total radioactivity of the site. Interim storage for a period of 10-half-lives is not necessarily the best option**:** many of the capsules contain Cs-135, which has a half-life of 2.3 million years, and the dose received from the shorter-lived isotopes would remain dangerously high for several generations. The Cs and Sr capsules consist of a double-skinned container in which halides of cesium and strontium are sealed within inner and outer steel walls. The capsules vary in length between 0.51 and 0.53 m, and an outside diameter of about 0.067 m.

We have designed a baseline concept for disposing of the entire inventory of capsules at the Hanford site within a single borehole /TRA 15/, /ARN 14/. This baseline case involves putting two capsules end to end, axially aligned, inside a cylindrical disposal container 1.083 m in length and having an O.D. of 0.114 m and a wall thickness of 12.7 mm. This would require a 0.216 m (8.5 in) diameter borehole and 0.178 m (7 in) O.D. casing. Such a hole can be drilled to a depth of 4-5 km using existing drilling methods. To put this into perspective, the US demonstration hole will be drilled to a similar depth, but with a diameter of 17 in. Variations of the baseline concept could entail placing 6 capsules per container, requiring a borehole of 12.25 in diameter or 14 capsules per container requiring a 17 in diameter borehole. The greater the diameter of hole, the greater the cost of drilling (which rises exponentially with the diameter), but this should be more than offset by the removal of the need to drill to 5 km in depth and less unit operations needed to fabricate and fill a smaller number of disposal containers.

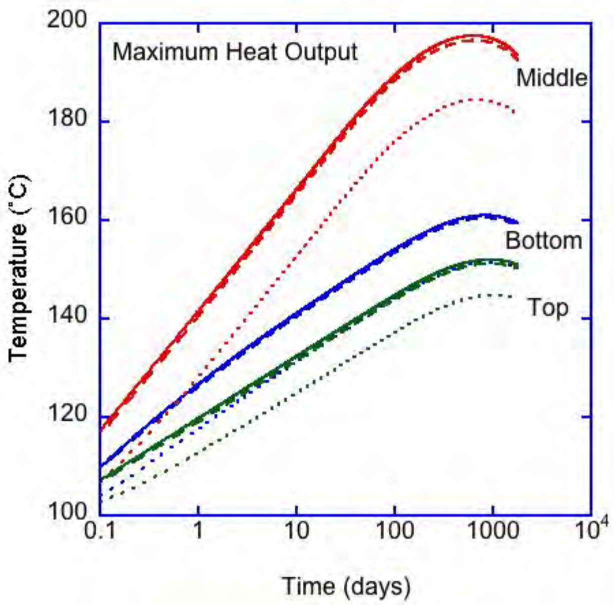

Fig. 6.2.4 Temperature time curves for disposal of a stack of 10 containers of SrF_2 at maximum heat output

Numerical heat modeling work provides important information about the temperature rise at the surface of a disposal container, and at the borehole wall, both as a function of time, and its variation with distance in both radial and vertical directions. Fig. 6.2.4 shows typical temperature time curves for a single container housing two SrF_2 capsules at its maximum heat output. The data confirm that the temperature rises to a maximum within a few years of disposal before subsiding again. The maximum temperature reached is about 195˚C at the middle of the container, high enough to begin melting HDSM (the data were obtained assuming saturated bentonite as the SSM), but elsewhere, the temperatures are simply too low to employ the HDSM. We are currently investigating increasing the temperatures with higher numbers of capsules per container than the baseline case presented above to enable use of the HDSM.

Fig. 6.2.5 shows the maximum temperature attained along radii from a single container with 2 capsules of SrF_2 at maximum heat output. The most important message from this plot is that the temperature returns to near ambient (100˚C at the bottom of the DZ) within 5-10 m of the borehole axis. This constitutes a very small thermal footprint. This, together with the observation from Fig. 6.2.1 that the overall temperature rises are not too great, strongly suggest that DBD could be a viable disposal option for the Handford capsules.

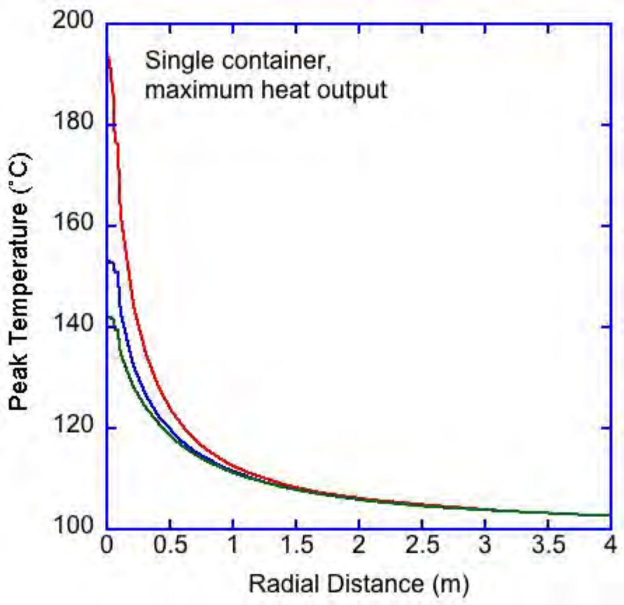

Fig. 6.2.5 Variation of peak temperature reached along horizontal radii at the top (green), middle (red) and bottom (blue) for a stack of 10 containers, each with two capsules of SrF_2 at maximum heat output

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7 Geochemistry and Monitoring (Geochemie und Überwachung)

7.1 Kück J.: Downhole Logging

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Wireline downhole logging is a powerful and universal method to gain continuous, in-situ measured and highly depth-reliable data of various physical or structural rock and sediment parameters. The most common down-hole logging measurements are natural radioactivity, resistivity, bulk density, sonic wave velocity, formation porosity, magnetic field & susceptibility, borehole wall images, concentration of some elements and additional data. It provides a depth reference for the correction of core and cutting depths as well as for depth of seismic data and is able to bridge gaps of core data in case of core losses (core-log integration). Furthermore, logging is the base of formation evaluation, lithological classification, structural mapping and many other geological interpretations. It is instrumental for the identification and characterization of discrete borehole features like fluid and fracture systems, ore bearing zones or hydrocarbons. And it is essential for the investigation of the in-situ stress field and supports the drilling process with important information about borehole condition and geometry as well as directional orientation, drill mud condition, cement-bond quality etc. Special logging tools are also capable to deliver fluid and rock samples from discrete zones of interest or can identify lost-in-hole equipment or neighboring wells or objects.

7.1.1 Logging basics

Downhole logging is the continuous measurement of one or more parameters versus depth in a borehole. Downhole logging data is measured under the in-situ conditions given in a borehole and delivers the most accurate and closest-to-reality depth measurement in a borehole.

Various types of logging sondes, containing one or more sensors for different parameters, acquire downhole logs (Tab. 7.1.1). The sondes are connected to a downhole logging cable (wireline) that is pulled by and stored on a special wireline logging winch. The cable holds the sonde´s weight and contains electrical wires for power supply and telemetry (data transmission between sonde and surface and verse visa; Fig. 7.1.1). A logging winch has a rotatable lead-out of the cable wires allowing to continuously measure while the winch drum is revolving, i.e. moving the sonde up or down in the borehole (to run a log). The logging cable lines coming from the winch are connected to a data acquisition unit, consisting basically of an interface panel for power supply and sonde communication and a computer for control and data storage. Some sondes can be combined (sonde strings) to be logged together in order to reduce the number of necessary borehole runs (Fig. 7.1.2).

Most downhole logging is performed in open borehole sections (without a protective steel or plastic pipe inside) but some sondes can also be run inside a steel pipe like a casing or a drill pipe. Commonly the drill pipe and bit will be tripped out of hole to allow the wireline sondes to be run in for logging. In case of core drilling it might be possible to lift the drill string up to the top of the desired borehole section and the sonde is run in through the drill pipe and core bit into the open-hole section below. This very time saving method is the standard procedure for boreholes of the so-called mining drilling type, of which the very most lake drillings are (Fig. 7.1.3).

7.1.2 Sonde size

Logging sondes come in a variety of sizes (diameters). They may be separated into two groups, standard sized sondes and slimhole sondes, but there is no strict definition. Commonly sondes with a diameter less than about 60 mm are regarded to be slimhole sondes, whereas standard sondes have a diameter of 86 mm ($3^3/_8$") and up. There are intermediate sondes available with a diameter of around 60 to 75 mm. Obviously big sondes cannot be run in a slim borehole because they simply do not fit into the hole, while slim sondes placed in a wide borehole is usually not recommended either. Most of the slimhole sondes lose their performance in holes that are too wide. Slimhole sondes perform best in boreholes with a diameter less than 130 mm. Many standard sondes have an upper limit of the hole size of approx. 500 mm. Even bigger boreholes will require for special borehole logging sonde configurations.

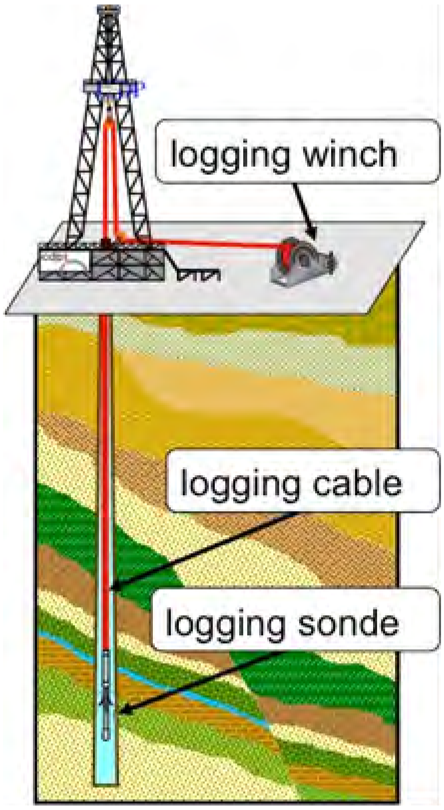

Fig. 7.1.1 Downhole logging scheme

Fig. 7.1.2 Helicopter portable logging winch with 2.2 km of a 4-conductor cable

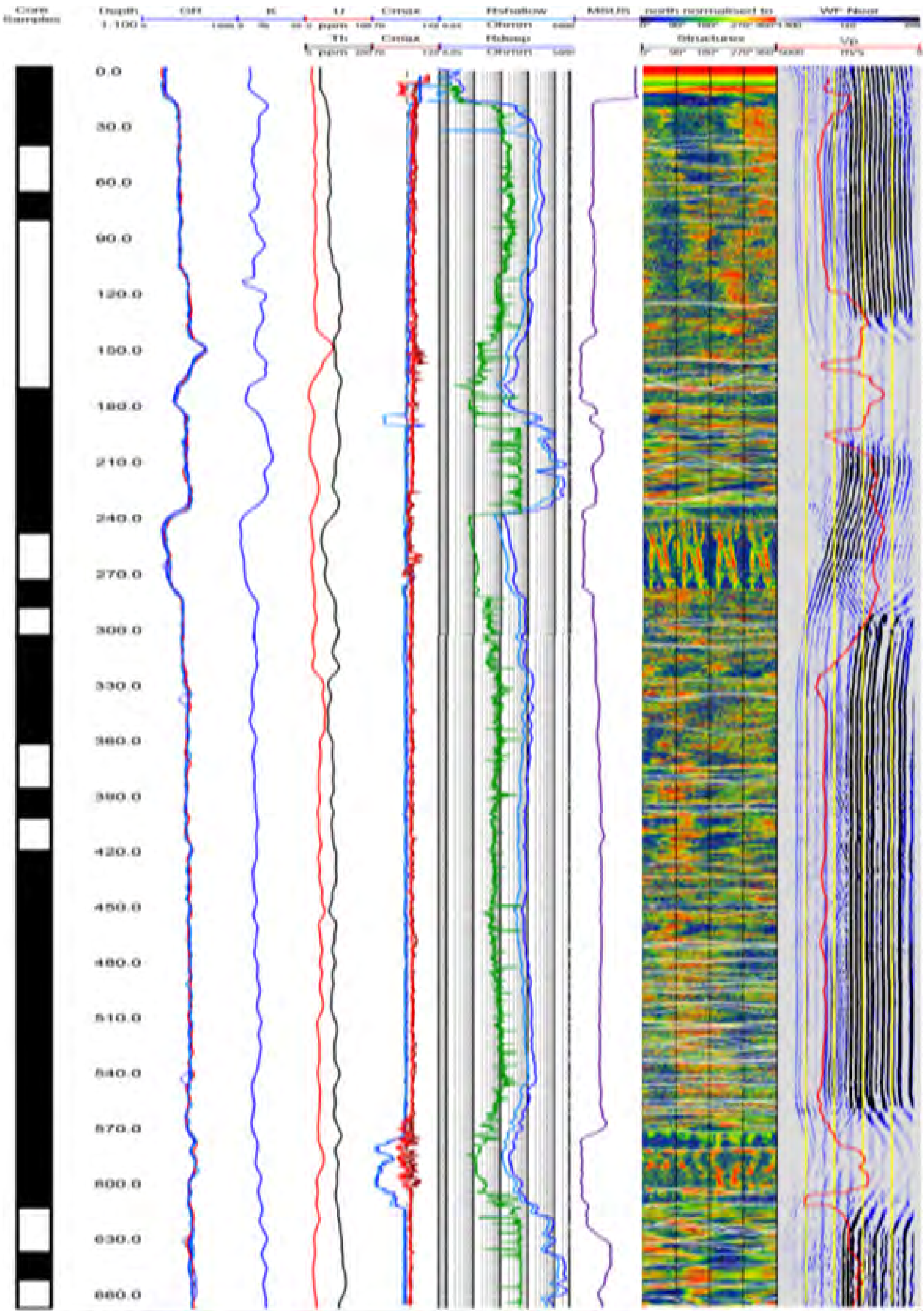

Fig. 7.1.3 Core recovery (left; black zone core recovery) and summary of downhole log measurements (right, including natural gamma ray, spectrum gamma ray, calipers, resistivity (shallow and deep), magnetic susceptibility, borehole televiewer, and sonic log)

Tab. 7.1.1 Overview on parameters and applications of downhole logging sondes

Parameter	Applications	Sonde Names	Examples of typical Sonde Mnemonics	Type
borehole wall images	borehole condition/stability, structural features, bedding/ lamination, breakouts, stress field orientation by breakout direction & induced vertical fractures	Acoustic Imager (Televiewer)	BHTV, ABI, UBI, CBIL, CAST	d
	like above but stress field orient. only by induced vertical fractures	Electric Imager	FMS, FMI, STAR, EMI	d
	like Acoustic Imager but works only in clear water not in drill mud	Optical Imager	OPTICAL SCANNER	d
	structural features, bedding/ lamination, stress field orientation by breakout direction (multiple runs)	Dipmeter	DIP, SHDT, HDT	i
caliper, borehole geometry/ orientation	borehole condition: size, shape, volume, orientation/direction, path, stress field orientation by breakout direction (multiple runs), technical hole inspection	Caliper, Oriented Caliper, Geometry Tool, Gyro Survey	BGL, CAL-ORI, DIP	d
density	lithostratigraphy, core-log correlation, derived: porosity, mineral identification	Density	LDT, DENS, FDC	i
electric resistivity	lithostratigraphy, conduction type metallic/electrolytic, fluid invasion, porosity, ground truthing of magnetotelluric & electromagnetic models	Laterolog Resistivity	DLL, LL3	d
		Induction Resistivity	DIL, IND	d
		Micro-Resistivity	MSFL, MRS	d
elements Si,Ca,Fe,S, Ti,Cl,H	mineral composition for some rock types, lithostratigraphy	Elemental Sonde	ECS, GLT	i
gas saturation	reservoir characterization	Reservoir Parameters	RST	i
gravity	large scale density profile (even in cased holes), ground truthing of gravimetric models	Borehole Gravity Meter	BHG	d
magnetic susceptibility	core-log depth correlation, depositional stratigraphy, inter- & intra lava flow differentiation, lost-in-hole metal detection, lithology	Sus-Log	MS, MSUS, MagSUS	d
magnetic field	profile of the magn. field vector	Magnetometer	BHM	d
	total magnetic field magnitude	Borehole Geometry	DIP, BGL, CAL-ORI, Imagers	d
natural radioactivity	lithostratigraphy, shale volume, core-log depth correlation	Total Gamma Ray	GR	d
	U, Th & K contents, lithostratigraphy, heat production, fracture localization	Natural Gamma Spectrum	SGR, NGR, NGS, GRS	i
porosity	reservoir characteristics, fracture/flow zones, lithology, texture, compaction	Neutron Porosity	NPOR, PORO	i
		Nuclear Magnetic Resonance	NMR, CMR	i
sonic velocity	lithostratigraphy, compaction, reservoir characteristics, fracture/flow zones localization, seismic ground	Sonic	BS, BCS, DSI	d

Parameter	Applications	Sonde Names	Examples of typical Sonde Mnemonics	Type
	truthing			
mud parameters: temperature, pressure, resistivity, flow, fluid samples	fracture and flow zones localization & characterization, fluid regime, deep fluid circulation patterns, heat flow, fluid flow, hydraulic transmissivity & permeability, mud density, cement head localization, gas detection, fluid samples; often combined with hydraulic tests	Mud Parameter, Temperature, Salinity Flowmeter	TEMP, MP TEMPSAL, MRES FLOW, FM, MPFM, DIGISCOPE	d
rock samples	rock anisotropy, structural analysis, fill core gaps	Sidewall Coring Tools, Formation Sampler	MSCT, RFT	d

d = directly measured, i = indirect, i.e. derived by processing

7.1.3 Developing a logging plan

In an early planning stage of a drilling project it is possible to include logging demands such as limitations on hole size, hole deviation, drilling method, drill mud type, logging section length etc. into the drilling planning to provide the best possible logging conditions. This is usually the case in projects where downhole logging has a high priority (Case A). In other projects logging has to be adjusted to the given borehole conditions (Case B). Furthermore, in an ongoing project technical or financial reasons can cause significant changes to the original drilling plan and hence suddenly impose very different conditions for the logging technique or preclude such downhole measurements.

In Case-A logging requirement lists are provided for the development of a drilling plan to assure best possible borehole conditions for logging including: drilling location (accessibility), hole size, hole deviation, mud type, mud weight, cooling rates by mud circulation, length of logging sections and frequency of logging runs.

In Case B the drilling scheme and borehole conditions set a constraint for the maximum achievable downhole logging, by the hole size, hole deviation, mud type. mud weight, expected temperature and pressure, achievable cooling by mud circulation and the available time for each logging session or single runs (see Tab. 7.1.2 with typical logging speeds below).

Limitations for wireline logging do usually arise from hole size (very small or very big), borehole deviation, mud type (oil based or air, e.g. with air drilling), mud weight, pressure/temperature and the type of drill bit. Further constrictions limiting or even prohibiting the use of some sondes are, for example, deployment and/or import (cross-border transportation) of nuclear sources. It is recommended to create at least two logging scenarios, one with the maximum desired amount of logging and one with a minimum, indispensable amount of logging runs. Reality will lie somewhere in-between.

A list of prioritized downhole measurements will help in the early stage of project discussions about the project and budget (Tab. 7.1.2). It is also useful when project delays reduce the effective time available for logging. The question which tool providers and sondes are available for the specific borehole conditions needs to be addressed during an early project stage.

Logging sondes and other logging equipment must be technically capable for the planned logging campaign

A lost in-hole scenario will complete a logging plan. This is needed because a lost sonde that cannot be fished (retrieved from the borehole) will cause several consequences: 1) The borehole will be inaccessible below the sonde stuck depth; 2) The logging service provider might not be able to continue logging in other boreholes of the project because essential equipment components were lost.

Also a contingency plan for options of equivalent sondes and/or providers will reduce planning times.

A logging contract/agreement between the project and each logging provider has to lay down the responsibilities, liabilities and duties of both sides. The most important components are:

- the lost-in-hole case
- explicit naming of the responsible persons and decision makers
- terms for data handling/processing and data ownership
- technical requirements for the logging operations
- cancellation terms
- payment terms

Tab. 7.1.2 Typical logging speed and time of some sonde types, times are exclusive of sonde rig-up time

Sonde	Speed m/min	Speed Ft/hr	Time (h) for 0 – 500m	Time (h) for 1 000 – 1 500m	Time (h) for 2 500 – 3 000m
Caliper	~ 13	< 4 000	1	1,8	3
Resistivity	10 – 15	2 000 – 3 000	1,2	2	3,2
Density	9	1 800	1,3	2,1	3,3
Neutron Porosi-ty	9	1 800	1,3	2,1	3,3
Sonic	7 – 10	1 400 – 2 000	1,8	2,4	3,6
MagSUS	8 – 10	1 600 – 2 000	1,4	2,2	3,5
Temp/Pressure	8 – 12	1 600 – 2 400	3,6	6	10
GR Spectrum	2 – 5	400 – 1 000	4,8	5,7	7
Elemental Log	2 – 3	300 – 600	4,8	5,7	7
Electric Imager	3 – 10	600 – 2000	3,3	4,1	5,4
Acoustic Imager	2 – 5	200 – 1 000	4,8	5,7	7
Gravity	20 – 30 per day		-	-	-
Fluid Sampler	1 – 3 per day		-	-	-

7.1.4 GFZ downhole logging equipment

A basic set of sonde inventory is held by the Helmholtz-Zentrum Potsdam - Deutsches GeoForschungsZentrum GFZ. The tool specifications allow utilization in very different bore-hole conditions. The lightweight equipment allows low cost shipment to remote locations and at difficult conditions. The acquired logging data is quality checked and depth corrected in the office. MSUS, GR and SGR data are corrected for hole size and casing effects. GFZ does not offer other borehole environmental corrections. The data output format is LIS/DLIS, ASCII and WellCAD format.

The GFZ slimhole tool set covers basic geophysical logging parameters:

- electrical resistivity (dual laterolog)
- sonic velocity (two receiver, one transmitter)
- natural gamma spectrum (full spectrum SGR)

- total gamma
- 4-arm caliper, borehole orientation, structural data (4-arm dipmeter)
- magnetic field (magnetometer inside dipmeter)
- magnetic susceptibility
- acoustic borehole wall images (televiewer)
- mud parameters (temperature, pressure, resistivity)
- fluid samples
- seismic (3-component borehole geophone chain, 17 levels)
- resistivity)
- fluid samples
- seismic (3-component borehole geophone chain, 17 levels)

GFZ does not operate tools with nuclear sources. All tools are rated for a minimum of 150 °C and 80 MPa, except for the televiewer (70 °C/20 MPa), and can be used in hole sizes with a minimum of 75 mm. The maximum borehole size differs for each tool. These tools are best run on a special slimhole logging winch but can also be operated with any logging winch system utilizing at least a 4-conductor cable.

7.1.5 Most common logging methods in research drilling projects

7.1.5.1 Borehole Caliper & Geometry

A caliper sonde measures the size of the borehole cross section. The standard caliper sonde has 4-arms arranged in 90 degrees, which are pressed against the borehole wall. Other types are 6-arm or also very widespread 3-arm calipers. 3-arm calipers are unable to depict an oval-shaped borehole cross section.

A combination of a caliper sonde with an orientation sonde gives an oriented caliper sonde, also called borehole geometry sonde. The spatial orientation determines the borehole's deviation from vertical (DEVI), the direction of this deviation with respect to magnetic north (hole- or drift-azimuth), and the orientation of the caliper arms with respect to the sonde axis and to north.

Caliper data is used scientifically e.g. to determine the stress field orientation by measuring the direction of induced breakouts, but mainly for technical purposes like to know the borehole shape and volume (e.g. before running in casings or to determine the necessary cement volume), its direction and trajectory (e.g. to apply directional drilling corrections) etc.

7.1.5.2 Natural Gamma Ray

The total gamma ray log (GR) is a measure of the natural radioactivity of the formation. It is measured by counting all incident gamma rays (gamma counts). The tool calibration converts the counts into a standardized unit named gamma-API [gAPI]. This log is particularly useful for distinguishing lithology, facies, conducting cyclostratigraphic analysis and analyzing deposition environments, e.g. to distinguish between sands and shales. This is due to the fact that sandstones contain usually non-radioactive quartz, whereas shales are radioactive due to potassium isotopes in clays and adsorbed uranium and thorium. The GR log is the standard log for depth correlation amongst several logging runs as well as between downhole log data and core/cutting data.

The total gamma ray log records the total radiation in the formation, and does not distinguish between the individual radioactive elements in the specimen. For this purpose a spectral gamma ray or natural gamma spectrum sonde delivers the contents of the three natural radioactivity bearing elements: potassium (40K), thorium (232Th) and uranium (238U). The sonde measures not only the total counts of the incident gamma rays but a full spectrum of their energies from which a calibrated best-fit algorithm derives the U, Th, and K content in parts per million [ppm] and percent [%]. The SGR is used for e.g. lithostratigraphy construction, determination of heat production, identification of fracture zones, and estimation of the clay content.

7.1.5.3 Electric Resistivity

Resistivity logging measures the capability of the formation to conduct electric currents. Formation´s resistivity is mainly controlled by the amount and distribution of saline water (electrolytic conduction) and/or the existence of conductive minerals (metallic conduction, e.g. graphite, pyrite). For instance a porous and saline water filled formation shows low resistivity values, whereas formations filled with hydrocarbons (poor conductivity) show higher resistivities. Resistivity logs are e.g. used for lithostratigraphy and to estimate the water saturation. The unit of resistivity is ohmmeter [Ωm]. Different resistivity sondes with different depth of investigation allow to radially distinguish borehole-surrounding zones with varying resistivity due to the mud invasion during the drilling process. In massive rocks with very low matrix porosity/perm resistivity logs identify fluid filled fracture zones (fracture permeability).

7.1.5.4 Sonic

The sonic sonde measures the velocity of sound waves of formations, which varies depending on lithology, rock texture and porosity. It is determined by measuring the travel time of sonic pulses between acoustic (sonic) transmitters and at least two, often more, acoustic receivers. The velocity unit is meters or kilometers per second [m/s] or [km/s]. In logging data also common is the slowness, the reciprocal value of the velocity given in [µs/m], sometimes named interval transit time (dt). The sonic velocity is used for stratigraphic correlation, identification of compaction of lithologies, facies recognition and fracture identification and furthermore for ground truthing of surface seismic data and to derive the porosity of a formation.

A technical application of the sonic wave principle in downhole measurement is the evaluation of the strength of the cement bond between a casing string in a borehole to the rock of the borehole wall.

7.1.5.5 Density

A density sonde provides the formation´s bulk density, which is the sum of the solid matrix density (minerals forming the rock) and the density of fluids enclosed in the pore space. The sonde contains a radioactive source, which emits gamma rays. These are back-scattered by the formation and registered by gamma ray detectors (scintillation crystal) in the sonde. The more dense the formation, the more gamma rays are absorbed on their way through the rock and hence less gamma rays reach the detectors. The density is an important parameter for lithostratigraphy construction. It is also used to calculate the porosity of a formation. In conjunction with the sonic velocity data it is possible to calculate the acoustic impedance, and with the full sonic waveform to calculate rock strength.

7.1.5.6 Porosity

There are two downhole logging methods to determine formation porosity. The neutron porosity sonde measures the hydrogen content in the formation. A radioactive source emits neutrons, which are back-scattered and attenuated by hydrogen in the formation.

The nuclear magnetic resonance sonde delivers porosity by measuring the decay signal of the spin of hydrogen nuclei excited by an ultra-strong magnetic field generated by the sonde. This sonde directly determines porosity, pore size distribution and permeability. This sonde contains no radioactive source.

The traditional porosity tools (density, neutron and sonic) can calculate only a total porosity, whereas the NMR is able to divide the porosity into different pore size ranges (large pore for free fluids, pore in which the fluids are capillary-bound or irreducible, and clay-bound fluid). The NMR is almost independent of matrix type. The latter should be well known to calculate the porosity with traditional porosity logs. NMR can provide also information about fluid type (oil, gas, water).

In many sedimentary formations hydrogen content is equivalent with the pore space and hence a measure of the porosity. In other rocks, e.g. metamorphic and igneous rocks, hydrogen is also abundant as bound water in the mineral crystals yielding too high porosity values. This log is useful not just to derive porosity and formation water content, but also to identify lithologies as sand, limestone and shale/clay and fluid type. In oil & gas exploration density and neutron logs are run together to provide a good source of porosity data, especially in formations of complex lithology.

7.1.5.7 Dipmeter

The dipmeter sonde is a caliper sonde with electrode bearing pads mounted to the ends of the caliper arms. It provides both borehole geometry (caliper, deviation & azimuth) and the spatial orientation (dip and dip azimuth) of planar structures intersecting the borehole like planes of bedding, lamination, folding, faulting, fractures etc. These structures are detected by the electrodes as resistivity contrasts.

7.1.5.8 Magnetic Susceptibility

The magnetic susceptibility is the ability of the formation to be magnetized. The sonde imposes a magnetic field to the formation and measures the induced magnetic field. The magnetic susceptibility reflects the amount of magnetic minerals contained within the formation, in particular magnetite, as it has the strongest magnetic susceptibility of the major rock-forming minerals. This method determines the stratigraphic changes in mineralogy and lithology. It helps to localize boundaries of overlying lava flows and to identify zonation within a flow. In paleoclimate investigations of lake sediments it can act as a proxy for depositional conditions. In lake sediment drilling projects it is the most powerful parameter for both the core-log depth correlation as well as to fill in data at core gaps to provide a continuous profile.

7.1.5.9 Borehole Imager

For drillings using a drilling mud two imaging sonde types are available: acoustic imager and electric imager.

The acoustic imager (also called borehole televiewer) emits an ultrasonic pulse to the borehole wall and measures the amplitude and the travel time of the reflected signal. The sonic emitter rotates around the sonde axis and hence takes many measurements per revolution (typically between 70 and 300 pulses/rev). The amplitude of the reflected signal depends strongly on the acoustic impedance of the borehole wall yielding an acoustic impedance contrast image of the wall. The travel time measurement depicts variations of the borehole diameter, i.e. the caliper. This gives a caliper image of he borehole, which is at the same time a multi-arm caliper log with very fine vertical resolution. Depending on the hole diameter an image resolution (pixel size) of better than 5 x 5 mm can be achieved. The sonde is magnetically and gravitationally oriented.

The electric imager is basically an advanced dipmeter sonde but with much more and smaller electrode buttons on bigger pads. The small electrodes yield a pixel size of also 5x5 mm. This imager creates an image of electric resistivity contrasts. The sonde is magnetically and gravitationally oriented.

In result both imagers yield oriented high-resolution images of the borehole wall.

The analysis of both the acoustic and the electric images allows to detect and orient natural and induced fractures as well as breakouts in order to gain the present stress field orientation; moreover it allows in general to detect very thin beds, bedding, lamination, and layering. The set of fully oriented structures derived from imager logs and those derived from cores or core images can be used to orient these cores. Acoustic imager logs can also be used to inspect casing conditions.

7.1.5.10 Temperature and Fluid Resistivity

Logs of temperature and resistivity reflect the temporary status of the mud column inside the borehole. Both parameters show strong variations caused by drilling or testing activities inside the well but also by flow of fluids into or out of the formation due to the usually different salinity and temperature of formation fluids compared to the drill mud. Therefore these logs are the best indicators of active flow zones or open fractures respectively.

A temperature log almost always shows the mud temperature, and not the formation temperature. It represents a superposition of the original, undisturbed temperature field before drilling and the effects of mainly the mud circulation and other drilling process as well as hydraulic tests. Usually a deep borehole is cooled down in the lower half and heated up in the upper half. To estimate the original formation temperature several temperature logs have to be carried out repeatedly during several days without hydraulic disturbance in-between.

7.2 Kienzler B.: Conceptual ideas about the radio-geochemical monitoring in deep borehole disposal

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7.2.1 Introduction

To guarantee safe emplacement of nuclear wastes as well as safe operation of a nuclear waste disposal facility, various monitoring procedures are required. These procedures cover radiological monitoring with respect to the safety of the staff and environment, but also monitoring of the effects of the operation of the disposal on the affected geologic structures. According to the German atomic law, radiation protection law and other regulations, disposal of highly radioactive wastes in the deep boreholes requires the same monitoring efforts as in the case of disposal in a mine. The monitoring duration must range from the operational to the post-closure phase. The concepts applicable for monitoring vary depending on the disposal technology. The following contribution presents a short outline of conceptual ideas about the radio-geochemical monitoring and opens R&D issues in deep borehole disposal from the radio-geochemical point of view. Monitoring needs with respect to the overall performance of drilling, boreholes and technical devices are not considered in this contribution.

7.2.2 Radioactive waste and canisters

As outlined in /BRA 15a/ and /GRA 15/ about 11 000 Mg of spent nuclear fuel (SNF) assemblies from Boiling Water Reactors (BWR), Pressurized Water Reactors (PWR) and Water-Water-Energy-Reactor (VVER) and 7838 other canisters with vitrified and compacted high level radioactive waste have to be disposed of in Germany.

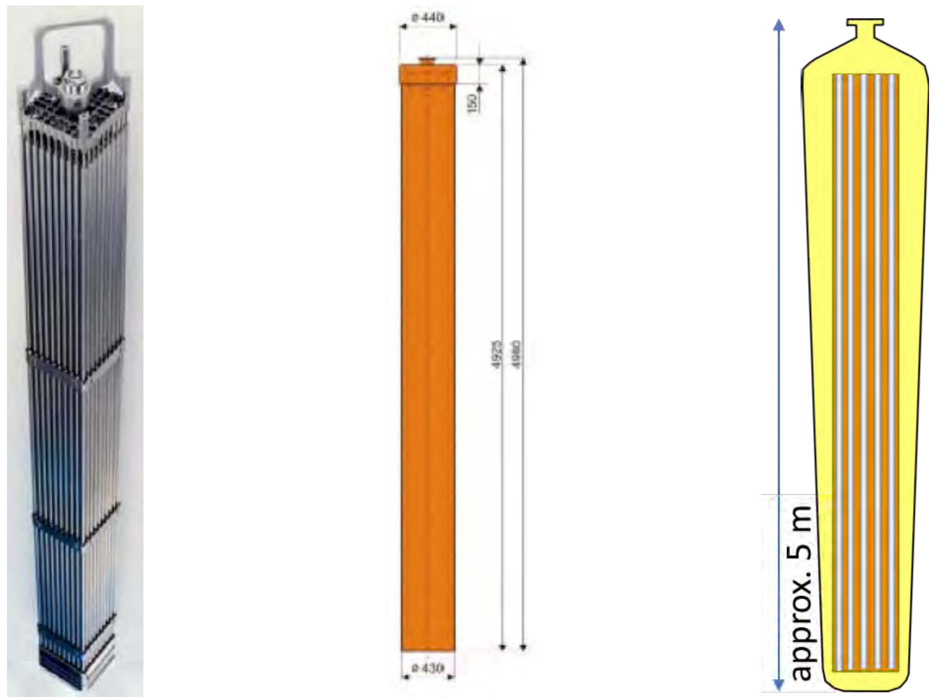
Tab. 7.2.1a High Level Radioactive Waste for disposal in Germany (Spent Nuclear Fuel assemblies)

SNF assemblies	UO_2 (pieces)	MOX (pieces)	UO_2/MOX mass per assembly	Dimensions
BWR	15 700	1 450	180 kg	L: 4 470 mm ∅: 134 mm
PWR	11 950	1 500	560 kg	L: 4 827 mm ∅: 230 mm
VVER	5 050		165 kg	L: 3 217 mm ∅: 145 mm

Tab. 7.2.1b High Level Radioactive Waste for disposal in Germany (Canister with vitrified and technology waste)

Canisters	AREVA (F)	BNFL (UK)	VEK (D)	Dimensions
High Level Waste Glass	3 024	580	130	L: 1 340 mm, ∅: 430 mm
Technology Waste	4 104	-	-	L: 1 340 mm, ∅: 430 mm

When discussing borehole disposal, the current concepts using the self-shielding POLLUX or CASTOR containers are not considered because of their size (POLLUX: diameter 1 560 mm) or weight (CASTOR: 126 Mg). Due to the available borehole techniques, it seems plausible that canisters for borehole disposal may be similar to the canister design proposed for drillhole disposal in a mined repository developed for the VSG /BRA 15b/. This concept, however, needs repacking of the spent fuel rods of the fuel assemblies into BSK2 or BSK3 containers.



Spent fuel assembly BSK2 BSK3

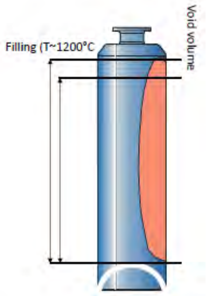
Fig. 7.2.1 BWR fuel element, canisters BSK2 and BSK3

Tab. 7.2.2 Data for BSK2 and BSK3 containers

Feature	**BSK2**	**BSK3**
Material	Steel 1.0566	Steel 1.0566
Diameter (outside)	420 mm	430 mm
Diameter (inside)	330 mm	350 mm
Length (inside)	4 800 mm	4 800 mm
Number of fuel rods	600	666 – 818
Mass (filled)	?	5 200 kg
Void volume	136 dm^3	158 – 89 dm^3

During the vitrification, the high level radioactive waste glass is poured into stainless steel canisters made of 1.4833 Cr-Ni steel with a thickness of 5 mm. Due to the shrinkage of the glass volume by more than 10 % during the cooling from melt temperature (~1 100 °C) to the transformation temperature (~500 °C), the 150 L canister has a void volume in the range of about 20 liters.

Tab. 7.2.3 Data for containers with vitrified High Level Radioactive Waste

Parameter	**Guaranteed data**	
Height	1 340 mm	
Diameter	430 mm	
Waste oxide loading	≤ 19 %	
Total alpha activity	≤ 10^{14} Bq	
Total beta/gamma activity	≤ 10^{16} Bq	
Total mass of U	≤ 7,200 g	
Total mass of Pu	≤ 190 g	
Decay heat power	≤ 734 W	

7.2.3 Regulations and safety requirements in Germany

Several regulation and safety requirements are defined in Germany and have to be complied. The following but not exhaustive list includes the most important regulations valid in Germany on the purpose of handling radioactive materials:

15. Atomic Act, as of 1.4.2015 (BGBl. I S. 434) /BUN 15/
16. German Site Selection Act as of 23.7.2013 (BGBl. I S. 2553) /BUN 13/
17. COUNCIL DIRECTIVE 2011/70/EURATOM as of 19.7.2011, Official Journal of the European Union, L199/48, 2.8.2011 /COU 11/
18. Radiation Protection Ordinance (StrlSchV) as of 11.12.2014 (BGBl. I 2. 2010) /BMU 01/
19. Safety requirements for disposal of heat generating radioactive waste, 2010; /BMU 10/
20. German Nuclear Safety Standards (KTA)
21. …

For discussing the concept of disposal in deep boreholes the following requirements are given in the Safety Requirements:

- A time frame of 1 million years is set for the safety case.
- The evolution of the hydrogeological system has to be described.

- The integrity of the confinement providing rock zone has to be shown using criteria for dilatancy or fluid pressure.
- A complete retrieval of the disposed waste needs to be guaranteed until the final closure of the disposal (borehole).
- Handling of canisters needs to be possible (for recovering) without a release of radionuclides for a minimum of 500 years after closure of the facility.

These requirements are technical challenges which have to be addressed in a safety case.

Tab. 7.2.4 shows the limit for unlimited release of some radionuclides according to the German radiation protection ordinance and the content of a BSK3 container holding 818 PWR rods. This comparison demonstrates clearly that even minor amounts of the wastes released into a deep borehole during the disposal operation could cause severe problems with regard to the radiation protection requirements.

Tab. 7.2.4 Threshold value for unlimited release for some nuclides compared to their concentration in BSK3 container

Nuklide	**Threshold value**	**Half-life**	**BSK3**
Unit	[Bq/g]	[y]	[Bq/g]
^{99}Tc	10	210 000	~ $3.1*10^5$
^{129}I	0.4	15 700 000	~ $6.9*10^2$
^{239}Pu	0.04	24 110	~ $5.6*10^6$

7.2.4 Disposal techniques and time needed

The information used in this paragraph was taken from presentation of the /BAT 14a/, /BAT 14b/, /BES 14/, /BRA 09/, /BRA 09/, /GIB 08/, /GRU 14/, /HAR 00/, /HOA 06/, /PUS 12/. A depth of the borehole of 5 km was assumed. The time needed to drill a borehole with a diameter of 610 – 660 mm is estimated from several months up to one year. One can assume that the borehole is equipped with a liner in order to keep the diameter open especially down to the designed disposal depth. It seems not likely, that a deep borehole can be kept dry during the drilling phase and after construction. Drilling muds may be replaced and it is not clear if and which fluids will be present in the steel tube (liner) during an emplacement and thereafter.

Aside from the free fall of a container in a borehole, which without doubt should not be occur from the viewpoint of operational safety, an emplacement can be performed using wirelines, a drill pipe or coiled tubing. Details can be found elsewhere /BES 14/. The time needed for emplacement of a single canister is estimated to be 8 hours when using wirelines or coiled tubing. Using drill pipes it is estimated to be approx. 18 hours for emplacement of a single canister.

Disposal of about 400 canisters (length 5 m, diameter 508 mm) in a depth from 3 to 5 km may then take 2 – 3 years when assuming approx. 1 canister per day for emplacement.

The sealing of the borehole and other final operations is estimated to take 1 year. So the total operation time of a single borehole site may be about 4 – 5 years.

7.2.5 Monitoring

7.2.5.1 General

The disposal and monitoring in the operational phase have to be done according to the requirements of the current KTA (The Nuclear Safety Standards Commission) and radiation protection standards. These standards include hot cell conditions and remote handling techniques, as during the disposal procedure the canisters are unshielded. All disposal operations at the site of the borehole have to comply with the general requirements.

- Every canister must have a unique ID.
- The tightness of the canister has to be ensured.
- The stress leveling of canister has to be given.
- Any deadlock must be manageable for retrieval.
- The contamination of disposal tools (wire, hook, pipe, tubing) must be checked.
- The conditions in the borehole must be monitored until closure.

Parameters to be monitored are amongst others the humidity, the temperature, the radiation field, gas generation and composition etc.. Interactions of casing, grouting and other functionalities have to be monitored as well.

In the Euratom 7th Framework Programme, the project MoDeRn addressed monitoring of a mined repository and it was aimed to provide a reference framework for development and possible implementation of monitoring activities during waste disposal processes. The topics included site characterization, construction, operation, staged closure and post-closure institutional control phase as well as stakeholder engagement (Who owns the data to be monitored?). In the project MoDeRn (2009-2013) following parameters were identified to be monitored:

- Temperature
- Mechanical pressure
- Water content & humidity
- Hydraulic pressure
- Radiation
- Displacement
- Gas concentration (O_2, CO_2, H_2 & CH_4)
- Gas pressure
- pH & Eh
- Concentration of colloidal particles
- Alkalinity

Not all of these parameters will be possibly monitored in the post closure phase in the borehole itself.

Not all of these parameters can be monitored in the post closure phase in the borehole, especially if a long-term monitoring is considered. Monitoring is an important topic for public acceptance along with public access to the data. Nuclear legislation / standards (see Safety requirements) will not become less restrictive in future. Today appropriate procedures may change and the number of parameters to be monitored may increase. Therefore research is ongoing.

7.2.5.2 Tools

Monitoring tools are applied regularly for underground injection control for CO_2 storage and in the field of geothermal exploration.

Oxygen-activity logs and temperature logs were used to assess external mechanical integrity of the wellbore. Oxygen-activity logs are able to measure the direction and velocity of water movement around the casing. If water is detected moving outside of the casing, this may indicate a loss of external mechanical integrity. Temperature logs can be used to identify fluid fluctuations that may indicate a poorly sealed wellbore.

Another possibility is the use of a Radioactive Tracer Survey (RTS) with γ-logger. Radioactive tracers can be used to monitor internal mechanical integrity during injection (I-131, $t_{1/2}$ = 8 days). Tracer is released within the casing and the subsequent gamma ray response is measured through a series of probes. This log is then compared to a baseline gamma ray log (without tracer) in order to identify any anomalies. Differences between the logs may indicate potential fluid movement and internal casing releases.

In order to detect or to confirm the presence of high permeability zones or water inflows during well drilling further tools can be used:

- Continuous helium (He) gas analysis on site for the isotopic ratio using a mass spectrometer (e. g. ALCATEL ASM 100) directly connected to the well can be carried out with an analytical uncertainty of 0.02 ppm. He-3 makes only 0.000137% of atmospheric He with the bulk being He-4. However, the decay of H-3 to He-3 can produce a local and significant variation in the Helium isotopic ratio. Thus even small amounts of He-3 can perturb the He-3:He-4 ratio and provide the potential to detect canister failure. Having a large He-4 background, a strong He-4 production would be needed to perturb the signal and subsequently the He-3:He-4 ratio, which needs to be tested within a R&D program.
- Xenon isotopes are a product of fission and encased in the fuel rod. They are also a product of spontaneous fission, dominated by even-mass-number isotopes of Pu, Am, Cm and Cf but total spontaneous fission yields are not large. Xenon isotopes are encased in fuel rods. Since the fissiogenic isotopic ratios of Xenon in fuel rods vary compared to the natural background detection the analysis of the isotopic composition of Xenon could allow the delineation /DRE 06/ and therefore the detection of the leakage of disposed container and fuel rods in the deep borehole.

7.2.5.3 Expected conditions

Compared to operating conditions in the reactor (325 °C and higher, 16 MPa) the temperature in the borehole at 5 km depth will be lower (approx. 150 °C + the heat load of the spent fuel) depending on the temperature gradient. The hydrostatic pressure will be above 50 MPa. Spent fuel rods were designed to withstand these conditions for the time of operation in the reactor.

If the use of tight liner is foreseen to provide a dry borehole, then the tightness of the liner has to be monitored regularly during disposal operation. Any fluid has to be detected in order to prevent corrosion of the canisters. Any contamination in the gas phase (e.g. fission gas Xenon) has to be monitored.

If the casing is perforated in the disposal zone, then the borehole will be wet and a corrosion of the canisters with hydrogen generation will occur. Depending on pressure evolution at the disposal depth and the stability of the canisters as well as on the corrosion of the canister materials, a contamination of fluids is possible and has to be monitored.

7.2.5.4 Post-closure

Any planning disposal of radioactive waste in deep boreholes requires the demonstration of some key technical features. This includes the long-term integrity of borehole seals, plugs and grout and the availability of equipment and approaches for monitoring in the post-closure phase.

Currently new materials under development may facilitate this monitoring e.g. self-monitoring fibers or seals that communicate their performance with new technologies, which sense wall rock bonding or fracture densities /BRA 15c/, /CUS 15/.

7.2.5.5 Corrosion

7.2.5.5.1 Corrosion studies

Fluids at the disposal depth in deep boreholes contain a high salinity which causes corrosion processes of many metals, especially under the elevated temperature conditions. Corrosion studies which can be considered relevant for conditions of a wet borehole have been performed on different metals. In these experiments, typical solutions were either 4 M $MgCl_2$ solutions or saturated NaCl solutions and were performed under reducing conditions (autoclaves). The temperatures ranged from 35 to 200 °C. The pressure was varied between 0.1 to 13 MPa with most experiments in the range from 5 – 13 MPa. The size of different metal samples was 40×20×4 mm^3. A series of experiments were performed under gamma-irradiation simulating a relatively thin-walled canister /SMA 02/, /SMA 99/, /SMA 99/, /SMA 04/, /SMA 95/, /SMA 97/. The experiments comprised fine grained steels, Hastelloy C4, Ti-Pd and Cu alloys.

The Fig. 7.2.2 illustrates the experimentally determined reduction in thickness of carbon steel samples 1.0566 versus time under the different temperatures in $MgCl_2$ solutions. This steel was selected as it showed a more or less general corrosion behavior without tendency of localized corrosion processes (pitting corrosion).

The reduction in thickness of the 1.0566 steel is clearly depending on the temperature. At 200 °C the thickness reduction amounts up to almost 1 mm within 2 years. Significant increase of corrosion rates or thickness reduction was observed under irradiation, or if sulfides were present in the solutions. Furthermore, the pH is another parameter of extremely high importance.

A Ti Pd alloy showed very little corrosion under these conditions also without localized corrosion. However, the effect of contact corrosion between different materials having different electronegativity's "local elements" was shown in the Fig. 7.2.2. The rate calculated for the 1.0566 steel which was in contact with TiPd at 170 °C for about 13 years is about 50 µm/a (each side of the metal sample). These results demonstrate the need of avoiding contact corrosion by selecting the different metallic materials accordingly (canister, liner, etc.) or substitute the material by other metals (e.g. copper or copper coating). This needs certainly to be monitored.

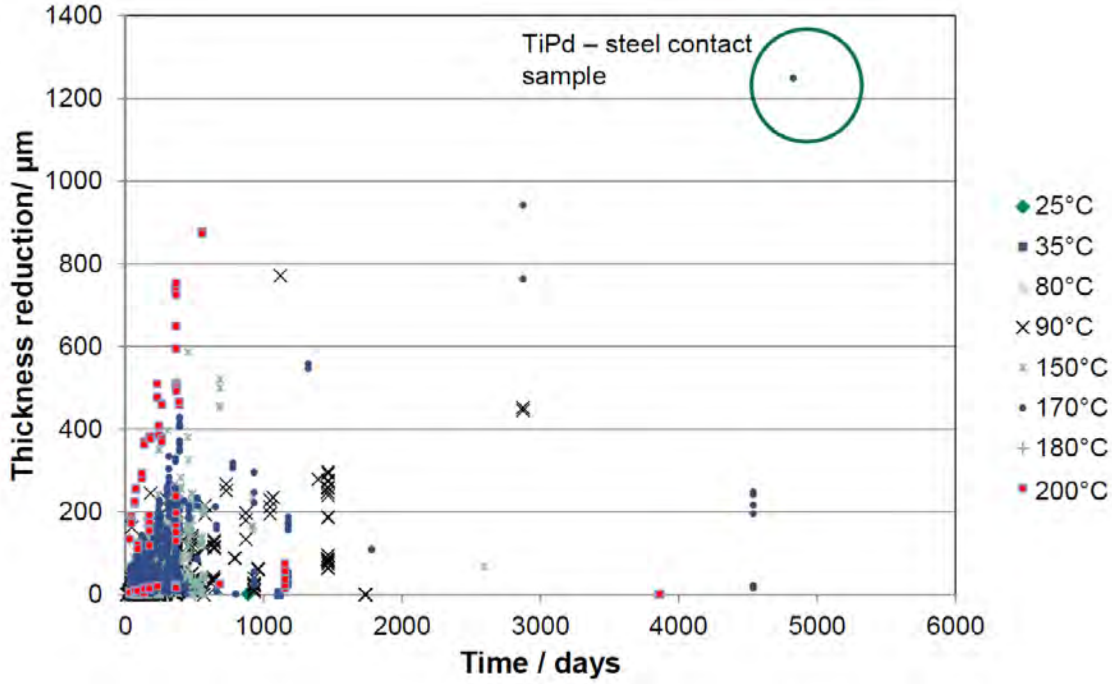


Fig. 7.2.2 Reduction in thickness of steel plates by corrosion with brines versus time

7.2.5.5.2 Hydrogen generation

A corrosion rate of 500 µm/a and unlimited water access is used as a conservative approach in the following modeling of a corrosion scenario. Applying this corrosion rate on a canister of a diameter of 500 mm, a length of 5 000 mm and a steel density of 8 g/cm^3 yields a total mass of corroded iron of 561 mol Fe generating up to 746 mol H_2 per year and container. This is equivalent to a gas volume of 16.7 m^3 under standard conditions.

A comparable calculation for hydrogen generation by radiolysis yields only 0.7 mol H_2 per canister and year, assuming a dose rate of 4 Gy/h, a $G(H_2)$ of 0.047 µmol/Gy and 432 kg water surrounding the canister.

From this data it can be concluded that the generation of hydrogen needs to be monitored during the operation phase to detect corrosion and to avoid explosive hydrogen-air mixtures, if presence air cannot be excluded.

Besides hydrogen, the corrosion of steel generates corrosion products with a lower density in comparison with steel. The corrosion products increase the volume of the solids around the disposed canisters.

Considering 561 mol Fe/y/canister, the increase in the solid volume by corrosion products is 23.9 l. This increase in water saturated volume of more or less crystalline Fe-OH-Mg/Na phases may potentially prevent grouting or complicate considerably recovery or retrieval of canisters. Therefore corrosion processes need to be considered and monitored, if possible.

Tab. 7.2.5 Volume of educts and products of steel corrosion

Reaction	3 Fe	+	4 H_2O	→	Fe_3O_4	+	2 H_2
Mol	3		4		1		2
Mass	171 g		72 g		235 g		4 g
Volume (solid)	21.4 cm^3				47 cm^3		
Volume (solution)			72 cm^3				
Volume (gas)							44.8 cm^3

7.2.6 Radionuclide detection techniques and applications for deep boreholes

The concept of disposal in deep borehole may change the transport pathways under investigation compared to disposal in a mined repository. The disposed waste is an order deeper than in a mined repository. The concept shall make use of the expected very low bulk hydraulic conductivities ($<10^{-11}$ m/s) usually found at such depths, even in fractured rocks. The density stratification combined with low lateral flow rates and almost non-existent vertical flow shall ensure that any radionuclides that eventually escape from the waste packages and disposal zone will go effectively nowhere in 1 Mio. years. Therefore highly sophisticated analytical techniques are needed to study these processes and to substantiate this assumption.

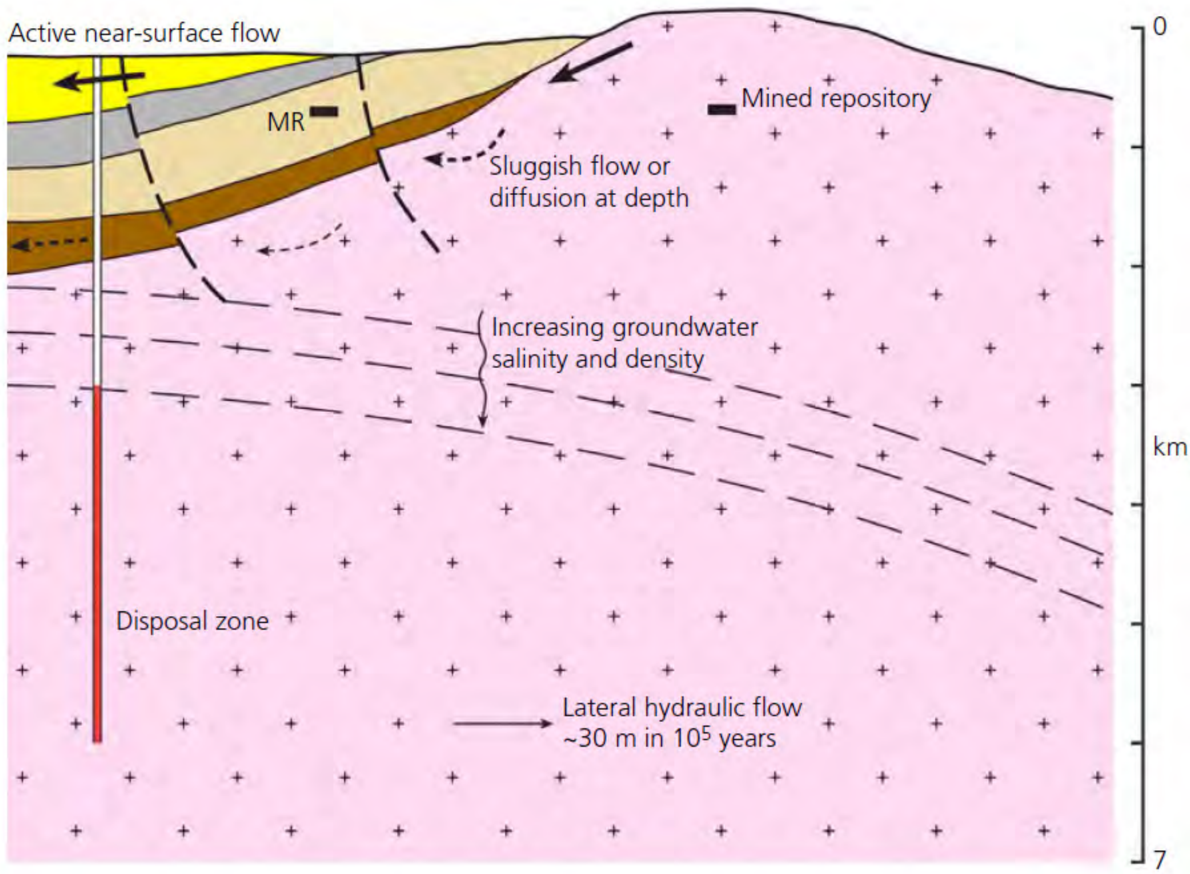


Fig. 7.2.3 Schematic sketch for disposal in a borehole and a mined repository in a granitic environment (graph taken from /BES 14/)

Drilling muds are used to drill deep boreholes and specifically to stabilize the borehole from break-outs. The composition can include inter alia bentonite suspension, polymers and deflocculants with different densities adjusted by variable amounts of barite [22]. The influence of residues of these highly sophisticated muds that may remain in deep boreholes on radionuclide mobility, when released from the container is currently unknown and has to be investigated.

Tab. 7.2.6 Drilling muds

Category	**Components**	**Concentration**
Clay	Bentonite, attapulgite, sepiolite	60 - 70 kg/m^3
Polymer (Protective Fluid)	CMC, PAC, Strach, PAA, VS/VA	10 - 20 kg/m^3
Deflocculant / Dispersant	Lignosulfate, SSMA Polymer	3 -6 kg/m^3
Regulator of alkalinity	Sodium Hydroxide, Carbonate	pH 9 - 10

7.2.6.1 Experiences in Germany

Experiences from the KTB borehole exhibited water influx at several depths from open fractures and a surprisingly high hydraulic conductivity of $4 \cdot 10^{-8}$ m/s of the 4 km depth fractured crystalline rocks showing possible advective flow conditions in the continental upper crust. A study from /STO 99/ of deep groundwater (3 - 4 km depth) in the crystalline basement of the Black Forest showed a mean permeability of Black Forest granite of about $K = 10^{-6}$ m/s and a significantly lower permeability in gneisses with mean $K = 5 \cdot 10^{-8}$ m/s leading to a preferential flow through granite. These highly permeable fracture and fault zones, particularly in granite, are groundwater ascent channels for high-TDS saline deep groundwater. Details on the KTB borehole are found elsewhere in these proceedings.

7.2.6.2 Analytical techniques

Examples of analytical techniques are presented in the following.

- A highly sensitive analytical technique is the Accelerator Mass Spectrometry (AMS) /QUI 15/. This technique allows studying concentrations below the ppq-level and has been applied to trace the nuclear weapons fallout and the mobility of radionuclides in fracture systems. As a result it was possible to show that U-236 from the weapon fallout is present in the background of samples from the Grimsel Test Site (GTS, Switzerland), but no Pu was detected.
- The colloid formation and migration with radionuclides can be relevant for granitic rocks and was studied at the Grimsel test site. The process of desorption as well as fast exchange processes was investigated in detail. Using the Laser Induced Breakdown Detection (LBID) the migration of contaminants in the presence of colloids was detected /REI 15/.
- Continuous helium (He) gas analysis on site using a mass spectrometer ALCATEL ASM 100, directly connected to the well can be carried out with an analytical uncertainty of 0.02 ppm. Isotopic ratios of He can be used since He-3 makes only 0.000137% of atmospheric He with the bulk being He-4. A strong He-4 production would be needed to change significantly the He-3/He-4 isotopic ratio. However, the decay of H-3 to He-3 can produce a local and significant variation in the He-3/He-4 isotopic ratio. Thus even small amounts of He-3 can perturb the He-3/He-4 isotopic ratio and provide the potential to detect canister failure.

- Xenon isotopes are a product of fission and encased in the fuel rod. They are also a product of spontaneous fission, dominated by even-mass-number isotopes of Pu, Am, Cm and Cf. Total spontaneous fission yields are not large in the Xenon isotopes of interest but Xenon encased in fuel rods has a fissiogenic composition. Since the fissiogenic isotopic composition of Xenon vary compared to the natural background the analysis of the isotopic composition of Xenon could allow to delineate its source /DRE 06/. This would allow the timely detection of the leakage of disposed container and fuel rods in the deep borehole in the gaseous phase.

7.2.6.3 Transport processes

Transport processes on the formation scale using the host rock as a self-analogue investigating diffusion controlled transport by stable isotope analysis have been studied at the Mont Terri Underground Research Laboratory /MAZ 11/. Without going into detail it was possible to show that tracer profiles record the evolutions over the last 1-10 Mio years and demonstrate that transport on the formation scale can be described by assuming solely diffusion even though fractures are present.

7.2.6.4 Source term

Unlike vitrified HLW SF in standard fuel rods has easily mobilized fractions of several radionuclides in gaps and in fuel grain boundaries. If a container with fuel rods is breached, then this ‘instant release fraction’ has the potential to contaminate the fluid in a deep borehole. This may be the case in the event of a serious accident or jam that destroys the integrity of the container. This may be resolved by more robust packages as in a GDF. The question is whether the radiological consequences at the surface with or without recovery or afterwards could actually be significant if the borehole is not already sealed and abandoned, and whether if it would matter economically to give up a single borehole. In case of an incident the source term and the transport processes of radionuclide will be analyzed differently compared to the disposal in a deep borehole.

The chemical speciation of easily mobilized radionuclides (^{135}Cs, ^{129}I, ^{14}C, ^{79}Se, ^{99}Tc and ^{126}Sn), which can instantly be released from the container and behavior of fission gases / noble gases (He, Xe) have to be determined in a case of an incident. In addition to the detection of radioactive isotopes as contaminants the detection of fissiogenic isotopes by analyzing isotopic ratios may be a valuable tool.

7.2.7 Conclusions

Besides many standard tools for monitoring boreholes further tools for monitoring radioactive waste in deep boreholes in the operational and closure phase are available in principle.

Measurement of hydrogen would allow assessing the corrosion process of canisters.

Tracer profiles give very valuable information on hydraulics on formation scale and drilling operations should be optimized to guarantee to find the best possible undisturbed locations.

The highly sophisticated AMS technique could detect trace amounts of U, Pu, Np, Am, Cm down to 10^4 atoms, but is currently not available as routine or monitoring technique.

Measurement strategy & technique on radionuclides and noble gas isotopes has to be adapted to the conditions of DBD but would allow the detection of leakages. Definitely, all the points listed above show the needs of R&D programs to be initiated.

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7.3 Eichinger F.: Transport of dissolved constituents in low permeable bedrock within the nuclear waste deposition in deep boreholes - Requirements on deep borehole disposal from the hydrogeological/hydrogeochemical point of view

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7.3.1 Abstract

Water present in fractured and layered aquifers and in the diffusive accessible rock matrix is the main transport media for potential released radionuclides during the disposal and storage of radioactive waste. Within the safety assessment of potential nuclear waste disposal sites the hydrogeological systems have to be detailed investigated down to depths, which clearly exceed the planned disposal level. For the disposal of radioactive waste in deep boreholes state of the art methods for the investigation of hydrogeological / hydrogeochemical parameters, which are applied in repository designs, have to be adapted to high temperature, high pressure and limited space conditions. Necessary investigations during the site characterisation / safety assessment, drilling and operation/monitoring phase are compiled here.

7.3.2 Introduction

Water present in layered and fractured aquifers as well as in the inter- and intragranular pore space of rocks (porewater) is the main transport media for dissolved constituents (ions, gases, radionuclides) in natural underground systems.

Radionuclides, which might be released into the geosphere after the disposal of spent nuclear fuel and high-level waste, enter the porewater in the inter- and intragranular porespace by diffusion. The porewater again interacts by diffusion with groundwater (Fig. 2.3.1). Hence, the natural porespace serves as retardation reservoir for released radionuclides.

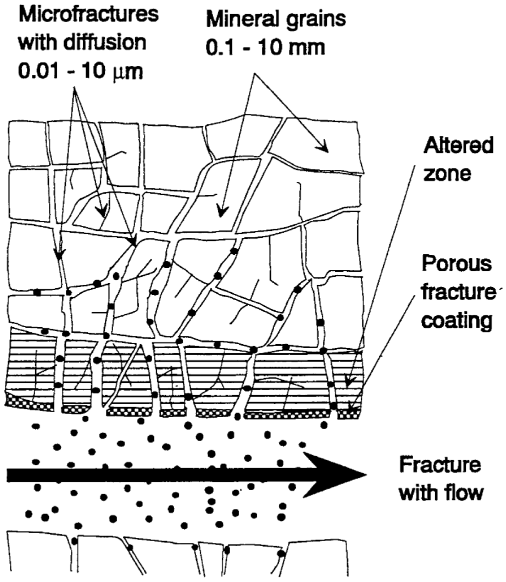

Fig. 7.3.1 Schematic Illustration of the transport of potentially dissolved radionuclides (black dots) in fractures and low permeable rock matrix, which serves as retardation space (/EIC 09/, modified after /RAS 97/).

Within the safety assessment of potential nuclear waste disposal sites the hydrogeological systems are investigated in detail down to depths, which clearly exceed the planned disposal level.

Thereby the natural groundwater systems are investigated for their hydraulic as well as chemical and isotopic composition to gain knowledge about the chemical characteristics, mean residence times and interaction of different groundwater components. Furthermore porewater of the occurring host rocks is investigated conducting in-situ and laboratory experiments to evaluate transport and retardation characteristics of the individual rocks and get information about the groundwater-porewater interaction and hence the palaeohydrological history of an investigation site (i. a. /MAZ 11/, /PEA 03/).

Due to the challenge to avoid entering of radionuclides into the biosphere within a period of several hundreds of thousands of years, a reconstruction of the palaeohydrological history of an investigation site is necessary /WAB 12/.

This can be done by detailed investigation of the ground- and porewater systems and a subsequent modelling of their interaction.

The task for the disposal of radioactive waste in deep boreholes is to adapt the state of the art methods for the characterisation of hydrogeological/hydrogeochemical systems, which are developed for the underground repository designs to the existing conditions.

The challenge is to adapt these methods to the great depths (3-5 km below surface), the high temperatures and pressures as well as the small space within the boreholes.

In the following, the tasks and potential processes for a hydrogeological/hydrogeochemical evaluation in terms of safety assessment of a radioactive waste disposal in deep boreholes are comprehensively explained. The suggestions of the individual methods and parameters are based on the programmes conducted within the investigations of underground repositories all over the world.

7.3.3 Mandatory knowledge

For a sound safety assessment and evaluation of a potential underground site the disposal of radioactive waste in deep boreholes the hydrogeological and hydrogeochemical settings have to be investigated and understood. Therefore multidisciplinary studies, including besides hydrological also i. a. geophysical, geological, mineralogical investigations have to be conducted and integratively interpreted. In terms of the hydrogeologial/hydrogeochemical evaluation of such a site following parameters have to be investigated and evaluated:

- Location of fracture networks and fault zones
- Occurrence of groundwater and groundwater flow paths
- Hydraulic properties of individual fractures and fracture systems
- Chemical and isotopic composition of individual groundwaters including gases and noble gases
- Interaction of individual groundwater components
- Mean residence time of groundwaters
- Transport properties of dissolved constituents (ions, gases, radionuclides) in the rock matrix and plugging/backfilling material (incl. sorption)
- Chemical and isotopic composition of matrix porewater and gases dissolved in porewater to achieve information about the palaeohydrogeological settings of an investigation site and about the porewater-groundwater interaction

- Composition, texture and petrology of fracture fillings and coatings as well as fluid inclusions in fracture material and host rock minerals
- Water-rock-material interaction of plugging / backfill material under in situ conditions.

All these parameters can be investigated in in-situ experiments, adapted to deep boreholes and laboratory experiments using naturally saturated core samples. All these parameters above are related to natural occurring tracers. The thereby gained information can be interpolated for artificial radioactive elements. Therefore additional laboratory experiments using certain radioactive tracers might be necessary.

7.3.4 Hydrogeological/hydrogeochemical requirements on the safety assessment of a planned nuclear waste deposition in deep boreholes

7.3.4.1 Tasks

For a sound safety assessment the state of the art methods for a hydrogeological/hydrogeochemical site characterisation have to be adapted, developed and designed for the deep borehole disposal.

The main tasks thereby are

- Evaluation of the high responsibility for the natural barrier due to limited extend of the technical barrier
- Performance of in situ experiments and in situ data generation in high temperature, high pressure milieus under limited space
- Obtainment of representative groundwater and core samples.

In the following tasks and requirements in the consecutive phases of the exploration, investigation, building and operation of a deep borehole repository for nuclear waste are shown.

7.3.4.2 Site characterisation / Safety assessment

The basis for a safe operation of a deep borehole disposal of spent nuclear fuel is a detailed and sound site characterisation with subsequent and integrated safety assessment. Due to the fact that water is the main transport medium for potential released radionuclides the investigation of the hydrogeological and hydeogeochemical conditions of an investigation site is of particular importance.

Additionally, a correlation with geological, mineralogical and geophysical data is necessary.

The required hydrogeological/hydrogeochemical programme comprises:

- Investigation and evaluation of shallow and deep groundwater circulation in a proposed investigation area based on chemical, isotopic and hydraulic data sets
- In hole and cross hole in situ diffusion experiments (bedrock, plugging material) to determine the diffusion of natural and artificial tracers in the rock matrix under in situ conditions and to determine the retardation capacity for radionuclides of the bedrock (natural barrier) under in situ conditions (Fig. 7.3.2).
- Determination of transport properties of natural and artificial tracers of individual lithologies of the encountered bedrock by out-diffusion and through diffusion experiments using naturally saturated core samples
- Characterisation of the palaeohydrogeological history of a bedrock system from the surface down below disposal depth
- Set-up of a hydrogeological and hydraulic model for a proposed investigation area, which exceeds the disposal depth.

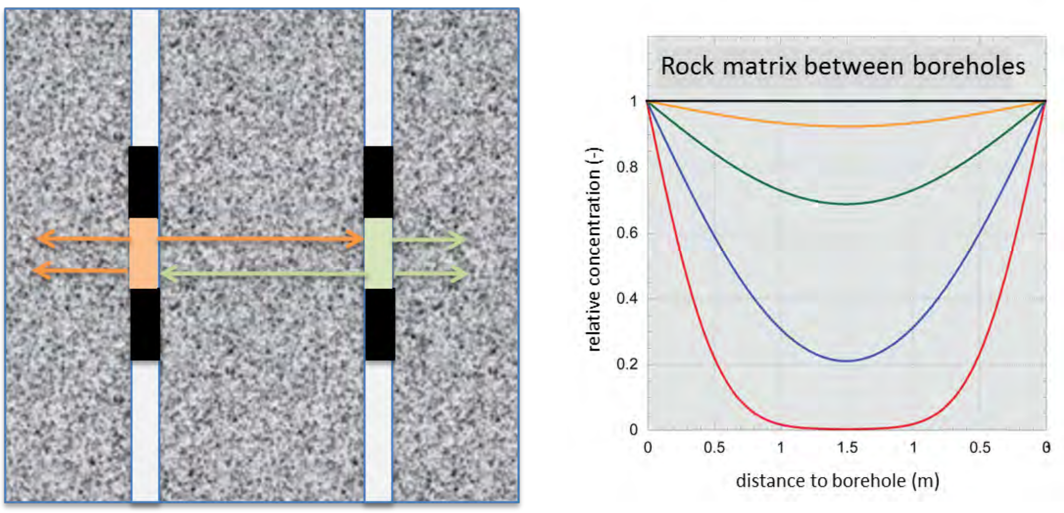

Fig. 7.3.2 left: Schematic illustration of potential cross-flow in situ experiments;
right: diffusive equilibration of potential ion concentrations within the rock matrix at different times (coloured diffusion profiles)

7.3.4.3 Drilling

Experimental boreholes, which exceed below the deposition depth are necessary for the conduction of i. a. hydrogeological/hydrogeochemical investigations and experiments for safety assessment reasons.

Thereby following requirements on the drilling technique exist:

- Continuous coring, application of tracered drilling fluid and recovery of good quality cores and minimising and control of the formation of a drilling disturbed zone and stress release
- Detailed borehole logging and fracture/aquifer specific hydraulic tests and sampling

During the drilling of the actual disposal hole, the above criteria have to be fulfilled and the entrance of water has to be monitored and the water sampled before cementation.

7.3.4.4 Hydrogeochemical monitoring during operation

Concepts for a hydrochemical monitoring of a deep borehole disposal site have to be developed and tested even during the safety assessment phase to observe a potential release of radionuclides into the biosphere or any changes of the hydrogeological system as early as possible. In situ monitoring after borehole closure should be done directly in the borehole by e.g. installation of analyses probes and in monitoring wells, which are drilled around the disposal borehole (Fig. 7.3.3). Therefore a regional monitoring grid has to be developed and installed.

During the filling, closure and storage phase following parameters and effects should be monitored:

- Water entrance in the borehole
- Potential release of radionuclide during borehole filling
- Radioactivity and changes of hydrochemical parameters in monitoring boreholes

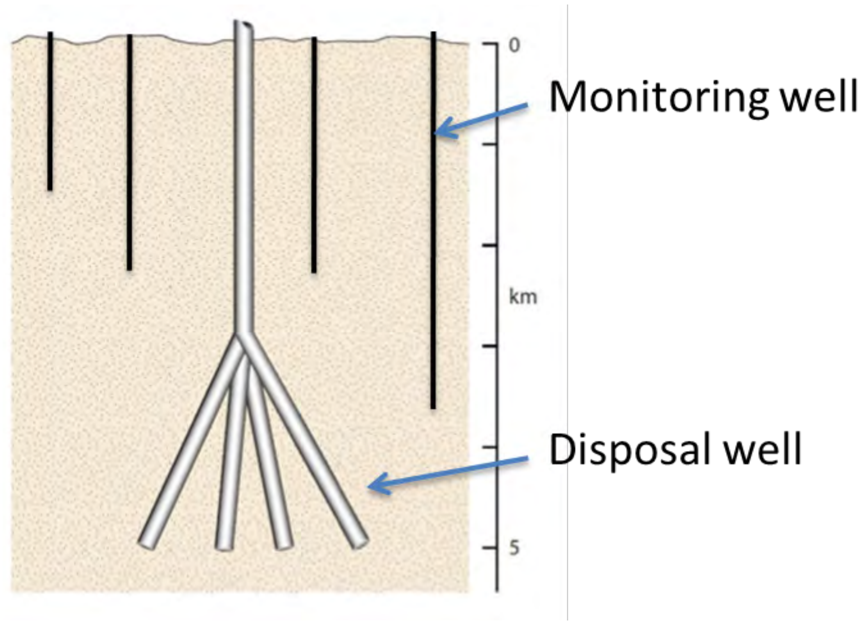

Fig. 7.3.3 Well concept for the regional monitoring of a potential radionuclide release and change of hydrochemical parameters (Disposal well concept adapted after /HIP 10/).

7.3.5 Conclusion

From the hydrogeochemical and hydrogeological point of view, high demands on the development and adaptation of methods for the evaluation of potential sites for the disposal of high level radioactive waste in deep boreholes have to be made. One major task will be to adapt state of the art methods, which are applied in repository designs to the high temperature, high pressure and limited space conditions in deep boreholes. Nevertheless, the disposal of high level radioactive waste in deep boreholes can be an alternative to the repository designs especially due to the extend of the natural geological barrier. Therefore this disposal concept should be open discussed and considered as deposit alternative.

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7.4 Merkel B.: Thermodynamic modeling of geochemical reactions under high pressure and temperature conditions

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7.4.1 Introduction

Spent fuel and hot radioactive waste may be buried at a certain depth in the earth's crust. While mining type repositories are planned at depths of 800 to 1 200 m, 4 to 6 km and even more are possible for borehole repositories. Yet, independent of the depth the most important questions with respect to the hydro-geochemical characterization of the potential repository are the following:

Is groundwater present? If this is the case, the next question is whether this water occurs as pore water or as water in fractures. After that the hydraulic and chemical properties (permeability of the rock(s), pressure, temperature, redox conditions, trace minerals) of the site have to be examined and whether the flow is density-driven or not. Then further chemical issues like diffusion-controlled processes on the one side and chemical reactions at high pressures and high temperatures on the other side have to be studied, because they significantly impact the speciation of elements and the precipitation or dissolution of minerals. Other important processes one has to consider are sorption and the generation of gases under the respective boundary conditions (temperature and pressure).

7.4.2 Method

Assuming for example a groundwater with a temperature of 12 °C, a pH of 6.5, 200 ppb of uranium and 25 ppb of arsenic at a pressure of 0.1 MPa and a concentration of the major elements in mol/L the speciation can be calculated assuming thermodynamic equilibrium conditions.

PHREEQC /PAR 14/ version 3.06 was used for calculating the species distribution using different common databases (Wateq4F, Minteq.V4, Lawrence Livermore National Laboratories (LLNL), SIT, NEA 2007, Hatches).

7.4.3 Results and Discussion

Fig. 7.4.2 shows that even for this very simple example the results for the uranium speciation are extremely different. This is due to the fact that phosphorus was assumed to be a constituent in the water.

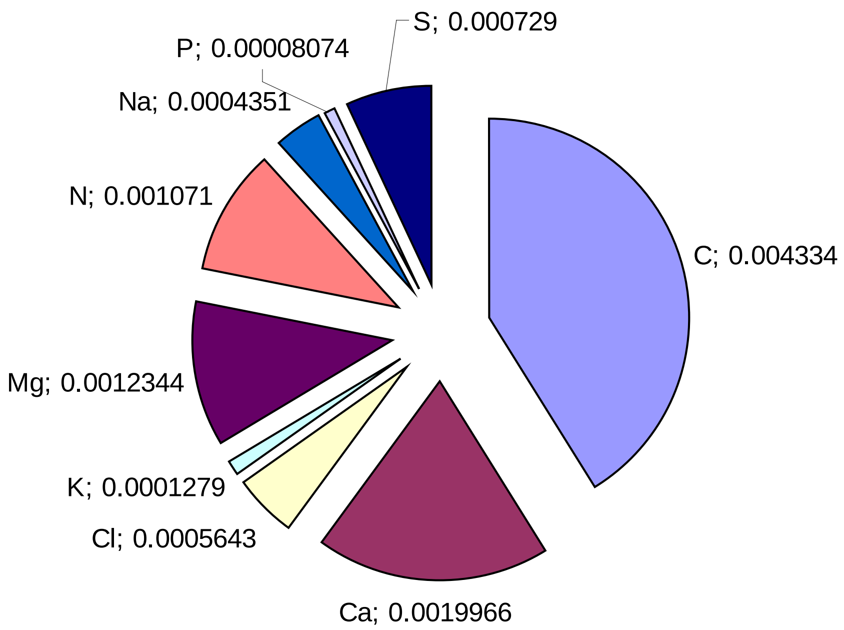

Fig. 7.4.1 Assumed chemical composition of a groundwater (mol/L) with respect to major cations and anions plus uranium (200 µg/l) and arsenic (25 µg/L) not shown in the diagram

The reason for the very different results shown in Fig. 7.4.2 is that very different thermodynamic data on uranium-phosphate species is published and has been selected and incorporated in different ways in the respective databases. It is beyond the aim of this paper to discuss which database is more suitable and realistic for this specific case. It is worth mentioning that even without phosphorus the distribution of the uranium species is not the same for the five databases used because these five databases also contain considerably different data on uranium-carbonate and uranium-hydroxide species.

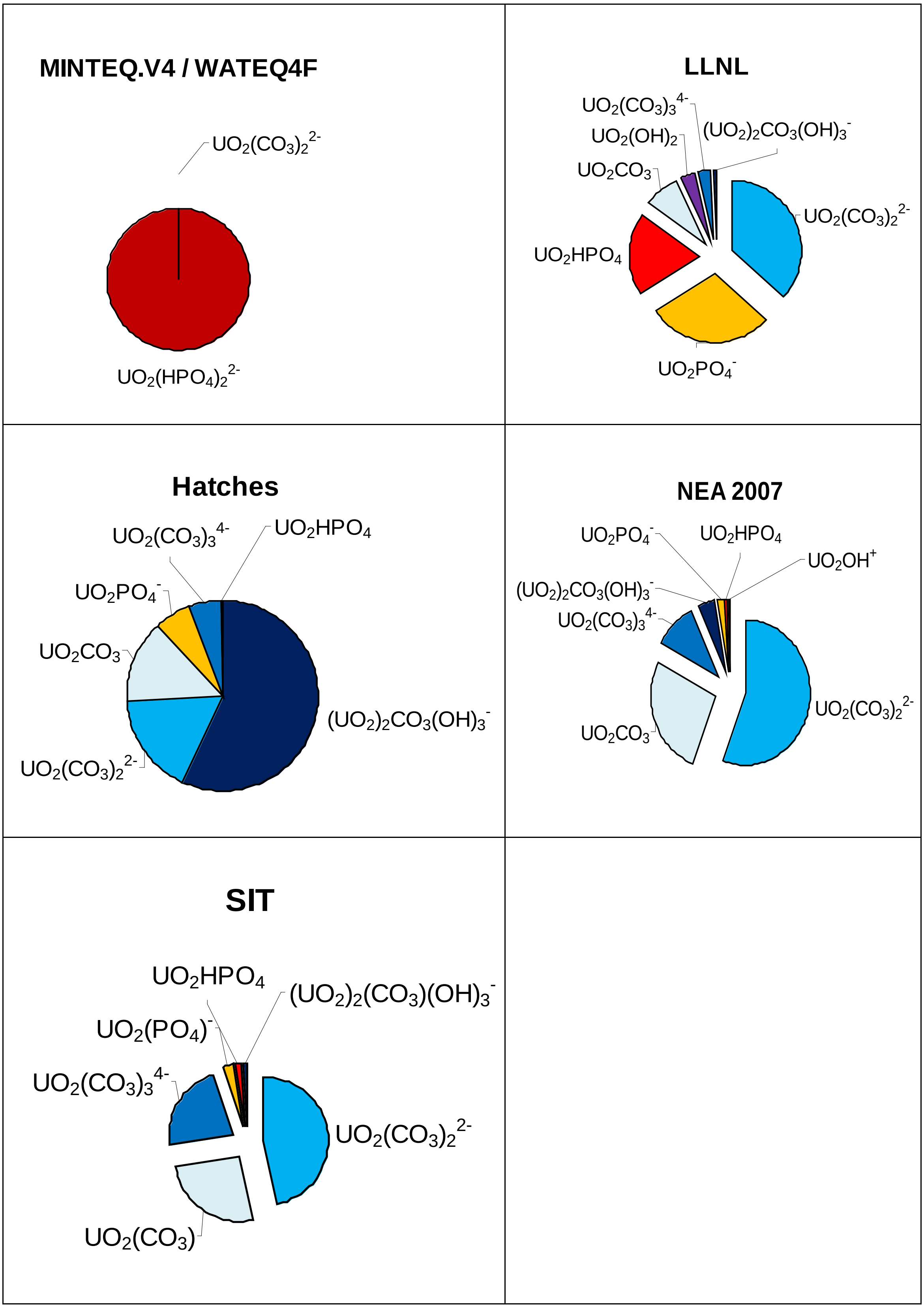

Fig. 7.4.2 Speciation of uranium based on the data from Fig. 7.4.1 (12 °C, pH 6.5, pressure 0.1 MPa and different databases using PHREEQC 3.06

The aim of the paper is rather to emphasize the importance of choosing an appropriate database, which in certain cases is not easy. In some cases it might be as well necessary to change a database by removing and adding data. Basically there is still a need to determine thermodynamic data for certain species and minerals of uranium, thorium, radium, and other relevant radionuclides. It has to be mentioned that several attempts have been made to evaluate existing thermodynamic data and databases e.g. /WAN 92/, /GUI 03/, /HUM 02a/, /HUM 02b/.

Thermodynamic models are based on an equation of state (EOS) with respect to temperature and pressure. Former versions of PHREEQC and other geochemical codes such as WATEQ, MINTEQ, EQ3/EQ6 etc. only considered temperatures of up to 100 or 300 °C and they did not consider pressure at all. However, PHREEQC version 3 defines the specific volume of aqueous species as a function of temperature, pressure, and ionic strength with a Redlich-type equation (for example /RED 64/). Therefore, the solubility of gases in gas mixtures at high pressures is calculated with the Peng-Robinson equation of state /PEN 76/. This makes PHREEQC much more suitable for the simulation of geochemical reactions and processes in deep repositories.

PHREEQC 3.06 offers the option to calculate pressure effects as a function of temperature, pressure, and ionic strength based on the Redlich-Kwong equation of state.

$$p = \frac{RT}{V_m - b} - \frac{a}{\sqrt{T}\,V_m\,(V_m + b)}$$

$$a = \frac{0.42748\,R^2\,T_c^{2.5}}{p_c}$$

$$b = \frac{0.08662\,R\,T_c}{p_c}$$

The solubility of gases in gas mixtures at very high pressures in PHREEQC is calculated with the Peng-Robinson EOS /PEN 76/.

$$
\begin{aligned}
p &= \frac{RT}{V_m - b} - \frac{a\,\alpha}{V_m^2 + 2bV_m - b^2} \\
a &= \frac{0.457235\,R^2\,T_c^2}{p_c} \\
b &= \frac{0.077796\,R\,T_c}{p_c} \\
\alpha &= \left(1 + \kappa\left(1 - T_r^{0.5}\right)\right)^2 \\
\kappa &= 0.37464 + 1.54226\omega - 0.26992\omega^2 \\
T_r &= \frac{T}{T_c}
\end{aligned}
$$

For calculating the specific volume of aqueous species, the Peng-Robinson parameters for gases and molar volumes of minerals have been added to the databases phreeqc.dat, Amm.dat, and pitzer.dat by the developers of PHREEQC. But, these three databases do not contain elements relevant for nuclear repositories (U, Th, Cs, Pu, Np, Am, Cm, Ra, Sr, I, Tc, etc.), which are listed in Tab. 7.4.1. The Peng-Robinson parameters are so far not included in the databases, which have frequently been used for speciation calculation of uranium. However, it is possible to add the Peng-Robinson parameters for relevant gases to the respective PHREEQC version 3.06 input file.

Sorption is another important process controlling the concentrations of radionuclides. The Kd concept based on isotherms is a simple and empirical approach, which may be applied for industrial reactors with constant boundary conditions. In natural systems with changing boundary conditions (temperature, pressure, pH, redox potential, and ionic strength) and multiple elements and species competing for binding sites on minerals, the Kd concept will not deliver reliable and meaningful results. Thus surface complexation models have to be applied that are based on the law of mass action and chemical thermodynamics. Several surface complexation models are implemented in PHREEQC including the CD-MUSIC approach /HIE 96/. However, all databases contained in PHREEQC only contain a demonstration dataset for FeOOH, a oxyhydroxide that plays a central role for surface complexation in many systems. Thus in most cases own data has to be provided for meaningfully simulating sorption processes. One has to consider that sorption experiments have rarely been performed at temperatures above 25 °C and mostly only under oxidizing conditions. Furthermore, pressure and temperature dependency are not known and not implemented in PHREEQC version 3.06.

Tab. 7.4.1 List of relevant radionuclides, solubility-limiting minerals, and the availability of thermodynamic data for these minerals (solubility products)

Element	Thermodynamic data available	Assumed solubility-limiting mineral
U	Yes	UO_2
Th	Yes	ThO_2
Pu	Yes	PuO_2
Cs	No	?
Sr	Yes	$SrCO_3$
Ra	Yes	$RaSO_4$
Am	Yes	Am_2O_3
Ac	No (analog to Am)	Ac_2O_3
Cm	No (analog to Am)	Cm_2O_3
I	-	No mineral
Np	No	NpO_2
Pa	No (analog to Np)	PaO_2
Tc	No	TcO_2
C	Yes	$CaCO_3$, $FeCO_3$

Gas generation is a process that impacts the geochemical conditions is deep repositories. H_2 might be produced by radiolysis, metal corrosion, and microbial degradation. Besides H_2, N_2, H_2S, CO_2, CH_4, and methyl iodine may occur due to microbial activity. In case gases occur, the solubility of these gases in water has to be modeled considering pressure and temperature, which has consequences for speciation and mineral precipitation.

As mentioned before experiments at high pressure and high temperature are needed to get more reliable thermodynamic data. For that purpose, autoclave experiments can be used in the temperature range from 20 to 250 °C and a pressure range from 0.1 to 80 MPa. These experiments are challenging because the online measurement of pH and the redox potential under high pressure and temperature conditions is not possible with common sensors. Furthermore, sampling is often only possible under ambient pressure and temperature conditions and thus secondary minerals may precipitate during cooling and de-pressurizing. Thus methods are needed for taking samples under high pressure and temperature conditions and for immediately injecting them into the analytical device (e.g. ICP-MS).

In addition to that deep groundwater sampling from depths of several kilometers for site-specific investigations is needed for the evaluation of thermodynamic simulations. For that purpose it is necessary that the sampled groundwater is not contaminated by drilling fluids. Reading temperature and electric conductivity online is not difficult. However, pH and the redox potential can only be determined with standard sensors as long as the total pressure is less than 35 MPa. For a pressure above 35 MPa, pH readings are possible with laser spectroscopy at least in a range of pH 5 to 8. Redox readings at a pressure above 25 MPa have not been reported yet.

7.4.4 Conclusions

Thermodynamic data in particular for uranium, thorium, radium, and other relevant radionuclides are partly critical or missing. Thus further experiments in particular at high pressure and high temperatures are needed. Peng-Robinson parameters have to be added to relevant databases. Furthermore, methods have to be developed for deep groundwater sampling (small volumes) without contamination by drilling fluids and other drilling-related impacts and subsequent immediate analysis.

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8 Summary

Kurze Zusammenstellung der Ergebnisse des Workshops „Deep Borehole Repository Using Multiple Geological Barriers" vom 5. - 6.Juni 2015 Berlin-Schönefeld mit anschließender Gelegenheit zur Besichtigung der kontinentalen Tiefbohrung in Windischeschenbach (9 101 m Endteufe, Ø > 40 cm in ca. 3 000 m Tiefe).

Frank Schilling, Professor für Technische Petrophysik (KIT)

Nationale und internationale Spezialisten[6] zu verschiedenen Aspekten der Geologie und Hydrologie sowie der Bohr-, Messtechnik und Endlagerung von hochradioaktiven Abfällen trafen sich, um den Stand der Technik, ebenso wie den Stand von Forschung und Entwicklung interdisziplinär zu diskutieren. Neben an der Endlagerung beteiligten öffentlichen Einrichtungen, waren Wissenschaftler sowie Firmenvertreter und Vertreter von Genehmigungsbehörden anwesend. In der abschließenden Diskussion wurde festgehalten:

- Die Entwicklung der Endlagerung hochradioaktiver Abfälle in tiefen Bohrungen hat noch nicht den Reifegrad vergleichbar mit der einer Bergwerkseinlagerung erreicht.
- Für eine Endlagerung muss noch die Prozesskette als Ganzes überprüft werden
    - Genehmigungsanforderungen
    - Akzeptanz
    - Exploration
    - Erschließung
    - Rückholbarkeit und Bergbarkeit
    - Systemverständnis (inkl. Systemstabilität über 500 bzw. eine Mio. Jahre)
    - Überwachung
- Für die diskutierten Anforderungen an die Tiefbohrtechnik und die Untersuchung von Proben entlang des gesamten Bohrpfades ist entsprechendes Know-How vorhanden. Ein Beispiel, an dem die gesamte Prozesskette für die Fragen der Endla-

[6] USA, Österreich (IAEA), Schweiz, Schweden, Großbritannien, Deutschland (TU BA Freiberg, RWTH-Aachen, KIT, GFZ, BGR, DBE, GNS, GRS, IFG, BakerHughes, Herrenknecht)

gerung von hochradioaktiven Abfällen realisiert wurde – mit den Anforderung des nationalen Rechts – existiert nicht, auch wenn es für die Einlagerung von anderen Abfällen – auch radioaktiven – in Bohrlöchern im In- und Ausland Beispiele und Erfahrung gibt.

- In der Tiefenlagerung von Stoffen wird national und international davon ausgegangen, dass die Nutzung unterschiedlicher Barrieren und die Entfernung zum Schutzgut einen Sicherheitsgewinn darstellen kann (das Verlassen auf lediglich eine geologische Barriere wurde in der Legislative [CCS, Fracking] in den vergangenen Jahren in Deutschland verworfen).

Insbesondere von den Teilnehmern, die langjährige nationale und internationale Tiefbohrerfahrung nachweisen können, wurden die Aussagen zur Tiefbohrtechnik der aktuellen DAEF Kurzstellungnahme vom Juni 2015 zur Endlagerung in tiefen Bohrlöchern mit Verwunderung aufgenommen. Für viele der in diesem Report genannten Fragen (z.B. Bohrtechnik) sind heute in der industriellen Praxis bewährte Verfahren gängig, die auch im Workshop beispielhaft präsentiert wurden. Entweder handelt es sich um den Stand konventioneller Technik (z. B. Ein- und Ausbau oder Bergung zehner Tonnenschwerer Komponenten bei tiefen Bohrungen), die seit Jahrzehnten zum Bohralltag gehören bzw. die notwendigen Technologien, die bereits im Feld mehrfach erfolgreich erprobt wurden (z. B. Bohrungen im Kristallin mit großem Durchmesser). Gerade in Deutschland besteht mit der KTB und den damit einhergehenden technischen Entwicklungen ein erhebliches Know-How, das noch vorhanden ist und für diese Fragestellungen genutzt werden kann.

Ob gesellschaftlich eine Lagerung in tiefen Bohrlöchern – möglicherweise dezentraleine höhere Akzeptanz als die Lagerung in einem tiefen Bergwerkbesitzt wurde kontrovers diskutiert. Dies war jedoch nicht zentrales Thema dieses Workshops, sondern der Fokus lag auf den besonderen Anforderungen bei einer Endlagerung in tiefen Bohrlöchern.

Bezüglich des weiteren Vorgehens wurde angeregt, dass die zu adressierenden Fragestellungen für die Endlagerungstechnologie in tiefen Bohrlöchern, der Stand der Technik und deren Lösungsansätze sowie die noch erforderlichen Forschungsschwerpunkte in einem Dokument („White Book“) zusammengefasst werden sollten.

An einem Pilottest (Vorerkundung, Bohren, Einlagerung, Monitoring) könnten die wissenschaftlichen Fragen ganzheitlich adressiert und die Besonderheit der aktuellen nationalen Anforderung in Deutschland an Rückholbarkeit und Bergbarkeit berücksichtigt werden. Die Kosten für ein entsprechendes Projekt wurden auf ca. 130 Mio. € abgeschätzt (auf der Basis heute verfügbarer Technologie und aktueller Bohrkosten). Das Projekt sollte einen begrenzten zeitlichen Umfang (<10 Jahre) besitzen und nachweisen, dass Bohrlochdurchmesser von mehr als 60 cm bis in über 5 km Tiefe zuverlässig erstellt werden können und dass ein Handling von entsprechenden Containern in einem verrohrten Bohrloch in dieser Teufe sicher beherrscht werden kann.

An existierenden tiefen Bohrungen im Kristallin könnte das zugrundeliegende hydraulische Konzept überprüft, ein radiochemische Überwachungskonzept (auch gemeinsam mit internationalen Partnern) getestet und Bürger von Anfang an in das Projekt eingebunden werden.

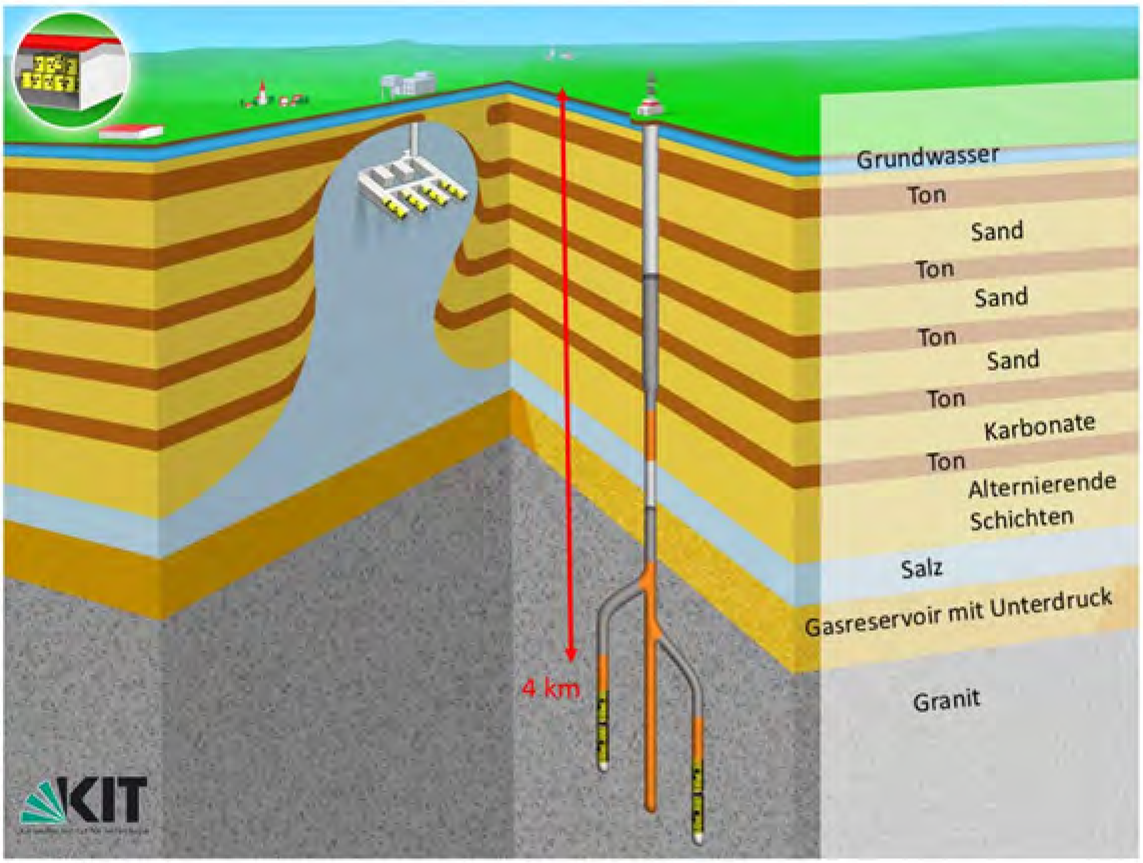

Abb. 7.4.1 Endlagerung in tiefen Bohrungen erlaubt die Nutzung eines Multibarrierensystems: Granit wegen Stabilität, Tone und Salze aufgrund ihrer Undurch-

lässigkeit als geologische Barrieren und ggfs. zusätzlich ein leergeförder-tes Reservoir als physikalische Barriere um aufsteigende Gase sicher und in großer Entfernung vom Schutzgut Mensch/Trinkwasser einzuschließen.

Die Lagerung hochradioaktiver Abfälle in tiefen Bohrlöchern stellt eine – aus heutiger Sicht – technisch realisierbare Option dar.

Internationale Perspektive: Diese noch eingehend zu prüfende Option könnte sich, insbesondere für Länder die keine geeigneten geologischen Strukturen für die Endlagerung in Bergwerke besitzen, als eine bezahlbare und an vielen Stellen realisierbare Alternative herausstellen.

Im Folgenden sind einige Ergebnisse zu den einzelnen Themenbereichen zusammen gefasst.

- Die Endlagerung in tiefen Bohrlöchern stellt eine zusätzliche Möglichkeit dar, welche den Entscheidungsspielraum vergrößern kann.
- Die größere Tiefe und damit Entfernung zum Schutzgut kann einen Sicherheitsgewinn darstellen.
- Die Idee wird in USA auch deshalb verfolgt, da sie lange Transportwege von radioaktiven Abfällen verkürzen könnte und dass der Genehmigungsprozess (USA) sich als weniger komplex darstellen könnte.
- Es wurde ein Projektüberblick über die Aktivitäten (USA) gegeben. Aktueller Status: Eine Standortauswahl für ein Pilotprojekt findet zur Zeit statt.
- Als Parameter/Indikatoren für einen Standort wurden unter Anderem diskutiert
    - Alter der Tiefenwässer (alte Wässer sind ein Hinweis, dass über geologische
    - Zeiträume keine Wasseraustausch mit oberflächennahen Wässern stattfand)
    - Reduzierende Bedingungen im Einlagerungsbereich
    - Ausreichende Dichte der Tiefenwässer um eine Konvektion von Fluiden effektiv zu eliminieren und um unabhängig von der Permeabilität des Einschlussbereiches eine Kontamination von Schutzgütern zu verhindern (physikalische Barriere).
    - Geologische Barrieren, die einen Transport zur Oberfläche unterbinden.

- Bei einem Bohrlochverschluss der nahezu ohne Abdichtwirkung („mit Sand gefülltes Rohr“) angenommen wurde ergab eine Sicherheitsanalyse eine deutlich Unterschreitung der Kriterien für die potentielle Strahlenexposition über Tage (Modellbetrachtungen 1,4 10^{-12} mSv/yr - diffusionskontrolliert).

- Multibarrierenkonzepte beim Bohrlochabschluss können zu einem Sicherheitsgewinn führen.

- Große Durchmesser wurden bereits erfolgreich gebohrt. Bisher gab es keine Notwendigkeit größere Durchmesser in großer Zahl zu bohren.

- Der aktuelle Stand der Diskussion in Deutschland zu den Sicherheitsanforderungen, - Kriterien, Analysen sowie zur Akzeptanz wurde vorgestellt und diskutiert. Neben den technischen Herausforderungen (bei der Lagerung in Bergwerken oder in tiefen Bohrlöchern) und regulatorischen Anforderungen (Sicherheitskonzept) wird die Akzeptanz in der Gesellschaft als große Herausforderung für die Endlagerung hochradioaktiver Abfälle gesehen.

Inhalt der Vorträge und Diskussionen zu den geologischen und physikalischen Barrieren einer geeigneten Geologie und Ausschlusskriterien waren:

- Die Dichtigkeit über geologische Zeiträume von Salz für Gase kann als nachgewiesen angesehen werden. Als Beispiel wurde die fatale CO_2-Erruption im Salzbergwerk Unterbreizbach (2013) angeführt, welche nachgewiesen hat, dass große Gasmengen in Salzstöcken über Jahrmillionen eingeschlossen sein können.

- Das plastische Verhalten und die hohe Wärmeleitfähigkeit von Salz sind große Vorteile für eine geologische Barriere. Dies erlaubt in Salzbergwerk einen sicheren Einschlussbereich zu definieren.

- Über die Erfahrungen im Bereich der Erdöl- und Erdgasgewinnung, sowie durch die

- Untersuchungen im Rahmen der Endlagerforschung (z.B. NAGRA Schweiz) ist nachgewiesen, dass auch Tonsteine über Jahrmillionen eine dichte Barriere darstellen können. Durch ihre mechanischen und chemischen Eigenschaften können Tonsteine eine effektive geologische Barriere darstellen.

- Anhand von Untersuchungen an sogenannten „Cap Rocks“ (häufig Tonsteine oder in Deutschland Salz) von Erdgaslagerstätten wurde nachgewiesen, dass sie auch Gase unter erhöhten Drücken über Jahrmillionen sicher einschließen können.

- Die Nutzung von Gesteinen des Grundgebirges (Granit und Gneis) ist nicht unabhängig von lokalen und regionalen Grundwasserbewegungen zu betrachten. Werden über einen längeren Zeitraum auch Hebungen und Senkungen durch Be- und Entlastung bei Vergletscherung betrachtet, werden auch in großen Tiefen Wässer mit geringen Salinitäten und Altern beobachtet. Für die Skandinavischen Länder haben sich die hydraulischen Vorhersagen bisher bestätigt. Ein vertieftes Systemverständnis sollte angestrebt werden.
- Im Grundgebirge sollte nur dort etwas gelagert werden, wo ein ausreichend hohes Alter von Tiefenwässern nachgewiesen werden kann. Dies zeigt an, dass in dem Zeitraum keine Zirkulation mit Kontakt zu Frischwasser stattgefunden hat.
- Die Rolle der Tiefe zum Schutzgut und das Konzept von Multibarrieren wurden anhand der Geologie Deutschlands diskutiert.
- Aufgrund der Stratigraphie sind in Deutschland viele Standorte denkbar, bei denen tiefe Bohrlöcher ins Grundgebirge durch eine mächtige Salzschicht (und Tonschicht) abgeteuft werden könnten. Damit kann die Barrierewirkung von Salz und Ton für die Lagerung in tiefen Bohrlöchern zusätzlich genutzt werden.
- Wird diese Salzschicht in das Einschlusskonzept einer tiefen Bohrlochlagerung integriert, können verschiedene physikalische, chemische und geologische Rückhaltemechanismen kombiniert werden.
- Die Möglichkeit einer weiteren physikalischen Barriere durch entsprechendes Reservoir- Management wurde diskutiert. So könnte eine weitere physikalische Barriere entstehen (welche größere Gasmengen aufnehmen könnte) die eine zusätzliche Sicherheitsfunktion darstellen könnte.

Inhalt der Vorträge und Diskussionen Bohren/Schachtbau (Deep Drilling / Shaft building) waren:

- Die meisten Tief-Bohrungen weltweit (allein in den USA gibt es über 1 Mio aktive Bohrungen auf Kohlenwasserstoffe) werden für die Kohlenwasserstoffindustrie abgeteuft. Dort sind aber geringere Enddurchmesser von max. 150 – 250 mm üblich.
- In der Geothermie werden größere Durchmesser wegen der erforderlichen hohen Wasserproduktionsraten schon routinemäßig gebohrt.

- Bohrungen auf Kohlenwasserstoffe werden mit Durchmessern gebohrt, die optimal für die Förderung sind.
- Bis in Tiefen von ca. 5 000 m ist der Durchmesser von Tiefen Bohrungen (bis > 50 cm) vor allem durch die Kosten begrenzt.
- Mit moderner Richtbohrtechnik können beliebige Punkte im dreidimensionalen Raum gezielt angebohrt werden. Die Richtbohrtechnik wurde maßgeblich durch das Kontinentale Tiefbohrprogramm im bayerischen Windischeschenbach beeinflusst.
- Bereits vor 25 Jahren wurden Durchmesser von mehreren Dezimetern auch im Grundgebirge sicher beherrscht (Bsp. KTB: 34 cm Durchmesser in 6 km Tiefe)
- Die Bohrtechnik für große Durchmesser und Tiefen existiert, wird jedoch nicht routinemäßig eingesetzt, da dafür noch kein „Markt“ vorhanden ist.
- Für die Endlagerung in tiefen Bohrlöchern gilt es weitere Anforderungen zu erfüllen und technische Randbedingungen zu definieren u. A.:
    - Notwendiger Durchmesser
    - Ist es günstiger, kleine Durchmesser zu bohren oder in kleinere Behälter umzupacken oder mit höherem Kostenaufwand größere Bohrungen abzuteufen
    - Wie können Behälter wieder geborgen werden.
    - Wie sollen die Behälter eingebracht werden (Winde, Bohrgestänge, Coiled Tubing)
    - Soll es eine trockene Bohrung („Schacht“) oder eine mit Bohrspülung gefüllte Bohrung sein.
    - Welches Konzept soll für die Verfüllung der Bohrlöcher verwendet werden und wie reagiert dieses bei Veränderung der Länge der Behälter.
    - Welche mineralogischen und chemischen Reaktionen müssen betrachtet werden

Inhalt der Vorträge und Diskussionen zu den technische Barrieren und Einbringungstechnologie bei hohen Temperaturen und hohen Drücken:

- Die Möglichkeiten für die geologische Tiefenlagerung in einer intakten Tonschicht wurden von der NAGRA anhand eines konventionellen Tiefenlagerkonzeptes (mined repository) demonstriert.
- Ein aktuelles Projekt zur maßstabsgetreuen Einlagerung von wärmeentwickelnden Behältern und deren Einbettung in eine Kaverne wurde gezeigt.
- Der Status der Endlagersuche, die Zeitplanung und angelegte Kriterien wurden diskutiert.
- Aus der Zusammensetzung der Wässer in den Tonen kann auf die Dichtigkeit der Barrieren geschlossen werden. Die Mobilität der Radionuklide ist diffusionskontrolliert. Bei einem sicheren Einschluss sind die so überprüften Diffusionskonstanten maßgeblich, da das Gestein selbstabdichtende Eigenschaften besitzt.
- Die Einbindung von Bürgern in den Prozess und deren Rolle im Entscheidungsprozess wurde
- dargelegt. Das Vertrauen in die im Prozess handelnden Akteure wurde als wichtige
- Randbedingung für die Akzeptanz angesehen.
- Demonstriert wurden der Stand der Behälterentwicklung sowie die Entwicklung und der bisherige Einsatz der Behälter.
- Vorgestellt wurde zudem die Entwicklung der Komponenten (z.B. Winden und Kabel), die für das Einbringen der BSK3 Behälter in 300 m tiefe Bohrungen notwendig sind und die bereits seit den Jahren 1987 bzw. 1997 entwickelt bzw. getestet wurden, sowie das DIREGT Konzept für die Endlagerung in Castor-Behältern.
- Die der Pilotanlage in Gorleben zur Umkonditionierung der radioaktiven Abfälle für Pollux Container ist beispielhaft für entsprechende Anlagen, die radioaktive Abfälle in kleinere Container einschließen können. Für den Fall einer Bohrlocheinlagerung ist abhängig vom Bohrlochdurchmesser und Behältertyp von einer höheren Behälteranzahl auszugehen. Aufgrund des erhöhten Außendrucks im tiefen Untergrund müssten die Behältern für höhere Drücke ausgelegt sein.
- Die verglasten radioaktiven Abfälle können nicht mehr neu konditioniert werden sondern nur in neue Behälter (z. B. BSK 3) verpackt werden. Für deren Einlagerung wären Bohrungen mit einem Durchmesser von ca. 60 cm Ø notwendig.

Inhalt der Vorträge und Diskussionen Rückholung/Bergung (Recovery) und Stillegung (Abandonment):

- Dargestellt wurde der Stand der Technik zum kontrollierten Ein- und Ausbau von Messsonden – welcher für tief liegende Monitoring-Sonden routinemäßig durchgeführt wird.
- für den Fall von einem Verlust von Komponenten z. B. Bohrgestänge und Logging-Tools aus tiefen und geneigten Bohrungen wurden verschiedene Technologien, die vor allem beim Bohrprozess vorkommen (Fishing), vorgestellt.
- Es existiert ein breites Spektrum an Tools, die beim Fishing zum Einsatz kommen können.
- Selbst bei einem Totalverlust einer Bohrung (z.B. bei Öl & Gas Bohrungen), auch in großer Tiefe und komplexen Randbedingungen (z.B. off-shore), kann durch die heutige Richtbohrtechnik das Bohrloch kontrolliert gesichert/verschlossen und sogar weiter genutzt werden (von außen das alte Bohrloch angebohrt werden). Unter diesen Voraussetzungen ist auch ein Wiederfinden und Anfahren von „alten“ und tiefen Entsorgungslokationen zur sicheren Bergung der Container schon heute als realistisches Szenario anzusehen.
- Vorgestellt wurden die Voruntersuchungen für die Tiefbohrlagerung der sogenannten Hanford Capsules. Die Forschergruppe um Karl Travis und Fergus Gibb sehen in der Tiefbohrlagerung insbesondere für radioaktive Abfälle mit vergleichsweise kurzlebigen Radionukliden ein großes Potenzial. Sie werden 2016 eine Versuchsbohrung zu ihrem speziellen Konzept durchführen, bei der keine Rückholbarkeit/Bergbarkeit vorgesehen ist. Dabei sollen verschiedene Verfahren, die sich noch in der Entwicklung befinden, getestet werden.

Inhalt der Vorträge und Diskussionen Hydrogeochemie (Hydro-geochemistry), Mobilität der Radionuklide (Radionuclide mobility), Migration bei hohen Drücken und hoher Temperatur (Migration at P&T), Monitoringtechnologie (Robust monitoring technology), Sicherheitsvorkehrungen (Nuclear Safeguards):

- In der Erdöl/Erdgasindustrie steht ein großes Spektrum an Messgeräten (Logging Tools) auch für hohe Druck- und Temperaturbereiche (auch > 200°C) kommerziell zur Verfügung. Diese nutzen unterschiedliche physikalische Prinzipien oder dienen zur in-situ Beprobung.

- Für unterschiedliche Eindringtiefen werden unterschiedliche Logging Tools verwendet, diese können z.B. über die Porosität, die Art der Porenfüllung, die Dichte des Gesteins, Mineralzusammensetzung, Klüftigkeit, das Spannungsfeld im nahen und fernen Umfeld der Bohrung Aussagen liefern.
- Diese Technologie wird auch in Deutschland für den Weltmarkt entwickelt und gefertigt.
- Die Standard-Logging-Geräte sind für Bohrungen von 12.25 und 17 inch Durchmesser vorhanden. Für größere Durchmesser gibt es momentan noch nicht alle Messgeräte. Dies liegt am bisherigen Bedarf. Die Adaption aller Tools für größere Durchmesser ist mit geringem maschinentechnischen Aufwand möglich („geometrische Anpassung“).
- Für die Charakterisierung der umgebenen Gesteinsformationen (z.B. des einschlusswirksamen Gebirgsbereichs) befinden sich Tools mit größeren Eindringtiefen und höherer vertikaler Auflösungen in Entwicklung wie z.B. das SPWD-Tool des GFZ (Seismic- Prediction-While-Drilling mit einer Eindringtiefe von bis zu 200 m Umkreisradius und einer Messwertauflösung im Zentimeterbereich).
- Der Stand des (radio-)geochemischen Monitorings und die damit beobachtbaren Prozesse wurden vorgestellt. Für Tiefbohrungen ist z. B. notwendig die möglichen Reaktionen der Bohrspülung mit Radionukliden und Behältern zu untersuchen.
- Dargestellt wurden Laboruntersuchungen als auch in situ Experimente z. B. zur Quantifizierung von Transporteigenschaften in den Wirtsgesteinen gegenüber natürlichen als auch künstlichen Tracern, um die Retardationseigenschaften der anvisierten Wirtsgesteine zu quantifizieren.
- Für die Überwachung der Bohrungen wurde vorgeschlagen, ein Monitoring des He3/He4 Verhältnisses als Indikator für das Versagen der Container zu nutzen. In der Diskussion wurden verschiedene weitere gasförmige Tracer angesprochen, die genutzt werden könnten.
- Durch die Herausforderung, den Eintrag von Radionukliden in die Biosphäre für Zeiträume von mehreren Hundertausenden von Jahren zu vermeiden, ist die Rekonstruktion der palaeo- hydrogeologischen Geschichte von Untersuchungsgebieten notwendig.

- Vorgeschlagen wurde das Bohren mit getracerter Bohrspülung, um Einflüsse von Druckentlastung und des Bohrprozesses auf die petrophysikalischen Eigenschaften der Gesteine quantifizieren zu können.

- Die Teilnehmer am Workshop waren sich einig, dass Diffusion ein wesentlicher Transportprozess für den Transport von Radionukliden in den verschiedenen diskutierten Einlagerungsbedingungen im Untergrund darstellt.

- Gefordert wurde das Gewinnen von hochqualitativen Bohrkernen für Laborversuche zur Bestimmung der Transporteigenschaften von Gesteinen. Die Teilnehmer des Workshops wiesen auch auf die Bedeutung der Beprobungsstrategie von Grundwasser hin (u. a. Klüfte, Porenraum, Porenfluide, Porendruck). Von Seiten der Vertreter der Industrie wurde angeführt, dass entsprechende Probennahmetools bereits existieren und eingesetzt werden. Inwieweit diese Tools für die zu erwartenden geringen Wassermengen geeignet sind, ist zu prüfen.

- Konsens bestand darin, dass Monitoring zu potenziellen Wegsamkeiten führen kann.

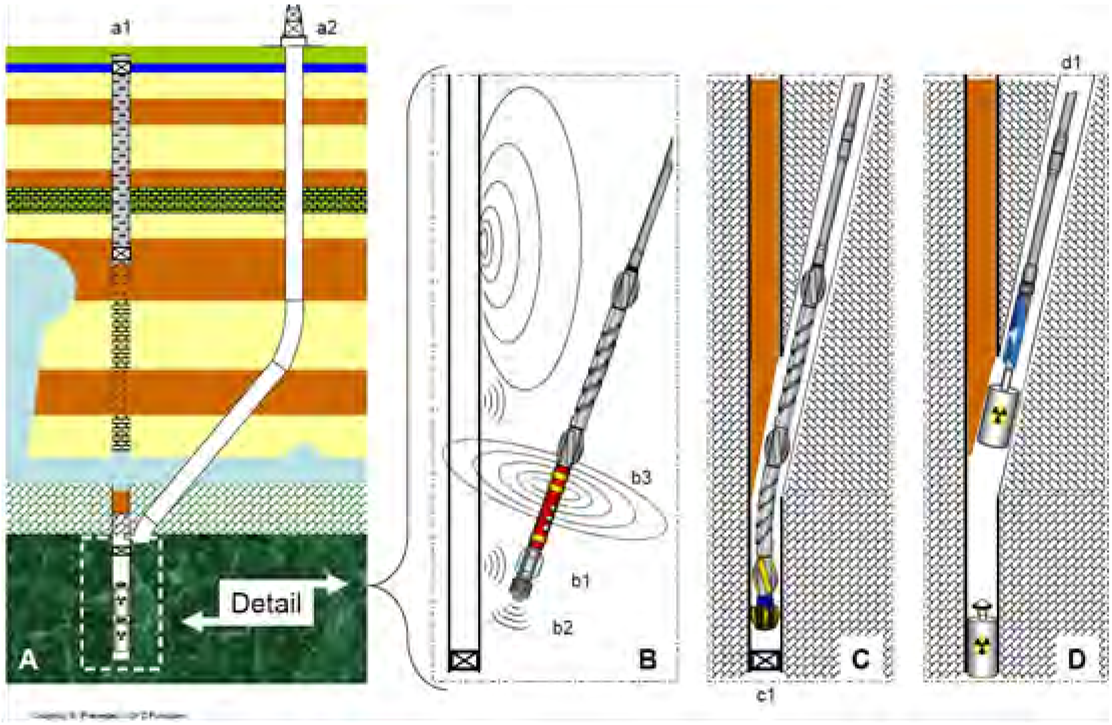

Abb. 7.4.2 (A) Auffinden einer permanent verschlossenen Endlagerbohrung (a1) durch eine Bergungsbohrung (a2), vergleichbar einer Entlastungsbohrung in der Öl & Gas Industrie zur untertägigen Reparatur von Blow-out Havarien.

(B) In unmittelbarer Nähe zur Endlagerkammer erfolgt die exakte Ortung dieser, mit Stahl-Casing verrohrten, Bohrlochsektion mittels akustischer (b1) und elektrischer Messverfahren (b2) während des Bohrens.

(C) Danach erfolgt das Auffahren der Futterrohre im Deckgebirge mittels einer Fräsgarnitur und Einfädeln der neuen Bergungsbohrung in die alte Endlagerbohrung oberhalb der Container, gefolgt von einer Aufwältigung bis zum mechanischen Verschluss (c1) oberhalb der Endlagerkammer.

(D) Öffnen und Ziehen des Verschlussmechanismus und Einfahren einer Fanggarnitur (d1) zur Bergung der Container durch die Bergungsbohrung nach übertage.

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