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NAGRA'S GRIMSEL URL: FROM UNDERGROUND TESTING TO THE DEMONSTRATION OF DISPOSAL SYSTEMS

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ABSTRACT

During 20 years of operation, Nagra's Grimsel underground research facility has seen a continuous evolution in the type and scale of work carried out. The focus on geological characterisation technology development in the '80s was followed by more emphasis on performance assessment model testing and studies of engineered barrier systems in the '90s. Although fundamental R&D is still included in the Grimsel programme, the 21st century has seen project goals concentrate more on directly supporting the implementing and licensing of repository projects. There has been an associated paradigm shift in project design, from an approach constrained by fixed 3 or 6 year programme phases to flexible projects with timetables set by the requirements to reach defined goals – potentially running over decades. The paper explains the justification of these changes and illustrates these by comparison of some projects from the recently completed Phase V to those being initiated (or under planning) for the present Phase VI.

INTRODUCTION

In 1983, Nagra (the Swiss National Co-operative for the Disposal of Radioactive Waste; www.nagra.ch), initiated a wide range of in situ experiments in its underground rock laboratory (or URL), the Grimsel Test Site (GTS), located in the crystalline rocks of the Aare Massif in central Switzerland (see, for example, www.grimsel.com, Vomvoris et al., 2003a and Kickmaier et al., 2005, for details). Although this facility is not considered for waste disposal, it provides convenient, horizontal access to the rock 450 m below the flanks of the Juchlistock Mountain. Experiments are carried out within an extensive network of tunnels and caverns, which provides all infrastructure and services found in a normal surface laboratory. Indeed, the GTS includes an IAEA level B radiation-controlled zone, which allows in-situ experiments with radionuclides - including actinides such as thorium, uranium, neptunium, plutonium and americium (see McKinley et al., 1988, Alexander et al., 1996 and Smith et al., 2001 for details).

The topics examined over the first 5 phases of research, extending over a total of 18 years, can be roughly classified as:

a) Development and testing of the characterisation technology for repository sites (e.g. McCombie et al., 1995); including a wide range of geophysical and hydrogeological methods. Components of the extensive toolkit of geological exploration methods are often not directly applicable to the special requirements of geological disposal facilities. The GTS provides an ideal test bed for such work – which becomes increasingly valuable due to synergies between all such studies.

b) Evaluation of methodology for repository construction and its influence on the geological barrier – particularly the extent of the excavation-disturbed zone (EDZ) around underground openings (e.g. Frieg, 2005).

c) Development and testing of the procedures for emplacement of the engineered barriers for high-level waste/spent fuel (HLW/SF) and low/intermediate-level waste (L/ILW) and the models evaluating their evolution with time, considering the coupled processes of saturation, heating, gas pressurisation, etc (e.g. Ulibarri et al., 1996, ENRESA, 2000).

d) Rigorous testing of the models and databases used to evaluate radionuclide migration in a fractured host rock – both under natural conditions and considering perturbations such as leaching of hyperalkaline fluids from cementitious structures or erosion of colloids from backfill/buffer materials (e.g. Alexander et al., 2003).

e) Training of staff: an ageing staff structure is a well documented problem in the nuclear power industry and the the radioactive waste disposal industry is no exception. Over the next decade, many experienced staff will reach retiral age and leave the industry so it is crucial that the training of new staff begins immediately. One problem with this is that, with one or two exceptions, few national programmes are actively characterising a repository site or building a repository. Therefore, it is necessary to train the new staff in URLs such as the GTS and this has long been an important area of focus in the GTS – so much so that this is a justification for locating the recently formed School of Underground Waste Storage and Disposal (ITC) in close proximity to the GTS (see www.itc-school.org for details).

In particular cases, the participation of several partner organisations provided the expert resources needed for complex, multi-disciplinary experiments and also allowed costs to be shared.

GTS projects are currently run by international teams drawn from 17 partner organisations from the Czech Republic, Finland, France, Germany, Japan, Spain, Sweden and Switzerland, as well as numerous universities, institutes and companies from around the world. The European Union (with the Swiss State Secretariat for Education and Research; SER) provides financial support to some projects. An overview of the GTS facilities, a list of partner organisations, updates on the status of ongoing experiments and a bibliography of publications is presented in the GTS homepage (www.grimsel.com).

DEVELOPING THE CONCEPT OF GRIMSEL PHASE VI

As the end of Phase V of Grimsel approached, there was open debate on whether further work at this site was justified or not. This was particularly important for a small programme like that in Switzerland, given that a second Swiss underground test site was already operational at this time in the sedimentary rock at Mont Terri (www.mont-terri.ch). Immediate response from partners indicated very strong support for continuation, particularly due to the unique ability to work in situ with safety-relevant radionuclides and the flexibility to accommodate large projects requiring extensive construction or use of heavy equipment due to ease of access.

Following a technical review (Kickmaier and McKinley, 1997) of work carried out in Grimsel and other underground test sites, however, a particular trend was noticeable; the types of question which could be addressed by small-scale, short duration studies have been repeatedly examined – remaining major challenges require experiments which move closer to full-scale simulation of repository structures and very much longer durations (even beyond the 6 years of Phase V; 1996 - 2002). The timescale issue is particularly critical – to significantly improve on multi-year studies, a step directly to multi-decade project durations is needed. Although such timescales represent new land for the experimental teams, they are quite compatible with the present national time plans for repository construction, operation and final decommissioning, which generally extend well into the next century (c.f. www.numo.org). Phase VI was thus launched with the foreseen long duration and explicit flexibility to fit in with the requirements of specific projects. These projects are, in turn, linked to specific milestones associated with the selection of sites and subsequent design, construction, operation and decommissioning of radioactive waste repositories – and associated licensing procedures.

In order to provide efficient support for implementation of national repository programmes, it is important that an integrated approach is taken when developing an R&D programme. Many repository concepts for radioactive wastes were developed decades ago for feasibility studies. Since then there have been great advances in the understanding of long-term repository evolution, better definition of critical operational constraints and, in particular, a greater awareness of the importance of public acceptance (requiring consideration of monitoring/institutional control, retrieval/reversibility, etc – see, for example, West et al., 2001). Projects can take advantage of relevant experiments which have been performed at the GTS in the past, together with the output from recent total system performance assessments, to further develop the concepts for disposal of specific types of radioactive waste. Such concepts can then be tested under representative conditions at Grimsel with respect to:

- Practicality (including tele- (or remote) handling of heavy waste packages under confined conditions, QA of the emplaced engineered barrier system (EBS), sensitivity of the overall system to operational perturbations, etc.)
- Monitoring (e.g. development of sensor and data transmission technology, testing of robustness of monitoring systems which may be required to survive harsh conditions for very long times without the possibility of maintenance or recalibration, assessment of how the inevitable 'false positive' indications of radionuclide leakage from the repository can be managed, etc.)
- Remediation procedures in the case of any potential engineered barrier defects/possible waste package retrieval (a tacit requirement resulting from the QA and monitoring programmes considered in national programmes – even if little studied to date)
- Long term performance of the EBS and the surrounding rock under
  - "Normal" evolution scenarios (e.g. considering expected slow degradation of EBS materials, subsequent release and migration of safety-relevant radionuclides)
  - Perturbed evolution scenarios (e.g. considering processes which are uncertain or poorly defined, such as effects of gas produced by degradation of specific emplaced materials, effects resulting from hyperalkaline leachates from any cement or concrete present, effects of microbial activity, etc.).

The challenge is to integrate current system understanding of this very complex area in order to form a basis for implementation of practicable, safe repository projects, which receive wide acceptance from all key stakeholders. To facilitate integration, focus will be placed on the operational and any post-emplacement/pre- or post-closure monitoring phases of repository implementation. Nevertheless, to ensure that optimisation preserves the critical long-term safety margins required, key aspects of long-term performance of the EBS and immediately surrounding host rock are also examined.

The evaluation of possible disturbances that could disrupt key services (e.g. power, ventilation and drainage) during repository operation has not yet been the focus of demonstration experiments. Such studies at Grimsel would allow such effects to be simulated and the recovery procedures to be tested under the constraints set by underground work. Such experience would provide feedback to develop more robust repository concepts and operational procedures.

Full-scale demonstration projects are certainly of relevance for testing that concepts can be implemented under the special conditions found underground. Past work has emphasised feasibility – showing that disposal operations were possible. A large step forward is required to develop and demonstrate concepts that are practical on an industrial scale (e.g. considering required throughput rates) with high levels of safety and with rigorous quality assurance. Further important justifications for such projects is that they are easy to explain to the general public and they address concerns about operational safety which are often more immediate for local populations around repositories.

EXAMPLES OF PROJECTS

The differences between the aims and boundary conditions for Phase VI (2003 – 2013)compared to previous phases of work can be illustrated by considering some of the experiments involved. One of the most successful of GTS projects has been FEBEX (Full-scale Engineered Barrier Experiment; Ulibarri et al., 1996, ENRESA, 2000), carried by a multi-national team under the leadership of ENRESA and supported by the EU and the Swiss SER. Although initially focussed on examination of coupled thermal-hydraulic-mechanical-chemical processes in the near-field around packages of spent fuel, this project was extremely valuable in demonstrating the fundamental feasibility of – but the many practical problems associated with – emplacement of compacted bentonite buffer/backfill (Fig. 1).

Figure 1: FEBEX - EBS emplacement. Steel canister, in the centre, is pushed into the bentonite backfill (note blocks of compacted used in this case)

Even after the planned 5 year duration of this experiment, the extent of bentonite saturation was limited and processes tended to be dominated by transient effects. At the end of Phase V, therefore, only 1 of the 2 heaters was excavated and the decision was taken to continue the experiment further. The unique, long-term database provided has proven invaluable for coupled-code modellers and the final decision about when and how to finish and decommission the experiment is still open (see www.grimsel.com for updates). The latter point is particularly relevant in the light of the extensive information gained during the dismantling of the first heater. Many of the sensors used to characterise the bentonite environment were observed to be heavily corroded, with microbially-induced corrosion being implicated in several cases. This unexpected finding is particularly relevant to ongoing discussion of the extent to which repositories should be (or, indeed, can be) monitored over extended periods.

FEBEX can be contrasted with the proposed Tele-Handling (TH) experiment for Phase VI. The latter is focussed more on the process of emplacement of the EBS considering that, in an operating repository, this process has to be not only feasible but also practical when implemented in a tele-operated mode. Building on the experience of many nuclear processes which utilise tele-handling methodology, the approaches could be extended to the conditions underground, which require an especially robust approach which will meet very strict quality standards and show low vulnerability to, and ease of recovery from, potential operational perturbations. Based on the FEBEX experience, handling the compacted bentonite was identified as a critical issue and this led to concepts using, for example, bentonite pellets for in situ emplacement. Another approach which is receiving increasing interest internationally is the emplacement of key components as a Prefabricated EBS Module (PEM), which greatly simplifies the quality assurance process. Nevertheless, transportation, emplacement, backfilling and, if required, recovery of such a large, heavy module in the confined conditions underground involve considerable challenges (Table 1).

Table 1 Characteristics of the planned TH project as compared to FEBEX

Characteristic	FEBEX	TH
EBS	Steel overpack Steel liner Bentonite blocks	Metal overpack/Bentonite **or** PEM/backfill
Emplacement	Manual	Tele-handled **or** Robotic
Main focus	Scientific experiment	Engineering practicality
QA	Standard (ISO) QA, internally defined	Under the auspices of national regulators
Operational perturbations	Not considered	A focussed project sub-task
Recording	Photo/video	Live webcam Photo/video
Reversal/ retrieval	Only "post-mortem" Manual	Tele-handled **or** Robotic

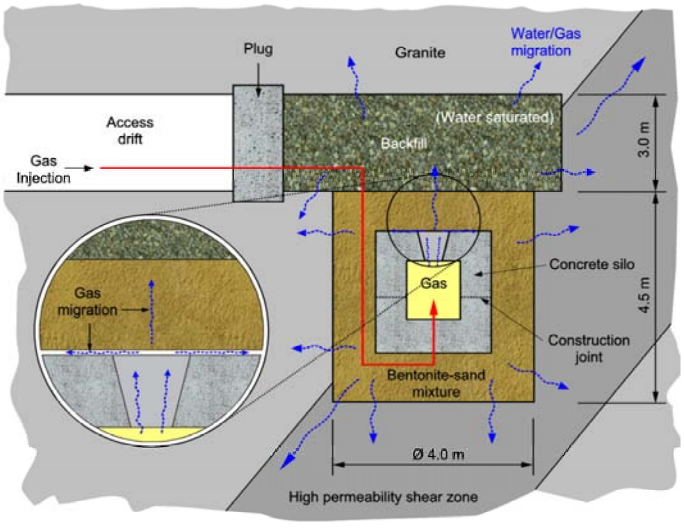


Figure 2: GMT overview (see Vomvoris et al., 2003b, for details)

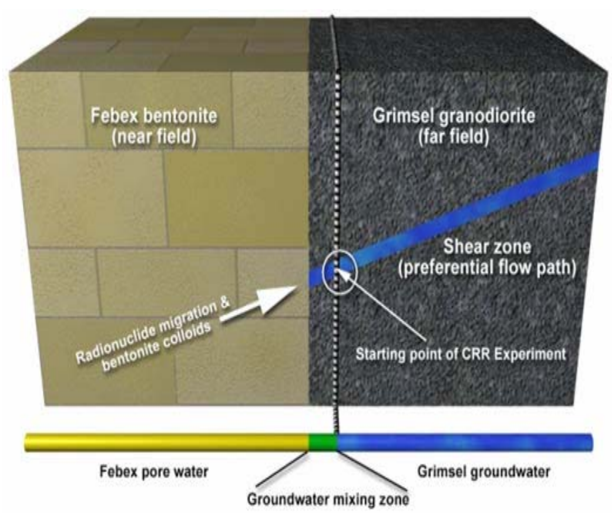
In Phase VI, it has been proposed to extend the information base on the long-term behaviour of potential EBS materials and associated monitoring systems in an underground environment in a Material Testing Facility (MTF, Table 2). This facility will provide the opportunity to examine corrosion/alteration of materials and degradation of their essential properties over periods of decades in a well-defined, relevant environment. Although planning is at an early stage, the potential exists to test materials individually or in combination under either the natural conditions found at Grimsel or the perturbed conditions (temperature, pH, redox, etc.) resulting from the presence of the repository itself. Continuous monitoring over the test period would be combined with extensive analysis of samples removed after particular time periods. The testing would also include extensive photo and video documentation due to the value of such work for public communication activities.

The final examples considered involve more detailed studies of far-field processes relevant to long-term safety which utilise the infrastructure available in the radiation-controlled zone at the GTS. The Phase V Colloid and Radionuclide Retardation (CRR) experiment involved a first attempt to quantify the role of natural and introduced colloids in the transportation of radionuclides in a fractured rock (Fig. 3). This study (Möri et al., 2003) was extremely challenging from a technical point of view, requiring extensive conventional laboratory support studies and model development to help disentangle the range of different processes influencing the transport behaviour of reactive radionuclides (particularly actinides) in the in situ experiment. A clear result (Geckeis et al., 2004), however, was that strongly sorbing radionuclides could be transported in a colloidal phase, although there was evidence that uptake on colloids was reversible.

Table 2 Characteristics of the planned MTF project as compared to materials tests within FEBEX and GMT

Characteristic	FEBEX	GMT	MTF
Materials	Steel overpack / liner Bentonite blocks Concrete walls/plugs Instrumentation & sensors	Concrete silo Bentonite/sand (in-situ compacted) Crushed rock Instrumentation & sensors	Steels, possibly coated Bentonite – pure, mixtures, grout Concrete (OPC & low pH), cement grouts, steel & fibre reinforcing Instrumentation & sensors
Environment	Natural, partially desaturated Perturbation by heat	Natural, partially desaturated Perturbation by heat	Natural, variable saturation Variable temperature Variable chemical perturbation Radiation field possible
Timescale	10 (+) years	5 years	Flexible, decades
Evaluation	Only "post-mortem"	Indirectly by real-time monitoring	Continuous focused monitoring Extensive post mortem
Recording	Photo/video	Photo/video	Live webcam Photo / video

Figure 3 CRR concept (after Möri et al., 2003). The migration of radionuclides (associated with colloids eroded from the EBS) through the geosphere was studied



From the beginning, it was acknowledged that, in order to be able to measure radionuclides and observe colloid transport over the timescale available, highly unrealistic conditions had to be selected in terms of injected colloid concentrations, water flow rates, etc. With the greater freedom provided by Phase VI, it was decided to develop this work further within a Colloid Formation and Migration (CFM) project. A major advance will be the source of the colloids which in CFM will be more realistic than the injection of colloidal suspensions as in CRR. Design tests are currently ongoing to define a repository-relevant source term for the experiment (Biggin et al., 2003). The much longer timescale is a critical factor, allowing identified artefacts due to slow reaction kinetics (significant on the experimental timescale of CRR but irrelevant on a repository scale) to be avoided completely. Details are still not fixed, but CFM may also consider explicitly the role of micro-organisms which are also encountered as part of the colloidal-size component of natural groundwaters.

LEARNING FROM MISTAKES

Apart from the special infrastructure and extensive database available at Grimsel, feedback from partners has indicated that the very fact that Grimsel is not a potential repository site is a distinct advantage. This is associated with the fact that development of new technology and research which is at the cutting edge is inevitably associated with risks of surprises, unexpected problems and even failures or other incidents. In most other technical areas this is accepted – and even expected. In nuclear areas, however, the general public is very sensitive to any perturbations and it has been seen that, at a repository site, even conventional, non-nuclear disruptions associated with construction can cause massive programme delays.

Table 3 Characteristics of the planned CFM project as compared to the earlier CRR study

Characteristic	CRR	CFM
System	Safety relevant radionuclides Natural colloids Introduced bentonite colloids	Safety relevant radionuclides Natural colloids/microbes Colloids generated from EBS
Environment	Natural fracture, potentially disturbed by high flows	Natural fracture, minimum perturbation
Timescale	Hours/days	Years/decades
Water flow rate	Many orders of magnitude above repository relevant rates	Repository relevant
Monitoring/Recording	On-line, off-line & post-mortem Photo/video	On-line, off-line & post-mortem Live webcam/photo/video

As repository programmes move closer to implementation, the difficulties caused by such public demands for "perfect" projects become more obvious and the need becomes critical for locations where prototypes can be developed and tested and lessons learned from the problems which will inevitably be encountered. Even if very robust operational systems can be developed, possible breakdowns or external perturbations cannot be excluded over the periods of decades over which repositories will be operational. These certainly do not need to be given a high profile, but it is necessary that implementers (and regulators) have examined such possibilities in advance and have procedures for recovery/remediation which are proven in practice and are not based entirely on desk studies. Such experiences should be integrated into "knowledge management systems" to ensure that the lessons learned are utilised in future repository designs.

Project documentation tends to focus on successes with the failures receiving much less coverage. In real life, however, the problems experienced and the approaches used to solve them are invaluable – even if they are mainly represented as part of the institutional experience of the expert staff involved. Extending this experience and transferring it to future generations is, as was noted above, an express goal of GTS Phase VI.

CONCLUSION

Even after 2 decades of work, the challenges facing the teams working at the GTS are, at least, as great as they ever were. Expansion of technical capacity and availability of longer experimental periods allows processes to be studied which were previously inaccessible. Supporting the development of practical and safe approaches to operating repositories is an area of expanding importance, where the reduced sensitivity associated with a research site like Grimsel, as opposed to a real repository site, has particular advantages. The basis for the programme for Phase VI has been presented along with some project examples, but it should be emphasised that there is considerable flexibility for new partners to join existing experiments, to modify such experiments to meet their own particular needs or to introduce new projects – to be carried out unilaterally or in a consortium of project partners.

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