

Technical Report 16-02

**The Nagra Research, Development
and Demonstration (RD&D) Plan
for the Disposal of Radioactive
Waste in Switzerland**

December 2016

National Cooperative
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Radioactive Waste

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ISSN 1015-2636

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Executive Summary

Nagra's mission is to construct safe deep geological repositories for all radioactive waste arising from the use of nuclear energy and from medicine, industry and research without delay and at reasonable cost. The applications for the general licences required for the repositories will be prepared and submitted within the framework of the Sectoral Plan for Deep Geological Repositories (*Sachplan Geologische Tiefenlager*). According to Art. 31 par. 1 of the Swiss Nuclear Energy Act (KEG 2003), the operators of nuclear installations are obliged to safely manage all radioactive waste arising from their installations. This includes the necessary preliminary activities such as research and geological investigations. Art. 36 of the Swiss Nuclear Energy Ordinance (KEV 2004) specifies the research activities. Art. 36 par. 2 of the KEV states that the licence holders must monitor technological developments, including those relating to organisation and personnel, and must examine the extent to which conclusions may be drawn therefrom concerning the safety and security of the licence holder's installation, in Nagra's case the geological repositories. In a decision of August 2013, the Federal Council concluded that Nagra must submit a Research, Development and Demonstration Plan together with the Waste Management Programme. The present RD&D Plan is in line with the Federal Council's decision and in accordance with the regulatory framework in Switzerland.

Two types of repository are foreseen, one for low- and intermediate-level waste (L/ILW) and one for spent fuel, vitrified high-level waste and possibly long-lived ILW (SF/HLW/ILW). Repository implementation involves a stepwise process that takes several decades and a comprehensive planning base for the scientific and engineering work is therefore needed, which is presented in the RD&D (research, development and demonstration) Plan. The main objective of the RD&D Plan is to establish the purpose, scope, nature and timing of future RD&D activities, starting from the different requirements and planning assumptions. The focus is on the activities in the next decade, with broad indications of RD&D activities beyond that.

Chapter 1 presents the overall objectives of the report and a brief history of the steps leading to the present situation. The planning of work is conditioned by the Federal Government decision in 2006 that Nagra had successfully shown in *Project Entsorgungsnachweis* (disposal feasibility demonstration) that safe disposal of SF/HLW/ILW in Switzerland is technically feasible. Earlier studies and safety authority reviews had already led in 1988 to the Federal Government decision on the overall feasibility of safe disposal of L/ILW. Following the *Project Entsorgungsnachweis* decision, the Federal Government initiated the Sectoral Plan for Deep Geological Repositories, which elaborates the siting process. The Sectoral Plan (SGT) provides a framework within which specific objectives must be met for selecting suitable sites for disposal of both L/ILW and SF/HLW/ILW for which general licence applications are to be submitted. The overall planning is based on the status as of Nagra's submission of the siting proposals for Stage 2 of the Sectoral Plan, which will result in the selection of the siting regions for the L/ILW and HLW repositories that will be subject to surface-based geological investigations in the next years.

Chapter 2 presents the overall planning premises for implementation of the repositories for L/ILW and SF/HLW/ILW, including the assumed schedule, the waste types and volumes and the safety strategy for the repositories. The time plan is presented, which includes the Sectoral Plan and general licence procedure, construction and operation of the facilities for underground geological investigations at the sites, the construction licence procedure and the operating licence procedure. It is expected that emplacement of L/ILW could begin around 2050, while SF/HLW emplacement would begin about 2060. Waste emplacement is followed by a monitoring period (planning assumption of at least 50 years), at the end of which an application

would be made for closure. The various waste types and volumes produced by the nuclear power plants and medicine, industry and research are summarised and the safety concepts for the two repositories are illustrated.

Chapter 3 provides an overview of the programme stages and outlines the implications for RD&D activities. The Sectoral Plan process is discussed in some detail in order to explain the requirements on Nagra's RD&D programme for each of the stages of site selection up to the general licence application. For Stage 1, the selection of geologically suitable siting regions, the steps that led to the acceptance of the six geological siting regions for the L/ILW repository (Südranden, Zürich Nordost, Nördlich Lägern, Jura Ost, Jura-Südfuss, Wellenberg) and the three geological siting regions for the HLW repository (Zürich Nordost, Nördlich Lägern, Jura Ost) are outlined. Stage 2 of the Sectoral Plan has two main goals: firstly, to select at least one site for the surface facilities in each of the geological siting regions and, secondly, to narrow down the number of siting regions to at least two for each repository type. Nagra proposed the two regions "Jura Ost" and "Zürich Nordost" for further investigation in Stage 3 in December 2014, with the Opalinus Clay as the host rock. The proposal is being reviewed by the regulator at the time of publication of this report. In Stage 3, the sites approved at the end of Stage 2 will be subjected to a more detailed examination and supplementary geological investigations from the surface will be performed. This will provide the basis for Nagra to select, for each of the repositories, the site for which the general licence application will be prepared. The specificity of the requirements of the Sectoral Plan combined with the results of the prior work programme lead to a clear definition of the RD&D activities foreseen for the next 5 to 10 years.

Chapter 4 presents the strategic requirements for developing the two types of repository. The definition of the waste types, their properties and the legal and regulatory requirements for disposal set the framework for the timing of implementation as well as for the repository concepts needed to safely dispose of the waste. In the repository concepts, long-term safety must be provided by multiple passive safety barriers with a balanced contribution from the engineered and geological systems. The repository design concepts include: i) the main facility, where wastes will be disposed of and which will be backfilled and sealed in due time after waste emplacement; ii) test areas, where site-specific data on the safety-relevant properties of the host rock are acquired to confirm safety and technical feasibility; iii) the pilot facility, where the behaviour of the waste, backfill material and host rock is observed until the end of the monitoring period and where data are collected to confirm safety with a view to closure. Host rocks with favourable properties must be selected within stable large-scale geotectonic situations, which ensure a significant contribution of the geological barrier to the safety functions. The current concepts for the SF/HLW and L/ILW repositories are described and their position compared to other concepts discussed. The nature and purpose of a safety case as well as the strategy for dealing with uncertainties in the framework of repository implementation and safety case development is also elucidated.

Chapter 5 discusses the RD&D planning process, the methodology and the resources available for implementing the RD&D programme. Possible approaches for dealing with outstanding issues are listed, taking into account that Nagra is a project management organisation. The role of the generic underground research laboratories (URLs) at Mont Terri, managed by swisstopo, and the Grimsel Test Site as well as the role of Nagra's key research partners is highlighted.

Chapter 6 describes the status of the RD&D for disposal of HLW and L/ILW. Significant progress has been made in the last years regarding the development of the engineered barrier systems, resulting in the full-scale demonstration of the Nagra barrier concept at the Mont Terri Rock Laboratory and the further development and testing on a large scale of the engineered gas transport system for the L/ILW repository for the mitigation of repository-induced effects. In

the area of radionuclide transport, the methodology for deriving sorption values based on clay mineral content and porewater composition was thoroughly tested on a vast amount of data, allowing the derivation of sorption values for different clayey sediments and contributing significantly to the argumentation for the SGT Stage 2 selection. The Swiss schedule for repository implementation is then placed in an international context, demonstrating that LLW repositories are already in operation in many countries. Several countries (Finland, Sweden and France) are in the final licensing steps for HLW repositories, a stage which Nagra is anticipated to reach in approximately a generation from now. A significant return of experience from more advanced programmes allows optimising and focusing of Nagra's RD&D programme through international collaboration with other clay-based programmes (France, Belgium) and other organisations at the European and global level. Cross-fertilisation is expected particularly in the domains of technology development for buffer and backfill, seal construction and technology, development of tunnel excavation methods, retrieval and development of disposal canisters. At specific points in the repository implementation programme, most prominently in anticipation of the documentation regarding the proposals for the steps in the Sectoral Plan, but also in the future development of the safety cases, the whole body of RD&D results will be interpreted and integrated into syntheses supporting decision-making or directly into the safety assessments. The results of the RD&D activities related to geological aspects have been integrated into the reports supporting the proposals for Stage 2 of the Sectoral Plan. Other examples discussed are the assessment of the impact of repository gases and possible options for mitigating their impact and the overall framework developed to bound and assess the impact of repository-induced effects.

Chapter 7 comprises the major part of the report and provides an overview of the technical programme for the next 10 years, encompassing the timeframe up to the general licence application, including the objectives, status and principal focus in the various areas.

Geological investigations (compliance with requirements on properties of host rocks and confining units and long-term geological evolution; data for key safety-relevant parameters)

With respect to geological investigations, the state-of-the-art was compiled in Nagra (2014b) and supporting reports, which describe the sedimentological and tectonic conditions, the long-term geological evolution, the geomechanical and hydrogeological data and conditions, the barrier properties of the host rocks and the confining units and the conflicts of use for all siting regions. In the future, the focus of the RD&D will shift towards the development of the site descriptive models (SDM) for each of the sites (establishing local properties and state parameters), which will serve as a basis for selecting the final sites and developing the safety case. For certain aspects, such as the long-term geological evolution, regional assessments remain of high importance. In the next years, substantial additional data based on field work from the surface (reflection seismic surveys, shallow and deep boreholes) will become available. From a safety assessment point of view, the most important information will relate to the geometry and quality of the host rock and the confining units (thickness of the host rock and location and quality of lithofacial units within the confining units with the potential for strongly increased water flow). It is expected that the exploration programme will complement and/or enhance this information so that the associated uncertainties will be further reduced. For other site-specific geological information to be used directly in the safety analysis and that is important for the radiological dose calculations (hydraulic parameters and mineralogy of host rock, etc.), it is not certain that there will be a notable reduction in the associated uncertainties. However, reducing these uncertainties is not critical as the parameter values currently being used provide a sufficient safety margin.

Supporting the geosphere characterisation for the selected sites and their long-term evolution is a primary objective of the RD&D activities in this domain. This consists of a suite of conceptual models of the geological conditions at the proposed repository sites; these comprise static models (lithostratigraphic layer models, fault models), property distributions (mineralogy, porosity, hydraulic conductivity, radionuclide retention properties, gas transport properties, stiffness and strength, seismic velocities) and dynamic models (defining and predicting the in-situ state conditions: pore pressure, water saturation, chemical composition of waters, temperature, stress state, strains/deformation). One of the tools will be the investigation of the palaeo-hydrogeological evolution at the chosen repository sites. Knowledge about processes that occurred in the past provides valuable information on what is expected over the lifetime of the repository system.

The long-term geological evolution, including neotectonics, climate evolution and erosion, will receive much attention in the next years. For a geological repository in Northern Switzerland, future erosion is one of the key aspects in site selection and the safety case. Erosion may lead to a decreasing overburden and, as a consequence, to increasing host rock permeability (decompaction) or even the partial or total denudation of the repository. With respect to neotectonics, it is aimed to improve the characterisation of past neotectonic activity and extend the instrumental record of recent crustal movements. Possible future neotectonic scenarios will be explored. Of particular interest are the likelihood and potential effects of future reactivation of regional basement faults and ongoing deformation of the Jura fold-and-thrust belt. Potential effects of neotectonic movements and seismicity on the various elements of a repository and the geological and engineered barriers will be evaluated. With respect to climate evolution, the understanding of the local climate in the Central Alps and their northern foreland over a full glacial-interglacial cycle will be enhanced to assess how the global climate system influences local conditions. Regarding future erosion, testing of advanced methods for dating the Quaternary sediments is foreseen, the understanding of the past evolution of the local topography will be improved as a basis for developing future erosion scenarios and the behaviour and extent of ice-flow systems such as the Rhine glacier, Aare glacier and Rhone glacier and the evolution of the landscape of the northern alpine foreland will be investigated by means of ice-flow modelling under different climatic conditions. To better constrain the factors that control the depth of glacial overdeepening, it is planned to carry out coupled numerical simulations of ice-flow, glacial hydrology and glaciofluvial erosion and sediment transport. Based on the outcome, defendable erosion scenarios for the sites will be developed to constrain assumptions in safety assessment calculations.

A final primary objective of RD&D activities related to geology is to improve the process understanding of key safety-relevant phenomena in the host rock (and the confining units) which contribute to the important role of the host rock in the multibarrier concept. The already mature area of radionuclide transport will be further refined. The fundamental understanding of gas transport in the low-permeability host rock will be further elaborated as it also improves the understanding of transport in the engineered barriers and the excavation-damaged zone (EDZ). Further development of plausible descriptions of how gas transport alleviates generated gas pressures is planned and further characterisation at the small scale and interpretation at larger scales are foreseen. Self-sealing is essential in the Opalinus Clay, as it ensures the restoration (recovery) of the barrier function of the rock when fractured. Its efficiency has already been demonstrated and the conceptual understanding is mature. This will be further refined given the importance of self-sealing and how it affects water and gas transport also in the EDZ. The fundamental understanding of thermal effects on the host rock, including at the larger scale, will be evaluated mainly through monitoring of large-scale experiments in the Mont Terri Rock Laboratory (hereafter Mont Terri URL). In the domain of geomechanics, it is planned to develop more robust testing protocols and a larger database, leading to constitutive models that

are improved by better accounting of mineralogical variability, material anisotropy and the post-failure domain, including time-dependent processes. This will improve the assessments of rock heterogeneities and thus provide better constraints for tunnel engineering. Finally, although undisturbed Opalinus Clay shows no evidence of any substantial microbial activity, the presence of microbes in disturbed areas (e.g. the EDZ) might affect the chemistry locally (hydrogen consumption, sulphide formation), as shown in the Mont Terri URL. Planned activities will further evaluate the viability of microbes, focusing on repository-relevant conditions, which are in essence hostile to bacteria.

Characterisation of radioactive wastes and their properties (compliance with requirements for wastes)

Activities focus on the refinement of the inventories and characteristics of waste package types which are already sufficiently characterised in the context of long-term repository safety analyses. However, additional efforts are foreseen to refine inventories in the context of spent fuel handling and loading of the final disposal canisters, inventorying of low-level decommissioning wastes relevant to the planning of the dismantling of nuclear power plants and packaging and logistics considerations, as well as low-level waste radionuclide inventories for waste originating from research activities.

The properties of greatest importance in safety assessment are the rate of release of radionuclides and the rate of gas production under disposal conditions, as well as confirmation that wastes will not exceed criticality requirements in either handling operations or under long-term disposal conditions.

In relation to radionuclide release, experience from prior safety assessments shows that improving the understanding of radionuclide release from spent fuel, as well as reducing uncertainties in the release rate of ^{14}C from L/ILW, are the most relevant remaining issues. Further characterisation of the instant release fraction and the spent fuel dissolution rate under reducing conditions (with the focus on MOX) and the impact of the geochemical environment at the time of release are foreseen in order to expand the existing database. As part of international efforts, the release rate of ^{14}C , a dose-determining radionuclide, in the gaseous and the liquid phase, including the description of its molecular form, is being assessed in targeted experiments which are expected to be concluded in the next years. A methodology for criticality evaluations based on burnup will be finalised in the coming years. For all the spent fuel assemblies, this will provide the curves of minimum burnup versus initial enrichment that will ensure compliance with the defined upper subcriticality limit.

In contrast, while uncertainties associated with long-term HLW glass corrosion remain, the significance of these uncertainties in long-term safety assessment is low. In the case of release of radionuclides other than ^{14}C from L/ILW, there is little benefit in further improving understanding, as the consequences are acceptably low even with the very conservative assumption in release models that all nuclides are released from the waste within 100 years after being placed in the repository.

Long-term gas production experiments from organic materials in L/ILW will be continued together with corrosion and gas generation experiments from metals to refine the description of the source term in the gas impact analysis.

The long-term integrity of spent fuel assemblies during interim storage, including the long-term behaviour of the cladding, continues to receive attention, also regarding concerns of dealing with damaged fuel in the encapsulation facility. In addition to participating in international collaborations, experiments were launched in 2016 using Swiss spent fuel assemblies and these are expected to contribute significantly to the knowledge base.

Design and technology development for the surface and underground facilities for the repositories and for the engineered barriers (compliance with requirements for repository design)

The conceptual design of the repositories and the concepts for the associated facilities and their operation are continually being developed and refined based on the overarching requirements arising from long-term and operational safety and taking into account geological, spatial planning and environmental planning boundary conditions. For the general licence application, the conceptual design needs to be in place. This includes the basic size and location of the most important constructions as well as the waste categories and the maximum disposal capacity. Design studies on retrievability at the conceptual level are also planned, which have to consider the range of possible in-situ conditions that may exist at various retrieval times until final closure of the repository.

Pre-engineering of tailor-made tunnel excavation equipment in combination with liner concepts will be studied. These will feed into more detailed pre-engineering studies of suitable construction methods aiming at the definition of the design basis and the evaluation of the main concepts.

With regard to the emplacement technology, after the successful emplacement of the buffer in the Full-Scale Emplacement (FE) experiment in the Mont Terri URL, which demonstrated that the requirements in terms of overall emplacement density could be met, no major activities are foreseen in the near future apart from refinement and optimisation.

For the development of the SF and HLW canisters, maintaining flexibility and evaluation of options is essential as the final canister material and canister design will be selected a considerable time from now. The principal focus of the work will be on copper-coated canister concepts as an alternative to the carbon steel canister. The main work is on testing of electroplating and cold spray coating methods for depositing copper onto carbon steel and cast iron, including demonstration of the technology at full scale (as well as the design and demonstration of a weld closure method). Work will also be done to explore the feasibility of a cast iron substructure on which copper will be coated and to develop an adequate methodology for canister sealing.

Regarding the L/ILW containers, development and production of prototypes in close cooperation with the waste producers are planned to be finished soon, as the first decommissioning of a nuclear power plant in Switzerland is scheduled to start in 2019. The new disposal containers will be tested in order to demonstrate the fulfilment of all relevant requirements.

For the general licence application, a comprehensive closure (sealing and backfilling) concept is required based on the repository layout and the requirements arising from safety. The important technical fundamentals have been developed and demonstrated in experiments conducted in recent years, most of which continue to provide valuable information, especially regarding the performance at the 1:1 scale. Hence, the closure concept is expected to be based on desk studies and continued monitoring and interpretation of ongoing large-scale sealing experiments.

Specific aspects aiding the conceptual design of the encapsulation facility are discussed, such as transport and cask management, handling of fuel assemblies and canister loading.

Evolution of the safety-relevant properties and processes in the near-field (compliance with barrier requirements and safety function indicators)

The planned RD&D activities aim to develop the fundamental understanding, modelling capabilities and data needed to describe the near-field evolution, to evaluate the safety function indicators, and to support the dose calculations required to evaluate the consequences of any

resulting radionuclide releases. Particular focus is on the understanding of the temporal evolution of the conditions anticipated in the repository. Given the scale and timeframes involved, numerical thermo-hydro-mechanical (THM) modelling is an important aspect, but it needs to be underpinned by targeted laboratory and URL experiments. The ultimate objective is a reliable description of the evolution of the SF/HLW and the L/ILW near-field in terms of safety-relevant parameters that underpins the derivation of safety function indicators for the near-field and demonstrates how the derived criteria can be met.

The major activities with respect to the evolution of the HLW repository are listed below.

Regarding canister evolution, the main objective is to increase confidence in predictions of the period for which the canisters remain intact, particularly by developing improved understanding of relevant corrosion mechanisms. The studies of anoxic and high-temperature corrosion in lab-based and in-situ experiments that are currently running will continue in order to increase the understanding of relevant processes and to refine the reference corrosion rate values. Furthermore, experiments will be undertaken on the corrosion properties of candidate canister materials under irradiation conditions.

Bentonite performance is well characterised, also due to the large international effort in recent years, and remaining RD&D activities relate to specific issues such as its capacity to suppress microbial growth at certain swelling pressures and this will be further assessed. While the long-term bentonite performance at temperatures < 100° C is largely established, the property evolution at temperatures up to 150 °C (and the underlying constitutive models) under partly saturated conditions is less well documented. However, current observations do not suggest major impacts. In the future, activities will be undertaken to further enhance the existing dataset when the opportunity exists. A further issue that will be addressed is the development and impact of heterogeneities in the properties of emplaced bentonite due to the emplacement procedure or the post-closure impact of thermal and hydraulic processes.

Even though cement-clay interactions are currently understood in reasonable detail, uncertainties remain, especially regarding the relationships between porosity and permeability and between porosity and diffusivity at different saturations. Further effort is foreseen to reduce these uncertainties, although these are no longer considered to be critical.

To improve the assessment of the impact of the EDZ, compilations of EDZ-related data from Mont Terri and other underground laboratories will be completed, aimed at assessing the impact of tectonic overprint and mineralogical variability on the EDZ development. An integrated interpretation of evidence supported by site-specific data will allow a robust assessment of geo-mechanical rock mass behaviour on the future tunnels and will feed into engineering models for tunnel design. It needs to be kept in mind that effective measures to control the EDZ development in-situ can be achieved through direct subsurface access in later stages of the programme.

A more rigorous assessment of the description of gas release from a HLW repository and the induced thermal overpressures is foreseen. Sensitivity analyses will include both gas transfer within individual repository components and the behaviour of the overall system. A special focus will be the role of the EDZ of the backfilled SF/HLW drifts and the seal sections. For this, the existing coupled hydromechanical approach will be extended. This will allow a more balanced assessment of the maximum gas pressure build-up in the backfilled repository structures and thermal overpressures in the near-field.

Long-term monitoring of the buffer saturation processes in key experiments at the Mont Terri URL (full-scale emplacement (FE) and heater (HE) experiments) will produce additional data supporting the description of the evolution of the HLW near-field in the transitional phase, after

the peak temperature at the canister surface has been reached. While good agreement exists between models and measurements of thermo-hydraulic parameters and temperature fields in the engineered barrier system and host rock, saturation is slow (driven by host rock water supply) and it will require some years of monitoring to adequately validate models. The resulting databases are integrated in international modelling task forces, allowing for further model development and validation.

Overall, with many L/ILW repositories already in operation worldwide, the required support from RD&D activities for the development of the L/ILW repository near-field is lower compared to the HLW repository, while many activities benefit both repositories. The further development of the engineered gas transport system, including the continuation of the GAST (gas-permeable seal test) experiment at the Grimsel Test Site, examining the functionality of the sand/bentonite seal on a 1:1 scale and contributing to the understanding of gas-water flow under repository-relevant conditions, remains an important element for the performance of the L/ILW repository.

With respect to the databases on radionuclide transport in the near-field, the existing process understanding and databases for compacted clay systems at Nagra's disposal are already considered to be of high quality. Further RD&D is nevertheless planned to address residual uncertainties, potentially allowing more realistic assumptions to be used in safety assessment dose calculations and also an increase in robustness. The remaining uncertainties to potentially be reduced are associated with the transfer of data measured in dilute systems to compacted systems, as well as issues of competitive sorption, radionuclide speciation, the behaviour of redox-sensitive elements and the speciation, stability and retention of ^{14}C .

Safety assessment (compliance with requirements for operational and long-term safety)

The objective of work on the post-closure safety assessment is to further develop the methodology and the necessary assessment tools so that the comprehensive post-closure safety assessment will support the general licence applications and meet the requirements set out by the regulatory authorities. The assessment integrates the results of many of the activities described in previous paragraphs, but also the methodology itself requires certain RD&D activities. Particular aspects of the development work include FEP (features, events and processes) management and scenario development, as well as probabilistic safety and sensitivity analysis methods and tools. A special emphasis will be on the consistent treatment of uncertainty and risk. Improved treatment of the consequences of potential human intrusion, impacts of glacial erosion and repository exhumation and state-of-the-art biosphere modelling are among the activities foreseen.

With respect to operational safety assessment, the activities planned have the broad objective of further developing the methodology and the associated assessment tools with the focus on systematic accident assessments, a classification concept for radioactive waste tailored to the needs of operational safety assessment, and the development of safety concepts and associated requirements with a view to the minimisation/exclusion of malfunctions and accidents. It should be noted that well developed and highly relevant methods, knowledge and experience already exist in the nuclear community with respect to operational safety assessment.

Development of a concept for repository monitoring

The objective is to develop a concept, and eventually detailed methods and techniques, for reliable surface-based and underground monitoring of a repository. The first monitoring concept to be developed will cover baseline monitoring of the initial state, monitoring during construction of the access and the facility for underground geological investigations and the monitoring

plans for the pilot facility. Especially on the strategic level, participation in international research projects with partners more advanced in their disposal projects is ongoing and will allow learning from their experience. Progress in technological and methodology developments as well as feasibility testing for repository monitoring is expected from several experiments that are already initiated or will be implemented in the Swiss URLs. For surface monitoring of ground movements and seismicity, GNSS and seismic stations are already installed in the siting regions and further stations and remote sensing techniques can be added for the selected site(s).

Chapter 8 describes the anticipated evolution of the RD&D programme beyond the general licence application. In the first instance, the focus will be on the continuation of the programme between the submission of the licence application and its granting after review and approval by the regulator and the government. It is anticipated that this will take approximately 7 years (Nagra 2016a). In this period, the licence for the facilities for underground geological investigations will be prepared. After the granting of the general licence, the RD&D programme will enter a new phase in which technology development and engineering will become a major part of the programme, next to subsurface characterisation and the scientific programmes in the facilities for underground geological investigations.

The time needed for the construction of the access (exploration shaft and/or tunnel) to the facility for underground geological investigations will be used to initiate the characterisation of the rock and update the datasets and models. Once the repository depth is reached, the construction of the facility can be implemented, possibly in two phases, to host the planned experiments. The objectives of the activities are the improved characterisation of relevant rock properties, the performance confirmation of rock properties related to post-closure safety (self-sealing, gas transport, radionuclide migration, thermal impact), testing and optimisation of engineering aspects (drift / cavern construction and support) and components (seal test) and monitoring (concepts and techniques).

In addition to further developing other areas to refine the safety case, design and technology development in anticipation of the construction licence will become significant, covering many areas including:

- refinement of the tunnel design concepts and demonstration of the tunnel design at full scale (including the liner) based on the in-situ characterisation of rock performance
- selection of the final SF/HLW canister design and material and development and testing of full-scale canister prototypes
- testing, final selection and optimisation of backfilling materials, including their detailed characterisation
- design and testing of backfilling technology on an industrial scale, focusing on a robust design as well as further mechanisation of the backfilling process
- development and testing of equipment for handling SF/HLW canisters and L/ILW containers in the surface facilities and underground facilities and for their emplacement in the repositories, including design and testing of remote-controlled methods that satisfy radiation protection requirements.

In anticipation of the operating licence, while technologies for emplacement and retrieval will already have been developed, emplacement and retrievability will require to be demonstrated in depth. The constructability of the sealing elements will be demonstrated and the return of experience will feed into the specification and refinement of the construction method. Innovative mechanised procedures will be considered with the aim of enhancing working safety and optimising construction and emplacement efficiency.

Zusammenfassung

Die Nagra hat den Auftrag, sichere geologische Tiefenlager für alle radioaktiven Abfälle aus der Nutzung der Kernenergie sowie aus Medizin, Industrie und Forschung in der Schweiz zeitgerecht und zu vertretbaren Kosten zu realisieren. Die dazu erforderlichen Rahmenbewilligungs-gesuche werden im Rahmen des Sachplans geologische Tiefenlager (SGT) erarbeitet und einge-reicht werden. Gemäss Art. 31 Abs. 1 des Kernenergiegesetzes (KEG 2003) sind die Betreiber von Kernanlagen verpflichtet, die aus ihrer Anlage stammenden radioaktiven Abfälle auf eigene Kosten sicher zu entsorgen. Zur Entsorgungspflicht gehören auch die notwendigen Vorberei-tungsarbeiten wie Forschung und erdwissenschaftliche Untersuchungen. Die Forschungs-aktivitäten sind in Art. 36 der Kernenergieverordnung (KEV 2004) festgelegt. Gemäss Art. 36 Abs. 2 muss der Bewilligungsinhaber die Entwicklung der Technik, einschliesslich Organisa-tion und Personal, verfolgen und prüfen, inwieweit daraus Erkenntnisse für die Sicherheit und die Sicherung der eigenen Anlage (im Fall der Nagra die geologischen Tiefenlager) abgeleitet werden können. In einem Beschluss vom August 2013 hat der Bundesrat verfügt, dass die Nagra zukünftig zusammen mit dem Entsorgungsprogramm ein Forschungsprogramm (RD&D-Plan) einreichen muss. Das vorliegende Forschungsprogramm steht im Einklang mit dem Beschluss des Bundesrats sowie mit dem gesetzlichen Rahmen in der Schweiz.

Es sind zwei Lager vorgesehen, eines für die schwach- und mittelaktiven Abfälle (SMA) und eines für die abgebrannten Brennelemente, die verglasten hochaktiven Abfälle und die langlebi-gen mittelaktiven Abfälle (BE/HAA/LMA). Die Lagerrealisierung erfolgt in einem schritt-weise Prozess, der sich über mehrere Jahrzehnte erstreckt, was eine umfassende Planung der wissenschaftlichen und technischen Arbeiten erforderlich macht. Diese Planung ist im vor-liegenden Forschungs-, Entwicklungs- und Demonstrations-Plan ("Research, Development & Demonstration", engl. Abkürzung RD&D) dokumentiert. Das Hauptziel des RD&D-Plans liegt in der Festlegung des Zwecks, des Umfangs, der Art und der zeitlichen Abfolge der verschie-denen zukünftigen RD&D-Aktivitäten, basierend auf den entsprechenden Anforderungen und Planungsannahmen für die Lagerrealisierung. Der Schwerpunkt liegt auf den Aktivitäten der nächsten zehn Jahre; RD&D-Aktivitäten über diesen Zeitraum hinaus werden allgemeiner behandelt.

Kapitel 1 diskutiert die übergeordnete Zielsetzung des Berichts und gibt einen kurzen geschichtlichen Abriss der Schritte, die zur heutigen Situation geführt haben. Die Arbeits-planung geht vom Bundesratsentscheid zum Projekt Entsorgungsnachweis aus dem Jahre 2006 aus, welcher den Nachweis der Nagra, dass die sichere Entsorgung der BE/HAA/LMA in der Schweiz technisch machbar ist, positiv beurteilt hat. Die Machbarkeit der sicheren Entsorgung der SMA wurde bereits 1988 vom Bundesrat anerkannt. Nach dem positiven Entscheid des Bundesrats zum Projekt Entsorgungsnachweis hat der Bundesrat im April 2008 den Sachplan geologische Tiefenlager genehmigt, in dessen Rahmen die Standortwahl erfolgt. Der Sachplan legt im Konzeptteil die Sachziele des Bundes sowie das Verfahren fest, wie die Auswahl geeigneter Lagerstandorte für BE/HAA/LMA (kurz HAA) und SMA zu erfolgen hat, für die später Rahmenbewilligungsgesuche einzureichen sind. Als Planungsgrundlage für den vorliegenden RD&D-Plan dienen die eingereichten Vorschläge der Nagra für Etappe 2 des Sachplans, die zur Auswahl von geeigneten geologischen Standortgebieten für das SMA- und das HAA-Lager führen werden, welche in den kommenden Jahren mittels oberflächenbasierten, geologischen Untersuchungen vertieft erkundet werden.

Kapitel 2 enthält die übergeordneten Planungsannahmen für die Realisierung der SMA- und HAA-Lager einschliesslich des angenommenen Zeitplans, der Art und Menge der Abfälle sowie der Sicherheitsstrategie für die Tiefenlager. Der Zeitplan umfasst das Sachplanverfahren und

das Rahmenbewilligungsverfahren, den Bau und Betrieb der Bauten für erdwissenschaftliche Untersuchungen untertag an den Standorten sowie das Bau- und das Betriebsbewilligungsverfahren. Es wird erwartet, dass die Einlagerung der SMA ungefähr im Jahr 2050 und diejenige der HAA ungefähr im Jahr 2060 beginnen werden. Nach der Abfalleinlagerung folgt eine Beobachtungsphase (Planungsannahme mindestens 50 Jahre), an deren Ende ein Gesuch für den Lagerverschluss eingereicht werden wird. Das Kapitel enthält eine Zusammenfassung der verschiedenen Abfalltypen und -mengen, die in Kernkraftwerken sowie in der Medizin, Industrie und Forschung anfallen, sowie eine Darstellung der Sicherheitskonzepte für die beiden Lagertypen.

In **Kapitel 3** werden die einzelnen Programmabschnitte und die sich daraus ergebenden Einflüsse auf die RD&D-Aktivitäten dargelegt. Das Sachplanverfahren wird im Hinblick auf die Anforderungen an das RD&D-Programm der Nagra für alle Etappen der Standortwahl bis zum Rahmenbewilligungsgesuch erläutert. Für Etappe 1 (Auswahl von geologischen Standortgebieten) werden die Schritte zusammengefasst, welche zum Vorschlag der Nagra von sechs geologischen Standortgebieten für das SMA-Lager (Südranden, Zürich Nordost, Nördlich Lägern, Jura Ost, Jura-Südfuss, Wellenberg) und drei geologischen Standortgebieten für das HAA-Lager (Zürich Nordost, Nördlich Lägern, Jura Ost) geführt haben. Etappe 2 des Sachplans hat zwei Hauptziele: zum einen, die Festlegung von mindestens einem Standort für die Oberflächenanlage in jedem der vorgeschlagenen geologischen Standortgebiete und zum anderen, die Anzahl der Standortgebiete auf mindestens zwei pro Lagertyp einzuengen. Im Dezember 2014 hat die Nagra die beiden Regionen Jura Ost und Zürich Nordost mit dem Opalinuston als Wirtsgestein zur weiteren Untersuchung in Etappe 3 vorgeschlagen. Der Vorschlag wird zum Zeitpunkt der Veröffentlichung dieses Berichts von den Aufsichtsbehörden geprüft. In Etappe 3 werden die am Ende der Etappe 2 genehmigten Standortgebiete vertieft untersucht und ergänzende oberflächenbasierte, geologische Untersuchungen durchgeführt. Basierend auf dieser Grundlage wird die Nagra für jeden Lagertyp den Standort auswählen, für den ein Rahmenbewilligungsgesuch auszuarbeiten ist. Die genau spezifizierten Anforderungen im Sachplan zusammen mit den Ergebnissen vergangener Arbeitsprogramme erlauben es, die RD&D-Aktivitäten für die folgenden 5 bis 10 Jahre abzuleiten und zu planen.

In **Kapitel 4** werden die strategischen Anforderungen für die Realisierung der beiden Lagertypen erarbeitet. Die Festlegung der zu entsorgenden Abfälle, deren Eigenschaften und die gesetzlichen und behördlichen Vorgaben für die Entsorgung setzen die Rahmenbedingungen sowohl für den zeitlichen Ablauf der Lagerrealisierung als auch für die Lagerkonzepte, die für eine sichere Tiefenlagerung der Abfälle erforderlich sind. Bei den Lagerkonzepten ist vorgesehen, dass die Langzeitsicherheit durch gestaffelte passive Sicherheitsbarrieren gewährleistet wird, wobei die geologischen und technischen Barrieren ausgewogene Beiträge leisten sollen. Die Auslegungskonzepte für die Lager umfassen: i) das Hauptlager, in dem die Abfälle eingelagert werden und das innerhalb einer angemessenen Zeit nach der Einlagerung verfüllt und versiegelt wird; ii) Testbereiche, in denen standortspezifische Daten für die relevanten Eigenschaften des Wirtsgesteins zwecks Bestätigung der Sicherheit und technischen Machbarkeit erhoben werden; iii) das Pilotlager, in dem das Verhalten der Abfälle, der Verfüllmaterialien und des Wirtsgesteins bis zum Ende der Beobachtungsphase mit dem Ziel überwacht werden, Daten für die Bestätigung der Sicherheit im Hinblick auf den Lagerverschluss zu gewinnen. Die aktuellen Konzepte für die HAA- und SMA-Lager werden beschrieben und anderen Lagerkonzepten gegenübergestellt. Die Strategie für den Umgang mit Ungewissheiten im Rahmen des Sicherheitsnachweises wird ebenfalls aufgezeigt.

In **Kapitel 5** werden das Vorgehen bei der Planung der RD&D-Aktivitäten, die Methodik und die verfügbaren Ressourcen für die Implementierung des RD&D-Programms diskutiert. Mögliche Lösungsansätze für noch offene Fragestellungen werden aus der Perspektive der Nagra als

Projektmanagementorganisation aufgeführt. Zudem werden die Rollen der generischen Felslabore ("Underground Research Laboratories", engl. Abkürzung URLs) Mont Terri (unter der Leitung von swisstopo) und Grimsel sowie der wichtigsten Forschungspartner der Nagra dargelegt.

Kapitel 6 beschreibt den RD&D-Status im Bereich der Entsorgung von HAA und SMA. Bedeutende Fortschritte wurden in den letzten Jahren in Bezug auf die Entwicklung der technischen Barrierensysteme erzielt. In diesem Zusammenhang sind das Demonstrationsexperiment zum Barrierenkonzzept der Nagra im Felslabor Mont Terri sowie die Entwicklung und das grossmassstäbliche Testen des Gastransportsystems für SMA-Lager zur Verringerung von (tiefen)lagerbedingten Effekten zu nennen. Im Bereich des Radionuklidtransports wurde die Methode zur Herleitung von Sorptionswerten aus dem Tonmineralgehalt und der Porenwasserzusammensetzung an einer grossen Datenmenge eingehend getestet. Die daraus abgeleiteten Sorptionswerte für verschiedene tonige Sedimente trugen wesentlich zur Argumentation für die Standortauswahl in SGT Etappe 2 bei. Darüber hinaus wird der Schweizer Zeitplan für die Realisierung der Tiefenlager in einen internationalen Kontext gestellt. Während Lager für schwachaktive Abfälle bereits in vielen Ländern in Betrieb sind, bewegen sich für HAA-Lager einzelne Länder (Finnland, Schweden, Frankreich) auf jenen höchsten Genehmigungsstufen, welche die Nagra erwartungsgemäss rund eine Generation später erreichen wird. Durch die internationale Zusammenarbeit mit anderen Endlager-Programmen in Tongestein (Frankreich, Belgien) und weiteren Organisationen auf europäischer und globaler Ebene, stehen der Nagra wesentliche Erkenntnisse aus weiter fortgeschrittenen Programmen für die Optimierung und Fokussierung des eigenen RD&D-Programms zur Verfügung. Ein bedeutender Gewinn durch den gegenseitigen Erfahrungsaustausch wird vor allem bezüglich der technologischen Entwicklung für Barrieren und Verfüllung, für den Versiegelungsbau und in der Versiegelungstechnik sowie bezüglich der Entwicklung technischer Einrichtungen für den Tunnelvortrieb, der Rückholbarkeit und der Entwicklung von Endlagerbehältern erwartet. Im Laufe des Programms zur Lagerrealisierung werden zu gewissen Zeitpunkten, vor allem im Hinblick auf die Dokumentation der Vorschläge für die Schritte im Sachplanverfahren wie auch für zukünftige Entwicklungen der Sicherheitsnachweise, die RD&D-Ergebnisse gesamthaft interpretiert und synthetisiert, um anschliessend in die Entscheidungsfindung oder direkt in die sicherheitstechnische Beurteilung einzufliessen. Die Ergebnisse der RD&D-Aktivitäten, welche die Geologie betreffen, wurden in den Berichten integriert, welche die Vorschläge für Etappe 2 des Sachplans begleiteten. Als weitere Beispiele werden die Bewertung von Auswirkungen der im Tiefenlager produzierten Gase und Möglichkeiten zur Reduzierung dieser Auswirkungen diskutiert und der Gesamtrahmen der Eingrenzung und Bewertung von lagerbedingten Effekten betrachtet.

Als Hauptteil des Berichts vermittelt **Kapitel 7** eine Übersicht des technischen Programms über die nächsten 10 Jahre und umspannt somit die Zeit bis zur Einreichung der Rahmenbewilligungsgesuche. Erläutert werden die Zielsetzungen, der Wissensstand und der Schwerpunkt innerhalb des jeweiligen Bereichs.

Geologische Untersuchungen (Erfüllung der Anforderungen an die Eigenschaften der Wirtsgesteine und Rahmengesteine sowie an die geologische Langzeitentwicklung; Daten für sicherheitsrelevante Schlüsselparameter)

Der Wissensstand im Bereich der geologischen Untersuchungen wurde in Nagra (2014b) und den begleitenden Berichten zusammengestellt. Diese beschreiben die sedimentologischen und tektonischen Verhältnisse, die geologische Langzeitentwicklung, die geomechanischen und hydrogeologischen Unterlagen und Verhältnisse, die Barriereneigenschaften der Wirt- und Rahmengesteine sowie die Nutzungskonflikte für alle Standortregionen. Zukünftig wird sich der Schwerpunkt des RD&D-Programms in Richtung Entwicklung von Standortmodellen ("Site Descriptive Models", engl. Abkürzung SDMs) verlagern. Als standortspezifische Kompila-

tionen der lokalen Eigenschafts- und Zustandsparameter werden diese als Grundlage für die Wahl der endgültigen Lagerstandorte und die Erstellung des Sicherheitsnachweises dienen. Für gewisse Aspekte, wie die geologische Langzeitentwicklung, wird der regionalen Beurteilung weiterhin eine hohe Bedeutung zugemessen. Mittels oberflächenbasierter Untersuchungen (Reflexionsseismik, untiefe und tiefe Bohrungen) werden in den kommenden Jahren erhebliche Mengen an zusätzliche Daten erhoben. Vom Standpunkt der Sicherheitsbewertung betreffen die wichtigsten Informationen die Geometrie sowie die Qualität des Wirtgestein und der Rahmen-gesteine (Mächtigkeit des Wirtgestein, Lage und Qualität von lithofaziellen Einheiten mit potenziell stark erhöhten Wasserflüssen innerhalb der Rahmengesteine). Aus dem Explorations-programm sollten ergänzende bzw. vertieftere Informationen hervorgehen, um bestehende Ungewissheiten weiter zu reduzieren. Für andere standortspezifische, geologische Informatio-nen, welche direkt in die Sicherheitsanalyse einfließen und für die Berechnung der Strahlen-dosis wichtig sind (hydraulische Parameter, Mineralogie des Wirtgestein, etc.), ist es noch ungewiss, ob zusätzliche Daten zu einer nennenswerten Reduzierung der jeweiligen Ungewiss-heiten führen werden. Allerdings ist die Eingrenzung dieser Ungewissheiten nicht kritisch, da die derzeit verwendeten Parameterwerte eine ausreichende Sicherheitsmarge beinhalten.

Beiträge zur Charakterisierung der Geosphäre für die ausgewählten Standorte und deren Lang-zeitentwicklung sind ein vorrangiges Ziel der RD&D-Aktivitäten in diesem Bereich. Sie bestehen aus einer Reihe von konzeptuellen Modellen der geologischen Verhältnisse an den vorgeschlagenen Lagerstandorten. Dies beinhaltet statische Modelle (litho-stratigraphische Schichtmodelle, Störungsmodelle), die Beschreibung der relevanten Eigenschaften und ihrer Variabilität (Mineralogie, Porosität, hydraulische Leitfähigkeit, Radionuklidrückhaltevermögen, Gastransporteigenschaften, geomechanische Eigenschaften, seismische Geschwindigkeiten) sowie dynamische Modelle zur Definition und Vorhersage der in-situ Zustandsbedingungen (Porendruck, Wassersättigung, chemische Zusammensetzung der Wässer, Temperatur, Spannungszustand, Beanspruchung/Verformung). Eine der Methoden wird die Untersuchung der paläohydrogeologischen Entwicklung an den gewählten Lagerstandorten sein. Das Ver-ständnis von Prozessen, die in der Vergangenheit aufgetreten sind, liefert wertvolle Informa-tionen darüber, was über die gesamte Lebensdauer des Tiefenlagersystems erwartet wird.

Die geologische Langzeitentwicklung, einschliesslich der Neotektonik, Klimaentwicklung und Erosion, wird in den nächsten Jahren vermehrt Aufmerksamkeit erhalten. Für ein geologisches Tiefenlager in der Nordschweiz spielt die zukünftige Erosion eine Schlüsselrolle sowohl in der Standortwahl als auch im Sicherheitsnachweis. Erosion kann zu abnehmender Überdeckung führen, was eine Erhöhung der Durchlässigkeit im Wirtgestein (Dekompaktion) oder sogar eine teilweise oder vollständige Freilegung des Tiefenlagers zur Folge haben kann. Hinsichtlich Neotektonik soll die Charakterisierung der tektonischen Aktivität im Quartär verbessert und die instrumentelle Aufzeichnung der rezenten Krustenbewegungen erweitert werden. Mögliche zukünftige neotektonische Szenarien werden untersucht, wobei die Wahrscheinlichkeit und die möglichen Auswirkungen einer zukünftigen Reaktivierung regionaler Störungen im Grundge-birge und eine anhaltende Deformation des Jura-Falten- und Überschiebungsgürtels im Vorder-grund stehen. Zudem werden die Auswirkungen von neotektonischen Bewegungen und Seismi-zität auf die verschiedenen Elemente eines Tiefenlagers sowie die geologischen und technischen Barrieren analysiert. Bezuglich der Klimaentwicklung soll das Verständnis des lokalen Klimas in den Zentralalpen und ihres nördlichen Vorlands über einen Glazial/Interglazialzyklus unter-sucht werden, um beurteilen zu können, wie das globale Klimasystem die lokalen Bedingungen beeinflusst. Im Hinblick auf zukünftige Erosion sind Methodentests zur Datierung quartärer Sedimente vorgesehen. Das Verständnis der damaligen Entstehungsprozesse der lokalen Topo-graphie soll verbessert werden und als Basis für die Entwicklung künftiger Erosionsszenarien dienen. Ferner sollen das Verhalten und die Ausdehnung der Eisstromsysteme (Rhein-, Aare- und Rhonegletscher) sowie die Entstehung der Topographie des nördlichen Alpenvorlands

durch Eisstrommodellierungen unter verschiedenen klimatischen Bedingungen untersucht werden. Gekoppelte numerische Simulationen von Eisstrom, glazialer Hydrologie, glaziofluviater Erosion und Sedimenttransport sollen helfen, die Faktoren, welche die Tiefe der glazialen Übertiefung kontrollieren, einzugrenzen und besser zu verstehen. Basierend auf den Ergebnissen werden belastbare Erosionsszenarien für die einzelnen Standorte zur Eingrenzung der Annahmen im Rahmen der Sicherheitsanalysen entwickelt.

Ein letztes primäres Ziel der RD&D-Aktivitäten in Zusammenhang mit der Geologie ist die Verbesserung des Prozessverständnisses sicherheitsrelevanter Schlüsselphänomene im Wirtgestein (und in den Rahmengesteinen), die zur wichtigen Rolle des Wirtgestein im Multi-barrierenkonzept beitragen. Die Thematik des Radionuklidtransports weist einen fortgeschrittenen Bearbeitungsstand auf, der in Zukunft weiter vertieft wird. Auch das grundlegende Verständnis des Gastransports im gering durchlässigen Wirtgestein wird weiter vertieft, da dies die Wissensbasis bezüglich technischer Barrieren und Auflockerungszone (AUZ) ebenfalls erweitert. Weiterentwicklungen plausibler Beschreibungen, wie Gastransport erzeugte Gasdrücke abbauen kann, sind geplant und eine weiterführende Charakterisierung auf kleiner Skala und Interpretation auf grösseren Skalen sind ebenfalls vorgesehen. Das Selbstabdichtungsvermögen des Opalinustons ist äusserst wichtig, da es die Wiederherstellung der Barrierenwirkung von mechanisch gestörtem Gestein sicherstellt. Die Wirksamkeit der Selbstabdichtung wurde bereits nachgewiesen und das konzeptuelle Verständnis ist ausgereift. Angesichts ihrer Bedeutung und auch ihrem Einfluss auf Wasser- und Gastransport in der AUZ, wird die Selbstabdichtung weiter untersucht. Das grundsätzliche Verständnis der thermischen Auswirkungen auf das Wirtgestein, auch in grösserem Massstab, wird insbesondere durch die Überwachung (Monitoring) von grossmassstäblichen Experimenten im Felslabor Mont Terri bewertet. Im Bereich der Geomechanik ist geplant, robustere Testprotokolle und eine umfangreichere Datenbasis zu entwickeln. Dies führt zu verbesserten konstitutiven Modellen, welche insbesondere die mineralogische Variabilität, die Gesteinsanisotropie sowie das Nachbruchverhalten, einschliesslich zeitabhängiger Prozesse, berücksichtigen. Dies verbessert die Beurteilung des Gebirgsverhaltens und damit die Bewertungsgrundlage für die Tunnelbautechnik. Obwohl ungestörter Opalinuston keine Anzeichen erheblicher mikrobieller Aktivität zeigt, könnte – wie im Felslabor Mont Terri beobachtet – das Vorhandensein von Mikroben in gestörten Bereichen (z.B. in der AUZ) die Chemie lokal beeinflussen (Wasserstoffverbrauch, Sulfidbildung). In den geplanten Arbeiten wird die Lebensfähigkeit von Mikroben unter lagerrelevanten Bedingungen, welche im Wesentlichen bakterienfeindlich sind, vertiefter bewertet.

Charakterisierung der radioaktiven Abfälle und deren Eigenschaften (Erfüllung der Anforderungen an die Abfälle)

Die Aktivitäten konzentrieren sich vorwiegend auf die Verfeinerung der Inventare und Eigenschaften der Abfallgebindetypen, welche im Kontext der Langzeitlagersicherheitsanalysen bereits ausreichend charakterisiert sind. Es sind jedoch weitere Arbeiten vorgesehen zur Verfeinerung der Inventare im Hinblick auf die Handhabung abgebrannter Brennelemente und die Beladung der Endlagerbehälter, zur besseren Inventarisierung schwachaktiver Stilllegungsabfälle, welche für die Rückbauplanung von Kernkraftwerken und für Fragestellungen zu Verpackung und Logistik relevant sind, sowie bezüglich der Inventare der aus der Forschung stammenden, schwachaktiven Abfälle.

Für die Sicherheitsbewertung von grössster Relevanz sind die Freisetzungsraten der Radioelemente, die Gasproduktionsraten unter lagerrelevanten Bedingungen, sowie der Nachweis, dass die Abfälle die Kritikalitätsanforderungen weder bei der Handhabung noch unter langfristigen Lagerbedingungen überschreiten.

Erfahrungen aus früheren Sicherheitsanalysen zeigen, dass ein verbessertes Verständnis der Radionuklidfreisetzung aus abgebrannten Brennelementen sowie die Reduktion der Ungewissheiten der Freisetzungsraten von ^{14}C aus SMA wichtig sind. Es ist vorgesehen, die Charakterisierung des spontan freigesetzten Anteils von besonders mobilen Radionukliden ("Instant Release Fraction") und der Auflösungsraten abgebrannter Brennelemente unter reduzierenden Bedingungen (mit Schwerpunkt auf Mischoxid-BE, MOX) fortzuführen und die Einflüsse des geochemischen Milieus zum Zeitpunkt der Freisetzung zu untersuchen, um die vorhandene Datenbasis zu erweitern. Im Rahmen der internationalen Aktivitäten laufen derzeit gezielte Experimente, um die Freisetzungsraten von ^{14}C (einem dosisbestimmenden Nuklid) in der gasförmigen und flüssigen Phase, inklusive seiner molekularen Form, zu beschreiben. Diese Untersuchungen sollten in den kommenden Jahren abgeschlossen werden. Auch die Entwicklung einer Methodik zur Bewertung der Kritikalität unter Einbezug des Brennstoff-Abbrands ("Burnup Credit") wird in den kommenden Jahren abgeschlossen. Für alle abgebrannten Brennelemente werden Diagramme des minimalen Brennstoff-Abbrands in Relation zur Anfangsanreicherung bereitgestellt, um die Einhaltung einer definierten Kritikalitätsobergrenze zu gewährleisten.

Im Gegensatz dazu ist die Bedeutung der noch bestehenden Ungewissheiten bezüglich langfristiger HAA-Glaskorrosion für die Langzeitsicherheitsanalysen gering. Im Falle der Freisetzung anderer Radionuklide als ^{14}C aus SMA, birgt eine weitere Wissensvertiefung wenig Nutzen, da die Auswirkungen selbst mit sehr konservativen Annahmen – wie der Freisetzung aller Nuklide innerhalb von 100 Jahren nach Einlagerung der Abfälle – akzeptabel gering sind.

Langzeitexperimente zur Gasproduktion aus organischen Materialien in SMA werden zusammen mit Experimenten zur Korrosion und Gasbildung von/aus Metallen fortgesetzt, um den Quellterm in Gasbildungs- und Konsequenzenanalysen noch besser zu definieren.

Die langfristige Integrität der abgebrannten Brennelemente bei der Zwischenlagerung, einschließlich des Langzeitverhaltens der Hüllrohre, wird weiter untersucht, auch im Hinblick auf die Handhabung von beschädigten Brennelementen in der Verpackungsanlage. Zusätzlich zu internationalen Kooperationsprojekten wurden 2016 erste Experimente mit schweizerischen abgebrannten Brennelementen lanciert. Diese werden erheblich zum Grundlagenwissen über die oben genannten Prozesse beitragen.

Auslegung und Technologieentwicklung der Oberflächen- und Untertagbauten für die geologischen Tiefenlager und für die technischen Barrieren (Erfüllung der Anforderungen an die Lagerauslegung)

Die Lagerkonzepte sowie die Konzepte für die zugehörigen Anlagen und deren Betrieb werden auf Grundlage der übergeordneten Anforderungen betreffend der Langzeit- und Betriebssicherheit und unter Berücksichtigung der geologischen, raum- und umweltplanerischen Randbedingungen kontinuierlich weiterentwickelt. Für das Rahmenbewilligungsgesuch muss ein Auslegungskonzept vorliegen. Dieses beinhaltet die grundlegende Grösse und Lage der wichtigsten Bauten sowie die Abfallkategorien und die maximale Entsorgungskapazität. Zudem sind konzeptionelle Studien betreffend Rückholbarkeit geplant, die mögliche In situ-Bedingungen zu verschiedenen Rückholzeiten bis zum finalen Verschluss des Gesamtlagers abdecken.

Vorstudien zu bedarfsgerechten technischen Einrichtungen für den Tunnelvortrieb werden zusammen mit den Tunnelausbaukonzepten erstellt. Diese führen zu detaillierteren Vorstudien über geeignete Vortriebsmethoden mit dem Ziel, die Konstruktionsgrundlagen festzulegen und die Grundkonzepte zu bewerten.

Nach der erfolgreichen Verfüllung eines modellhaften BE/HAA-Lagerstollens im 1:1-Massstab (FE-Experiment im Felslabor Mont Terri) – welche gezeigt hat, dass die Anforderungen in Bezug auf die Einlagerungsdichte erfüllt werden konnten – sind im Hinblick auf die Einbringtechnik in naher Zukunft keine grösseren Aktivitäten sondern Verfeinerungen und Optimierungen vorgesehen.

Die Festlegung des Behältermaterials und des Behälterdesigns für BE und HAA wird nicht in naher Zukunft erfolgen. Daher gilt es für die Entwicklung der Endlagerbehälter ein möglichst hohes Mass an Flexibilität zu bewahren und ein breites Spektrum an Optionen zu bewerten. Der Fokus der Arbeiten wird auf Konzepten mit kupferbeschichteten Lagerbehältern als Alternative zu solchen aus Karbonstahl liegen. Die Hauptarbeit entfällt auf das Prüfen der Galvanotechnik und kalten Sprühbeschichtungsverfahren zur Beschichtung von Kohlenstoffstahl und Gusseisen mit Kupfer, einschliesslich der Demonstration der Technologie im 1:1-Massstab (sowie die Entwicklung und Demonstration einer Schweißmethode für den Verschluss). Darüber hinaus sind Arbeiten geplant, um die Machbarkeit einer mit Kupfer beschichteten Gusseisenkonstruktion zu prüfen und eine angemessene Methode zur Behälterabdichtung zu entwickeln.

Die Entwicklung und Produktion von Prototypen der Lagercontainer für SMA, die in enger Zusammenarbeit mit den Abfallerzeugern erfolgt, wird bald abgeschlossen sein, da die erste Stilllegung eines Kernkraftwerks in der Schweiz für das Jahr 2019 geplant ist. Die neuen Lagercontainer werden getestet, um die Erfüllung aller relevanten Anforderungen zu demonstrieren.

Für das Rahmenbewilligungsgesuch wird ein umfassendes Verschlusskonzept (Versiegelung und Verfüllung) benötigt, welches auf dem Layout des Tiefenlagers und den Sicherheitsanforderungen basiert. Wichtige technische Grundlagen dazu wurden bereits entwickelt und in den letzten Jahren in Experimenten mit Erfolg getestet. Nebst dem Monitoring und der Interpretation der weiterlaufenden 1:1-Experimente werden die Arbeiten zum Verschlusskonzept vorwiegend analytisch-konzeptioneller Art sein.

Spezifische Aspekte zum Auslegungskonzept der Verpackungsanlage werden beschrieben. Dazu gehören Themen wie das Transport- und Abfallgebinde-Management, die Handhabung von Brennelementen und die Behälterbeladung.

Entwicklung der sicherheitsrelevanten Eigenschaften und Prozesse im Nahfeld (Erfüllung der Anforderungen an Barrierenwirksamkeit und Sicherheitsindikatoren)

Die geplanten RD&D-Aktivitäten sind darauf ausgerichtet, ein grundlegendes Verständnis der Prozesse aufzubauen, Modellierungsmöglichkeiten aufzuzeigen sowie die nötigen Daten bereitzustellen, um die Entwicklungen im Nahfeld zu beschreiben, Sicherheitsindikatoren zu bewerten und die für die Dosisberechnungen, welche zur Bewertung der Folgen einer Radionuklidfreisetzung benötigt werden, erforderliche Unterstützung bereitzustellen. Ein besonderes Augenmerk liegt auf dem Verständnis der zeitlichen Entwicklung der im Tiefenlager zu erwartenden Bedingungen. In Anbetracht des Grössenmassstabs und des entsprechenden Zeitrahmens, sind numerische (THM)-Modellrechnungen ein wichtiges Hilfsmittel. Sie müssen jedoch durch gezielte Laborversuche und Experimente im Felslabor gestützt werden. Letzten Endes ist das Ziel eine belastbare Beschreibung der Entwicklung der HAA- und SMA-Nahfelder in Bezug auf sicherheitsrelevante Parameter, welche eine Herleitung von Sicherheitsindikatoren für das Nahfeld erlaubt und aufzeigt, wie die abgeleiteten Kriterien erfüllt werden können.

Die wichtigsten Aktivitäten in Bezug auf die Entwicklung des HAA-Lagers sind nachfolgend aufgeführt.

Das Hauptziel in Bezug auf das Langzeitverhalten der Behälter besteht darin, das Vertrauen in die Prognosen für jenen Zeitraum zu erhöhen, für welchen der Behälter intakt bleibt. Dies soll vor allem durch ein vertieftes Verständnis der relevanten Korrosionsmechanismen geschehen. Um das Prozessverständnis zu verbessern und die Referenzwerte der Korrosionsraten einzugehen, werden die derzeit laufenden Laborversuche und in-situ Experimente unter anoxischen Bedingungen und bei erhöhter Temperatur fortgeführt. Desweitern werden Experimente hinsichtlich der Korrosionseigenschaften möglicher Behältermaterialien unter Bestrahlung durchgeführt werden.

Das Verhalten von Bentonit ist bereits gut charakterisiert, was zum Teil den grossen internationalen Anstrengungen der letzten Jahre zu verdanken ist. Die verbleibenden RD&D-Aktivitäten beziehen sich auf spezifische Fragestellungen, wie die Fähigkeit, mikrobielles Wachstum bei bestimmten Quelldrücken zu unterbinden. Hier sind weitere Untersuchungen vorgesehen. Während das Langzeitverhalten von Bentonit bei Temperaturen < 100 °C weitgehend erforscht ist, ist die Entwicklung der Bentoniteigenschaften (und die zugrunde liegenden konstitutiven Modelle) bei Temperaturen bis zu 150 °C unter teilweise gesättigten Bedingungen weniger gut dokumentiert. Allerdings deuten die derzeitigen Beobachtungen auf keine wesentlichen Auswirkungen hin. Wenn die Möglichkeit besteht, werden in Zukunft Massnahmen unternommen, um die bestehende Datengrundlage weiter zu verbessern. Zudem sollen die Entstehung und die Auswirkungen der Variabilität in den Eigenschaften des eingebrachten Bentonits als Folge des Einbringverfahrens oder der thermischen und hydraulischen Prozesse nach Lagerverschluss untersucht werden.

Auch wenn Zement – Ton-Wechselwirkungen zurzeit in angemessenem Detail verstanden sind, bestehen gewisse Ungewissheiten weiterhin und dies vor allem hinsichtlich der Beziehungen zwischen Porosität und Permeabilität und zwischen Porosität und Diffusionsvermögen in Abhängigkeit der Sättigung. Weitere Anstrengungen, diese Ungewissheiten zu verringern, sind vorgesehen, obwohl diese nicht mehr als kritisch betrachtet werden.

Um das Verständnis der Bedeutung AUZ für die Langzeitsicherheit weiter zu verbessern, werden AUZ-relevante Daten aus dem Felslabor Mont Terri und anderen Forschungslabors kompiliert. Dies wird ermöglichen, Einflüsse der tektonischen Überprägung und mineralogischen Variabilität auf die Entwicklung der AUZ zu evaluieren. Die integrierte Interpretation evidenzbasierter und standortspezifischer Daten erlaubt zudem eine robuste Einschätzung des felsmechanischen Gebirgsverhaltens in Zusammenhang mit künftigem Tunnelbau, welche in bautechnische Modelle der Lagerauslegung einfliessst. Es muss jedoch bedacht werden, dass in späteren Phasen geeignete bautechnische Massnahmen zur Einschränkung der AUZ in situ ergriffen werden können.

Die Gasfreisetzung aus einem HAA-Lager und die induzierten thermischen Über-drücke werden besonders gründlich untersucht. Sensitivitätsanalysen umfassen sowohl den Gastransport innerhalb der einzelnen Lagerkomponenten als auch das Verhalten des Gesamtsystems. Eine besondere Bedeutung wird der AUZ der verfüllten BE/HAA-Lagerstollen und der Abschnitte mit Versiegelungen beigemessen. Dazu wird der bestehende gekoppelte hydromechanische Ansatz erweitert. Dies ermöglicht eine ausgewogenere Einschätzung des maximalen Gasdruckaufbaus in den verfüllten Lagerbauten und der thermischen Überdrücke im Nahfeld.

Messwerte aus der Langzeitüberwachung während der Wiederaufsättigung der technischen Barrieren aus Schlüsselexperimenten im Felslabor Mont Terri werden zusätzliche Erkenntnisse hinsichtlich der Entwicklung des HAA-Nahfelds in der Übergangsphase nach dem Erreichen der maximalen Temperatur an der Behälteroberfläche liefern. Während zwischen den Modellen und Messungen der thermo-hydraulischen Parameter und Temperaturfelder in den technischen

Barrieren und im Wirtgestein eine gute Übereinstimmung besteht, verläuft die Sättigung langsam (bestimmt durch den Wasserzufluss über das Wirtgestein). Daher bedarf es mehrjähriger Überwachung (Monitoring), um die Modelle adäquat zu validieren. Diese Daten fliessen in internationale Arbeitskreise für die Prozessmodellierung ein, was die weitere Modellentwicklung und -validierung fördert.

Weltweit sind zahlreiche SMA-Lager in Betrieb. Daher wird im Hinblick auf das Nahfeld des SMA-Lagers – im Vergleich zum HAA-Lager – weniger Unterstützung aus den RD&D-Aktivitäten benötigt. Viele Aktivitäten sind allerdings für beide Lagertypen relevant. Die kontrollierte Ableitung von Gasen entlang den Lagerfeldzugängen ("Engineered Gas Transport System", engl. Abkürzung EGTS) ist ein wichtiges Sicherheitselement des SMA-Lagers. Hierzu wird das GAST-Experiment ("GAs permeable Seal Test") im Felslabor Grimsel fortgeführt, wobei die Funktionstüchtigkeit der Sand/Bentonit-Versiegelung im 1:1-Massstab untersucht wird, was zum Verständnis des Gas/Wasser-Flusses unter Tiefenlager-relevanten Bedingungen beiträgt.

Was die Informationen zum Radionuklidtransport im Nahfeld betrifft, so sind das der Nagra zur Verfügung stehende Prozessverständnis und die Datenbasis für kompaktierte Tonsysteme bereits von hoher Qualität. Betreffend die dennoch verbleibenden Ungewissheiten sind weitere RD&D-Aktivitäten geplant. Möglicherweise können darauf basierend weniger konservative Annahmen in den Dosisberechnungen der Sicherheitsanalyse getroffen und die Robustheit erhöht werden. Die verbleibenden Ungewissheiten beschränken sich auf die Übertragbarkeit von den in dispergierten Tonsystemen gemessenen Daten auf kompaktierte Systeme und beinhalten Aspekte der Sorption, Radionuklidspeziation, das Verhalten redoxsensitiver Elemente und die Speziation, Stabilität und Rückhaltung von ^{14}C .

Sicherheitsanalyse (Erfüllung der Anforderungen an die Betriebssicherheit und Langzeitsicherheit)

Ziel der Arbeiten hinsichtlich der Sicherheitsanalysen für den Zeitraum nach Lagerverschluss ist die Weiterentwicklung der Methodik und der erforderlichen Bewertungsinstrumente, damit die umfassenden Langzeitsicherheitsanalysen, welche das Rahmenbewilligungsgesuch unterstützen, die Anforderungen der Aufsichtsbehörden erfüllen. Die Sicherheitsanalyse beinhaltet zwar Ergebnisse vieler in den vorangegangenen Absätzen beschriebener Aktivitäten, jedoch erfordert die Methodik selbst bestimmte RD&D-Aktivitäten. Wesentliche Aspekte der vorgesehenen Arbeiten betreffen das Management von Ereignissen und Vorgängen ("Features, Events and Processes", engl. Abkürzung FEP), die Szenarienentwicklung sowie Methoden und Werkzeuge für probabilistische Sicherheits- und Sensitivitätsanalysen. Dabei wird insbesondere auf die konsistente Behandlung von Ungewissheiten und Risiken fokussiert. Die geplanten Aktivitäten beinhalten unter anderem die verbesserte Handhabung der Auswirkungen menschlichen Eindringens, der Konsequenzen einer allfälligen eiszeitlichen Erosion und Freilegung des Lagers sowie eine Biosphärenmodellierung nach Stand von Wissenschaft und Technik.

Für die Bewertung der Betriebssicherheit sind mit dem allgemeinen Ziel, die Methodik und die damit verbundenen Bewertungs- und Arbeitsmittel weiter zu entwickeln, folgende Aktivitäten geplant: Entwicklung einer systematischen Störfallbeurteilung, Entwicklung eines auf die Bedürfnisse der betrieblichen Sicherheitsanalyse zugeschnittenen Klassifikationskonzepts für die radioaktiven Abfälle sowie die Weiterentwicklung von Sicherheitskonzepten und damit verbundenen Anforderungen im Hinblick auf die Minimierung/Vermeidung von Betriebsstörungen und Störfällen. Dabei ist zu beachten, dass ausgereifte und äusserst relevante Methoden sowie reichlich Wissen und Erfahrung für die Bewertung der Betriebssicherheit bereits aus der Kerntechnik bekannt sind.

Entwicklung eines Konzepts zur Tiefenlagerüberwachung (Monitoring)

Ziel ist die Entwicklung eines Konzepts, sowie schliesslich die Ausarbeitung detaillierter Methoden und Techniken zur zuverlässigen oberflächenbasierten und in-situ Überwachung eines Tiefenlagers. Das erste zu entwickelnde Überwachungskonzept umfasst das Monitoring des Ausgangszustands, das Monitoring während des Baus der Zugangsbauwerke und der Bauten für erdwissenschaftliche Untersuchungen untertag sowie das Überwachungsprogramm für das Pilotlager. Insbesondere auf strategischer Ebene ist die Nagra an internationalen Forschungsprojekten in Gemeinschaft mit Partnern mit einem weit fortgeschrittenen Entsorgungsprogramm beteiligt, was es ermöglicht, von deren Erfahrungen zu lernen. Laufende respektive geplante Experimente in den beiden schweizerischen Felslabors führen zu Fortschritten bei der Lagerüberwachung im Sinne technologischer und methodischer Fragestellungen und erlauben Machbarkeitsprüfungen. Für die Oberflächenbeobachtung von Bodenbewegungen und Seismizität wurden in den Standortgebieten bereits GNSS- und seismische Stationen installiert. Bei Bedarf können diese an ausgewählten Standorten durch weitere Messstationen und Fernerkundungstechniken ergänzt werden.

Kapitel 8 erläutert die zu erwartende Entwicklung des RD&D-Programms über den Zeitpunkt des Einreichens der Rahmenbewilligungsgesuche hinaus. In erster Linie wird der Fokus auf der Fortsetzung des Programms zwischen der Einreichung des Rahmenbewilligungsgesuchs und seiner Genehmigung durch die Aufsichtsbehörde und den Bundesrat liegen. Es wird erwartet, dass dies in etwa sieben Jahre beanspruchen wird (Nagra 2016a). In diesem Zeitraum wird das Bewilligungsgesuch für erdwissenschaftliche Untersuchungen untertag vorbereitet. Nach Erteilung der Rahmenbewilligung tritt das RD&D-Programm in eine neue Phase, in welcher Technologieentwicklung und Bautechnik nebst der Charakterisierung des Untergrunds sowie den wissenschaftlichen Programmen in den Bauten für erdwissenschaftliche Untersuchungen untertag ein wichtiger Bestandteil des RD&D-Programms sein werden.

Die Zeit, die für den Bau des Zugangs (Sondierschacht und/oder -tunnel) zu den Bauten für erdwissenschaftliche Untersuchungen untertag benötigt wird, wird sowohl für die Charakterisierung des Gesteins als auch für die Aktualisierung der Datensätze und Modelle verwendet werden. Sobald die Lagertiefe erreicht ist, können die Bauten für erdwissenschaftliche Untersuchungen untertag – möglicherweise in zwei Phasen – erstellt werden, um dort die geplanten Experimente durchzuführen. Ziel der Aktivitäten sind eine verbesserte Charakterisierung relevanter Gesteinseigenschaften, die Eignungsbestätigung entsprechender Gesteinseigenschaften hinsichtlich Langzeitsicherheit (Selbstabdichtung, Gastransport, Radionuklidtransport, thermische Effekte), die Prüfung und Optimierung von bautechnischen Aspekten (Bau und Sicherung von Lagerstollen und -kavernen) und Komponenten (Test von Versiegelungsbauwerken) sowie der Überwachung (Konzepte und Techniken).

Neben der Weiterentwicklung anderer Bereiche zur Verfeinerung des Sicherheitsnachweises werden konzeptuelle und technologische Entwicklungen im Vorfeld der Erteilung der Baubewilligung zunehmend an Bedeutung gewinnen. Dies wird unter anderem folgende Bereiche betreffen:

- Verbesserung der Tunnelauslegungskonzepte und Demonstration der Lagerauslegung (einschliesslich des Lagerausbaus) in realistischem Massstab auf Basis der in-situ Charakterisierung der erforderlichen Wirtgesteinseigenschaften
- Festlegung der endgültigen BE/HAA-Behälterkonstruktion und -materialien, sowie Entwicklung und Prüfung der Behälterprototypen im 1:1-Massstab
- Prüfung, definitive Auswahl und Optimierung von Verfüllmaterialien einschliesslich deren detaillierter Charakterisierung

- Design und Prüfung der Verfüllungstechnologie für die industrielle Anwendung, mit Schwerpunkt auf einem robusten Design und automatisierten Verfüllungsprozessen
- Entwicklung und Prüfung von Einrichtungen für die Handhabung der BE/HAA-Behälter in den Oberflächen- und Untertaganlagen und für deren Einlagerung, einschliesslich Design und Prüfung von ferngesteuerten Methoden, welche die Strahlenschutzanforderungen erfüllen.

Die Technologien für die Einlagerung und die Rückholbarkeit werden bereits im Vorfeld der erwarteten Rahmenbewilligung entwickelt worden sein, die eigentliche Einbringung und Rückholbarkeit muss jedoch noch demonstriert werden. Die bautechnische Machbarkeit der Versiegelungsbauwerke wird aufgezeigt und die daraus gewonnene Erfahrung wird in die Spezifikation und Verfeinerung des Bauverfahrens einfließen. Innovative automatisierte Verfahren werden berücksichtigt, um die Arbeitssicherheit zu verbessern und die Bau- und Einlagerungseffizienz zu optimieren.

Résumé

La mission de la Nagra est de réaliser, sans retard inutile et à un coût raisonnable, des dépôts sûrs en couches géologiques profondes pour l'ensemble des déchets radioactifs produits par l'exploitation de l'énergie nucléaire ainsi que les applications de la médecine, de l'industrie et de la recherche en Suisse. Les autorisations générales nécessaires seront préparées et soumises aux autorités conformément aux exigences du plan sectoriel «Dépôts en couches géologiques profondes» (« Sachplan Geologische Tiefenlager »). Selon l'art. 31 par. 1 de la Loi sur l'énergie nucléaire (KEG 2003), les exploitants des installations nucléaires ont l'obligation de gérer à leurs frais et de manière sûre l'ensemble des déchets produits par leurs installations. Cette tâche comprend les activités préparatoires nécessaires, telles que la recherche et les études géologiques. Les travaux de recherche sont mentionnés à l'art. 36 de l'Ordonnance sur l'énergie nucléaire (KEV 2004). A l'art. 36 par. 2 de l'ordonnance, il est précisé que le détenteur d'une autorisation doit suivre le développement de la technique, y compris en ce qui concerne l'organisation et le personnel, et chercher les enseignements à en tirer pour la sécurité et la sûreté des installations concernées – à savoir, dans le cas de la Nagra, les dépôts géologiques. Une décision du Conseil fédéral datée d'août 2013 stipule que la Nagra doit soumettre un Plan de recherche-développement et démonstration (plan RD&D) en même temps que le Programme de gestion des déchets. Le présent plan RD&D répond à la demande formulée par le Conseil fédéral ainsi qu'aux exigences de la législation suisse.

Deux types de dépôts sont prévus, l'un pour les déchets de faible et de moyenne activité (DFMA) et l'autre pour les éléments combustibles usés, les déchets vitrifiés de haute activité et peut-être les déchets de moyenne activité à vie longue (EC/DHA/DMAL). Le processus de réalisation des dépôts comprend une série d'étapes successives et se déroule sur plusieurs dizaines d'années. Ceci rend nécessaire l'établissement d'un programme global des travaux scientifiques et d'ingénierie, qui fait l'objet du Plan RD&D (recherche-développement et démonstration). Ce plan directeur a pour fonction principale de poser les objectifs, l'envergure, la nature et le calendrier des futures activités de RD&D, sur la base des différentes prescriptions, contraintes et hypothèses de conception. Il est centré sur les activités de la décennie à venir et comporte des indications plus générales sur le programme de RD&D au-delà de cette période.

Le **chapitre 1** présente les objectifs généraux du rapport et contient un bref rappel historique. En 2006, une décision du gouvernement fédéral a établi que la Nagra, avec son projet *Entsorgungsnachweis* («démonstration de la faisabilité du stockage»), avait démontré que le stockage géologique en Suisse des EC/DHA/DMAL était techniquement réalisable. Sur la base d'études antérieures et d'expertises des autorités de sûreté, le Conseil fédéral avait déjà approuvé en 1988 la faisabilité globale d'un stockage sûr des déchets de type DFMA. Suite à l'étude de faisabilité « *Entsorgungsnachweis* », le gouvernement fédéral a initié le plan sectoriel «Dépôts en couches géologiques profondes» (« Sachplan geologische Tiefenlager » ou SGT), qui définit la procédure de sélection des sites d'implantation potentiels. Le plan sectoriel est un instrument qui détaille les critères à respecter pour sélectionner les sites d'implantation appropriés pour les dépôts destinés aux DFMA et aux EC/DHA/DMAL, et préparer les demandes d'autorisations générales correspondantes. La planification globale présentée ici repose sur les propositions effectuées par la Nagra dans le cadre de l'étape 2 du plan sectoriel. Cette étape aboutira à la sélection de domaines d'implantation potentiels pour les dépôts de déchets DFMA et DHA qui feront l'objet de travaux de reconnaissance géologique à partir de la surface au cours des prochaines années.

Le **chapitre 2** présente les conditions cadre de la planification en matière de réalisation des dépôts DFMA et EC/DHA/DMAL, en particulier le cadre temporel envisagé, les types et volumes de déchets ainsi que la stratégie adoptée pour garantir la sûreté des dépôts. Le calendrier prévisionnel présenté comporte les éléments suivants : le plan sectoriel, la procédure d'autorisation générale, la construction et l'exploitation des installations pour recherches géologiques souterraines sur les sites d'implantation, les demandes d'autorisation de construire et d'exploitation des dépôts. La date prévisionnelle du début du stockage en dépôt DFMA est située vers 2050, celle des EC/DHA/DMAL vers 2060. La période de stockage des déchets est suivie d'une phase d'observation (dont la durée a été fixée, pour les besoins de la planification, à 50 ans au moins). A la fin de la phase d'observation, une demande d'autorisation de fermeture du dépôt sera effectuée. Ce chapitre comprend en outre un aperçu des différents types et volumes de déchets issus des centrales nucléaires ainsi que de la médecine, de l'industrie et de la recherche. Il décrit de plus les concepts de sûreté pour les deux types de dépôts envisagés.

Le **chapitre 3** est consacré aux différentes étapes du programme et à leurs implications sur les activités de RD&D. La procédure du plan sectoriel est présentée de manière suffisamment détaillée pour expliciter les prescriptions qui en découlent pour le programme de RD&D de la Nagra et ceci pour chacune des étapes de la sélection des sites, jusqu'à la demande d'autorisation générale. Pour l'étape 1, consistant à sélectionner des domaines d'implantation géologiques favorables, les phases ayant mené à la validation de six domaines d'implantation géologiques pour un dépôt DFMA (Südranden, Zürich Nordost, Nordlich Lägern, Jura Ost, Jura Südfuss, Wellenberg) et trois domaines d'implantation géologiques pour un dépôt DHA (Zürich Nordost, Nördlich Lägern, Jura Ost) sont exposées. L'étape 2 du plan sectoriel vise deux objectifs principaux : premièrement, sélectionner au moins un emplacement pour les installations de surface dans chaque domaine d'implantation géologique et, deuxièmement, restreindre le nombre des domaines d'implantation à deux au minimum par type de dépôt. En décembre 2014, Nagra a proposé de poursuivre, dans le cadre de l'étape 3, l'étude des domaines d'implantation Jura Ost et Zürich Nordost, avec l'Argile à Opalinus (OPA) comme roche d'accueil. A la date de publication du présent rapport, cette proposition est en cours d'examen par les autorités de surveillance. Au cours de l'étape 3, les sites approuvés à l'issue de l'étape 2 seront soumis à un examen plus approfondi et des reconnaissances géologiques supplémentaires seront réalisées depuis la surface. C'est sur cette base que la Nagra sélectionnera, pour chacun des dépôts, le site pour lequel la demande d'autorisation générale sera élaborée. En prenant en compte les exigences particulières du plan sectoriel ainsi que les résultats des travaux menés antérieurement, il est possible de définir avec précision les activités de RD&D à prévoir sur un horizon de 5 à 10 ans.

Le **chapitre 4** décrit le cadre stratégique qui préside à la conception des deux types de dépôts. Le calendrier de réalisation et les concepts de dépôts nécessaires à un stockage sûr des déchets sont conditionnés par la définition des types de déchets, leurs caractéristiques et le cadre légal et réglementaire à respecter en matière de stockage. La sûreté à long terme des dépôts repose sur un système équilibré de barrières de sûreté passives qui comprend les barrières ouvrages et le milieu géologique environnant. Les concepts de dépôts en couches géologiques profondes prévoient: i) un dépôt principal dont les galeries seront remblayées et scellées après la mise en place des déchets, ii) des zones de test, où l'on collectera les données nécessaires sur les caractéristiques de la roche d'accueil afin de confirmer la sûreté à long terme du dépôt et sa faisabilité technique, iii) un dépôt pilote où le comportement des déchets, du matériau de remblai et de la roche d'accueil feront l'objet d'une surveillance jusqu'à la fin de la phase d'observation et où l'on compilera les données permettant de confirmer la sûreté du dépôt en vue de sa fermeture. Les concepts actuels pour les dépôts EC/DHA et DFMA sont décrits et comparés à d'autres concepts existants. La stratégie relative au traitement des incertitudes dans le cadre de l'élaboration de la démonstration de sûreté est explicitée.

Le **chapitre 5** est consacré à la méthodologie, aux ressources disponibles et à la procédure utilisées pour mettre en œuvre les activités du programme de RD&D. Les différentes options pour gérer les questions en suspens sont énumérées, en considération du fait que la Nagra est un organisme chargé de la gestion du projet. Le rôle des laboratoires de recherche souterrains du Mont Terri (géré par swisstopo) et du Grimsel, ainsi que le rôle des partenaires clés de recherche de la Nagra sont exposés.

Le **chapitre 6** présente l'état d'avancement du programme de RD&D pour le stockage des déchets DHA et DFMA. Au cours des dernières années, on a assisté à des avancées notables dans le développement des systèmes de barrières ouvrages, aboutissant d'une part au démonstrateur grandeur nature du concept de barrières de la Nagra au laboratoire souterrain du Mont Terri et d'autre part, aux développements et expérimentations supplémentaires à grande échelle du système technique de transport de gaz pour le dépôt DFMA, qui permet l'atténuation des effets induits par le dépôt. Concernant la problématique du transport des radionucléides, la méthodologie permettant d'obtenir les valeurs de coefficients de sorption à partir de la teneur en argiles des argilites et de la composition chimique de l'eau interstitielle a été testée de manière approfondie sur une large quantité de données, ce qui a permis l'obtention de valeurs de coefficients de sorption pour différents sédiments argileux. Ces données ont été largement utilisées pour la préparation des propositions de sites à l'étape 2 de sélection du plan sectoriel. Ensuite, le calendrier suisse de réalisation des dépôts est replacé dans le contexte international : on observe ainsi que des dépôts pour les DFA sont déjà en service dans de nombreux pays. Plusieurs pays (Suède, Finlande et France) sont au stade de la demande d'autorisation finale pour la construction de leurs dépôts DHA, un stade qui devrait être atteint par la Nagra d'ici environ une génération. Un retour d'expérience important de ces programmes plus avancés permettra d'optimiser et de concentrer le programme de RD&D de la Nagra, grâce notamment à des collaborations internationales avec les autres programmes de stockage dans des argilites (France, Belgique) et d'autres organisations au niveau européen et mondial. En particulier, il pourra être tiré profit du partage des résultats en ce qui concerne le développement technique des remblais, la technique de construction des scellements, le développement des méthodes de creusement des tunnels et enfin la récupération et le dimensionnement des conteneurs stockés. A des dates jalons du programme de réalisation des dépôts, et tout particulièrement lors de la préparation des propositions de sites aux différentes étapes du plan sectoriel, mais aussi dans le cadre des futures démonstrations de sûreté, l'ensemble des résultats de la RD&D sera interprété et intégré soit dans des synthèses appuyant les prises de décisions, soit directement dans l'évaluation de sûreté. Les résultats des activités de RD&D liées aux aspects géologiques ont été intégrés dans des rapports étayant les propositions de l'étape 2 du plan sectoriel. D'autres exemples abordés se rapportent à l'évaluation de l'impact des gaz du dépôt et les possibilités d'en atténuer les effets ainsi que le cadre général développé pour limiter et évaluer l'impact des effets induits par le dépôt.

Le **chapitre 7** constitue le cœur du rapport et expose l'ensemble du programme technique pour les dix années à venir, c'est-à-dire jusqu'à la demande d'autorisation générale. Il inclut les objectifs, la situation et les enjeux principaux dans les différents domaines suivants :

Prospections géologiques (respect des exigences sur les propriétés de la roche d'accueil et des roches encaissantes et de leur évolution géologique à long terme ; données sur les paramètres de sûreté clés)

Concernant les prospections géologiques, l'état des connaissances a été compilé dans Nagra (2014b) et les rapports afférents décrivant les conditions sédimentologiques et tectoniques, l'évolution géologique à long terme, les données et les conditions géomécaniques et hydrogéologiques, les propriétés de confinement des roches d'accueil et encaissantes et les conflits

d'utilisation pour tous les domaines d'implantation. A l'avenir, la RD&D se focalisera sur le développement de modèles descriptifs de sites (SDM : Site Descriptive Models) pour chacun des domaines d'implantation (en déterminant les propriétés locales et les variables d'état). Ces SDM serviront de base à la sélection des sites définitifs et à l'élaboration de la démonstration de sûreté. Pour certains aspects, par exemple l'évolution géologique à long terme, les évaluations à l'échelle régionale continueront d'être primordiales. Au cours des prochaines années, des quantités substantielles de données supplémentaires seront acquises grâce aux investigations de surface qui seront menées (campagnes de réfraction sismique, forages exploratoires profonds et superficiels). Du point de vue de l'évaluation de la sûreté, les informations les plus importantes se rapporteront à la géométrie et à la qualité de la roche d'accueil et des encaissants (épaisseur de la roche d'accueil, localisation et qualité des horizons plus perméables dans les encaissants à potentiel de transit de débits d'eau fortement accrus). Le programme de reconnaissance devra compléter et/ou améliorer les connaissances de telle sorte que les incertitudes associées en soient encore diminuées. Il n'est pas certain qu'elles conduisent à une réduction notable des incertitudes associées à d'autres données géologiques spécifiques à chaque site qui sont utilisées directement dans les analyses de sûreté, à savoir celles qui ont un impact sur les calculs de doses radiologiques (paramètres hydrauliques et minéralogie de la roche d'accueil, etc.). Cependant, une diminution de ces incertitudes n'est pas jugée critique vu la marge de sécurité suffisante attribuée à ces valeurs de paramètres dans les analyses actuelles.

Dans ce domaine, les activités de RD&D concernent notamment la caractérisation de la géosphère pour les domaines d'implantation sélectionnés et l'étude de leur évolution à long terme. Cette contribution consiste en une série de modèles conceptuels des conditions géologiques dans les domaines proposés ; ceux-ci comprennent des modèles statiques (modèles lithostratigraphiques, modèles de failles), des distributions de propriétés (minéralogie, porosité, conductivité hydraulique, propriétés de rétention des radionucléides, propriétés de transport de gaz, rigidité et résistance des matériaux, vitesses sismiques) et des modèles dynamiques (permettant la définition et la prédiction des conditions des variables d'état in-situ : pression de pore, saturation en eau, composition chimique de l'eau, température, état des contraintes et déformations/déplacements mécaniques). L'un des outils utilisés sera l'étude des évolutions paléo-hydrogéologiques dans les domaines d'implantation sélectionnés. Les connaissances des processus du passé sont riches en enseignements pour la dérivation du comportement probable sur l'ensemble de la durée de vie du dépôt géologique.

L'évolution géologique à long terme, incluant la néotectonique, l'évolution climatique et l'érosion, fera l'objet d'une attention accrue dans les années à venir. Pour un dépôt géologique dans le nord de la Suisse, l'érosion future représente un point crucial pour la sélection des sites et la démonstration de sûreté. En effet, l'érosion pourrait conduire à la réduction de la contrainte mécanique appliquée sur la roche d'accueil et, en conséquence, à une augmentation de la perméabilité (par décompaction), voire provoquer la mise à découvert de tout ou partie du dépôt. En ce qui concerne la néotectonique, l'objectif est d'améliorer la caractérisation des activités néotectoniques passées et d'étendre les enregistrements des mouvements récents de la croûte terrestre. Des scénarios possibles d'évolution néotectonique future seront examinés. La probabilité et les effets potentiels d'une réactivation future des failles dans le socle régional et de la déformation en cours de la ceinture de plissement et glissement du Jura présentent un intérêt tout particulier. Les effets potentiels des mouvements néotectoniques et de la sismicité sur les différents éléments constituant un dépôt et ses barrières ouvrageées et géologiques seront évalués. Concernant les évolutions climatiques, l'analyse du climat local des Alpes centrales et leur avant-pays nord au cours d'un cycle glaciaire-interglaciaire complet sera renforcée afin d'évaluer l'impact du système climatique global sur les conditions locales. En ce qui concerne l'érosion future, l'expérimentation de méthodes avancées de datation des sédiments du quaternaire est prévue, l'analyse des évolutions passées de la topographie locale sera améliorée

pour offrir une base au développement des scénarios d'évolution future et le comportement et l'extension des systèmes d'écoulement glaciaire tels les glaciers du Rhin, du Rhône et de l'Aare et les évolutions du paysage dans la bordure nord des Alpes seront étudiés par le biais de modélisations des écoulements glaciaires menées sous différentes conditions climatiques. Afin de mieux évaluer les facteurs qui contrôlent la profondeur du surcreusement glaciaire, il est prévu de réaliser des simulations numériques couplées des écoulements glaciaires, de l'hydrologie glaciaire, de l'érosion fluvio-glaciaire et du transport de sédiments. Sur la base des résultats obtenus, des scénarios d'érosion crédibles seront développés pour les différents sites, ce qui permettra de contraindre les hypothèses employées dans les calculs de sûreté.

Le dernier objectif principal des activités de RD&D se rapportant à la géologie est l'amélioration de la compréhension des phénomènes clés en termes de sûreté dans la roche d'accueil (et les encaissants) qui contribuent à donner à la roche d'accueil un rôle majeur dans le concept à barrières multiples du dépôt. La connaissance déjà bien aboutie du transport de radionucléides sera encore affinée. La compréhension fondamentale du transfert de gaz dans la roche d'accueil à faible perméabilité sera développée plus avant, car elle permet également une meilleure compréhension du comportement des barrières ouvrageées et des zones endommagées par l'excavation (EDZ : excavation damaged zone). On envisage en particulier le développement de conceptualisations additionnelles plausibles de l'effet atténuateur du transfert de gaz sur les pressions de gaz générées, et une caractérisation complémentaire à petite échelle ainsi qu'une interprétation à plus large échelle. Les propriétés d'auto-cicatrisation sont essentielles pour les Argiles à Opalinus, car elles assurent la restauration (réparation) des fonctions de confinement de la roche lorsque celle-ci a été fracturée. Son efficacité a déjà été démontrée et sa compréhension conceptuelle est arrivée à maturité. Cependant, cet aspect sera affiné compte tenu de l'importance de l'auto-cicatrisation et de l'impact sur les transferts d'eau et de gaz, également dans l'EDZ. La compréhension fondamentale des effets de la thermique sur la roche d'accueil, y compris à plus grande échelle, sera évaluée principalement par suivi des expériences à grande échelle menées au laboratoire souterrain du Mont Terri. Dans le domaine de la géomécanique, il est prévu de développer des protocoles de test plus robustes et une base de données plus importante qui permettront l'établissement de modèles améliorés grâce à une intégration accrue de la variabilité de la minéralogie, de l'anisotropie des matériaux et du comportement post-rupture, incluant également le comportement différé des matériaux. Cela améliorera l'évaluation des hétérogénéités de la roche et permettra de mieux définir les conditions à prendre en compte pour la construction des tunnels. Enfin, bien que les Argiles à Opalinus intactes ne présentent aucune trace d'activité microbienne substantielle, la présence de microorganismes dans les zones perturbées (notamment les EDZ) est susceptible de modifier localement la chimie (consommation d'hydrogène, formation de sulfure) comme cela a été mis en évidence au laboratoire souterrain du Mont Terri. Les activités prévues visent à évaluer plus avant les conditions de viabilité des microbes, dans les conditions d'un dépôt géologique qui sont par nature hostiles à la prolifération bactérienne.

Caractérisation des déchets radioactifs et de leurs propriétés (conformité aux exigences sur les déchets)

Les travaux sont centrés sur une meilleure définition des inventaires et les caractéristiques des différents types de colis de déchets. Celles-ci sont suffisantes pour les besoins des analyses de sûreté à long terme, mais des efforts supplémentaires sont prévus pour affiner les inventaires dans les contextes suivants: manutention des combustibles usés et chargement des conteneurs de stockage définitifs, recensement des déchets de faible activité issus de la mise hors service des réacteurs et pertinents pour la programmation du démantèlement des centrales nucléaires, y compris l'emballage et la logistique, ainsi que les inventaires des déchets de faible activité issus du secteur recherche.

Les propriétés les plus importantes pour l'évaluation de la sûreté sont les taux de relâchement de radionucléides et les débits de production de gaz en conditions de stockage, ainsi que l'assurance que les déchets ne vont pas dépasser les seuils de criticité fixés lors des opérations de manutention ou dans les conditions du stockage à long terme.

En ce qui concerne le relâchement des radionucléides, le retour d'expérience des études de sûreté antérieures a montré qu'il était crucial d'améliorer la compréhension du relâchement des radionucléides provenant des combustibles usés et de réduire les incertitudes sur le taux de relâchement de ^{14}C par les DFMA. Afin de compléter les bases de données existantes, on prévoit de poursuivre la caractérisation des fractions à relâchement instantané et de la vitesse de dissolution des combustibles usés sous conditions réductrices (avec un accent mis sur les MOX) et l'impact de l'environnement géochimique à l'instant du relâchement. Faisant l'objet d'une partie des efforts de collaboration internationale, le taux de relâchement en phase gazeuse et aqueuse de ^{14}C , un radionucléide déterminant pour le calcul de doses, comprenant la description de sa forme moléculaire, est évalué dans le cadre d'expérimentations ciblées dont les résultats sont attendus dans les prochaines années. Une méthode d'évaluation de la criticité basée sur les taux de combustion sera finalisée dans les années à venir. Elle vise à obtenir des courbes de taux de combustion minimal en fonction de l'enrichissement initial pour l'ensemble des assemblages de combustibles usés, ce qui assurera leur conformité aux limites supérieures de sous-criticité.

En revanche, bien que des incertitudes demeurent concernant la corrosion sur le long terme du verre des DHA, celles-ci sont de faible impact sur la sûreté à long terme. L'amélioration des connaissances sur le relâchement de radionucléides autres que le ^{14}C dans les DFMA ne se traduirait pas par des bénéfices notoires. En effet, les conséquences radiologiques en sont suffisamment faibles pour être acceptables et ce, même avec des modèles très pessimistes envisageant le relâchement de tous les radionucléides des déchets dans les 100 ans suivant leur mise en place dans le dépôt.

Les expérimentations à long terme de production de gaz issu des matières organiques dans les DFMA vont être poursuivies en parallèle avec des expérimentations de corrosion et de génération de gaz à partir des métaux afin d'affiner la description des termes sources pour les analyses d'impact du gaz.

L'intégrité à long terme des assemblages de combustibles usés durant le stockage intermédiaire, incluant le comportement à long terme des coques, continuera d'être étudiée, également dans la perspective de la future manipulation d'éléments combustibles endommagés dans l'installation de conditionnement des déchets. En complément d'une participation à des collaborations internationales, des expérimentations sur des assemblages de combustibles usés de centrales suisses ont démarré en 2016, et celles-ci devraient contribuer à accroître significativement le niveau de connaissances.

Conception et développement technique pour les installations souterraines et de surface des dépôts et les barrières ouvrageées (conformité aux exigences de conception des dépôts)

La conception des dépôts et des installations associées et leur exploitation font l'objet de développements et de mises au point continus sur la base des critères principaux résultant de la sûreté à long terme et en phase d'exploitation. Elles prennent en compte les conditions cadres géologiques, d'emprises spatiales et environnementales. La phase de conception devra être aboutie au moment de la demande d'autorisation générale. Celle-ci devra comprendre les spécifications de la taille globale et de l'emplacement des constructions principales ainsi que les catégories de déchets admissibles et la capacité maximale de stockage. Des études conceptuelles

sur la réversibilité du stockage sont également prévues. Elles devront envisager le spectre de conditions in-situ que l'on pourra rencontrer lors d'opérations de récupération des déchets avant la fermeture définitive des dépôts.

La conception d'équipements de creusement et de revêtements de tunnels spécialement adaptés fera l'objet d'études. Cela résultera en un avant-projet plus détaillé en ce qui concerne les techniques de construction adaptées dans le but de définir une conception de base et d'évaluer les concepts principaux.

En ce qui concerne les techniques de mise en place des colis de déchets, la mise en place du matériau de remblai dans l'expérience FE à taille réelle dans le laboratoire souterrain du Mont Terri a montré que les critères, en termes de densité globale de mise en place, pouvaient être respectés. Du fait du succès de cette expérience, aucune action majeure n'est prévue hormis des mises au point de détail et des optimisations.

Pour la conception des conteneurs EC et DHA, il est essentiel de conserver une certaine flexibilité dans l'évaluation des options possibles puisque leur matériau et leur conception définitive seront sélectionnés dans un avenir lointain. Les efforts seront concentrés sur une conception mettant en œuvre des conteneurs avec galvanisation au cuivre comme alternative des conteneurs en acier au carbone. Le travail principal consistera à tester les méthodes de galvanoplastie et de revêtement par projection à froid pour un revêtement en cuivre appliqué sur l'acier et la fonte, ce qui inclut un démonstrateur à échelle réelle de ces technologies (ainsi que la conception et la démonstration des méthodes de scellement par soudure). En outre, des travaux seront menés pour examiner la faisabilité d'une structure en fonte sur lequel le cuivre sera enduit et développer une méthode d'étanchéisation adéquate pour les conteneurs.

En ce qui concerne les conteneurs DFMA, l'achèvement du développement et de la construction de prototypes en collaboration étroite avec les producteurs de déchets est prévu à court terme, puisque le début du premier démantèlement d'une centrale nucléaire en suisse est planifié pour 2019. Les nouveaux conteneurs de stockage seront testés afin de démontrer leur conformité à toutes les exigences requises.

Pour la demande d'autorisation générale, un concept complet de fermeture (scellement et remblai) est requis, reposant à la fois sur la configuration du dépôt et les exigences de sûreté. Les bases techniques ont été développées et démontrées grâce à des expérimentations menées ces dernières années, dont la plupart continuent d'apporter de précieuses informations, particulièrement en ce qui concerne la performance à l'échelle 1. C'est pourquoi le concept de fermeture devrait reposer sur des études théoriques et la poursuite de l'observation et de l'interprétation des expérimentations de scellement à grande échelle en cours.

Les aspects particuliers participant à l'élaboration de la conception de l'installation de conditionnement des déchets sont traités, comme par exemple le transport et la gestion des fûts, la manutention des assemblages de combustibles et le chargement des conteneurs.

Evolution des propriétés ayant une incidence sur la sûreté et les processus dans le champ proche (conformité aux exigences sur les barrières et les indicateurs de sûreté)

Les activités de RD&D planifiées ont pour objectif de développer la compréhension fondamentale, les capacités de modélisation et l'identification des données nécessaires à la description de l'évolution du champ proche, d'évaluer les indicateurs de sûreté, et d'étayer les calculs de dose nécessaires à l'évaluation des conséquences de tout relâchement de radionucléides.

L'accent est mis sur la compréhension de l'évolution temporelle des conditions attendues dans le dépôt. Etant donné les échelles spatiales et temporelles concernées, la modélisation numérique (THM) joue un rôle important, mais celle-ci doit s'appuyer sur des expérimentations ciblées en laboratoire et en laboratoire souterrain. L'objectif final est d'obtenir une description fiable de l'évolution des champs proches des dépôts EC/DHA et DFMA pour les paramètres impactant la sûreté, de manière à pouvoir étayer la dérivation des indicateurs de sûreté et démontrer comment les critères en dérivant peuvent être remplis.

Les activités principales portant sur l'évolution du dépôt DHA sont énumérées ci-dessous.

En ce qui concerne l'évolution des conteneurs, l'objectif principal est de renforcer la confiance dans les prédictions relatives à la durée de leur intégrité, en particulier en améliorant la compréhension des mécanismes de corrosion. Les études en cours sur la corrosion en milieu anoxique et à haute température en expérimentations de laboratoire et in-situ seront poursuivies afin d'améliorer la compréhension des processus importants et d'affiner les valeurs de référence pour les taux de corrosion. De plus, des expérimentations en conditions irradiées sur les propriétés de corrosion des matériaux potentiels des conteneurs vont être menées.

La performance de la bentonite est bien connue, en particulier grâce à l'apport des efforts entrepris au niveau international ces dernières années. Les activités de RD&D restant à mener concernent des questions spécifiques comme la capacité de la bentonite à supprimer la prolifération microbienne pour certaines pressions de gonflement, ce qui sera étudié plus avant. Alors que la performance à long terme de la bentonite pour des températures inférieures à 100 °C est bien établie, l'évolution de ses propriétés pour des températures allant jusqu'à 150 °C (et les modèles constitutifs sous-jacents) en conditions partiellement saturées est moins bien documentée. Cependant, les observations actuelles ne laissent pas pressentir d'impacts majeurs. A l'avenir, des actions vont être entreprises pour améliorer la base de données existante quand les opportunités s'en présenteront. Une question supplémentaire à résoudre concerne le développement et l'impact d'hétérogénéités dans les propriétés de la bentonite en tant que matériau de remblai, hétérogénéités dues soit à la méthode de mise en place, soit à l'impact des processus thermiques et hydrauliques en phase de post-fermeture.

Bien que les interactions ciment-argile soient actuellement caractérisées avec un niveau de détail acceptable, des incertitudes demeurent en particulier en ce qui concerne les relations porosité-perméabilité et porosité-diffusivité à différents niveaux de saturation en eau. Un effort supplémentaire est prévu pour réduire ces incertitudes, bien qu'elles ne soient plus considérées comme critiques.

Afin de mieux appréhender l'impact des EDZ, des compilations de données relatives aux EDZ issues du Mont Terri et d'autres laboratoires de recherche souterrains seront effectuées, ce qui permettra d'évaluer l'impact de la tectonique polyphasée et de la variabilité minéralogique sur le développement des EDZ. Une interprétation intégrée des observations en laboratoire, complétées par des données spécifiques aux sites considérés permettra une évaluation fiable du comportement géomécanique du massif dans les futures structures souterraines. Elle fera partie intégrante des modèles de dimensionnement en phase de conception des tunnels. Des mesures techniques pour contrôler l'EDZ in-situ peuvent être adoptées dans les étapes futures.

Une évaluation plus rigoureuse du relâchement de gaz dans un dépôt DHA et des surpressions induites par l'impact thermique est prévue. Des analyses de sensibilité porteront aussi bien sur le transfert de gaz au sein des structures souterraines du dépôt que sur le comportement du système dans son ensemble. Une attention particulière sera portée sur le rôle des EDZ des tunnels EC/DHA remblayés et des sections de scellement. Pour cela, l'approche hydro-

mécanique couplée existante sera étendue. Cela permettra une évaluation plus différentiée de l'augmentation maximale des pressions de gaz dans les éléments remblayés du dépôt et des surpressions thermiques au champ proche.

L'observation sur le long terme du processus de saturation des remblais dans le cadre d'expérimentations-clés menées au laboratoire souterrain du Mont Terri générera des données supplémentaires renforçant la description de l'évolution du champ proche des DHA durant la phase transitoire, après que la température maximale à la surface des conteneurs aura été atteinte. Alors qu'il existe une bonne concordance entre les modèles et les mesures des paramètres thermo-hydrauliques et des températures dans la barrière technique et la roche d'accueil, la saturation est lente (contrôlée par l'apport d'eau de la roche d'accueil) et il faudra des années d'observations pour valider les modèles de manière appropriée. Les bases de données résultantes sont fournies aux groupes de modélisation internationaux, ce qui permet de suivre le développement des modèles et leur validation.

Du fait de l'existence de nombreux dépôts DFA déjà en service dans le monde, le besoin en RD&D pour le développement du champ proche du dépôt DFMA est moindre comparé au dépôt DHA, bien que de nombreuses activités profitent aux deux types de dépôts. Le développement ultérieur du système technique de transport de gaz, englobant la poursuite de l'expérience à grande échelle de perméabilité au gaz des scellements (GAST) au laboratoire du Grimsel, qui étudie le fonctionnement d'un scellement constitué de sable et de bentonite en grandeur nature et contribue à la compréhension des écoulements eau-gaz en conditions de stockage, demeure un élément important pour la performance du dépôt DFMA.

Concernant le transfert de radionucléides vers le champ proche, la compréhension phénoménologique actuelle et les bases de données pour les argiles compactées à disposition de la Nagra sont déjà très avancées. Un effort de RD&D complémentaire est néanmoins programmé pour résoudre des incertitudes résiduelles qui pourraient conduire à des hypothèses moins pénalisantes que celles utilisées dans les calculs d'impact radiologique en évaluation de sûreté et pour en accroître la robustesse. Parmi les domaines où les incertitudes sont susceptibles d'être diminuées figurent la transposition des données mesurées dans des systèmes dilués à des systèmes compactés ainsi que des questions relatives à la compétition de sorption entre différentes espèces, à la spéciation des radionucléides, au comportement des éléments sensibles aux conditions redox et à la spéciation, la stabilité et la rétention du 14C.

Evaluation de sûreté (conformité aux exigences de sûreté en phase opérationnelle et à long terme)

L'objectif des travaux sur l'évaluation de sûreté post-fermeture est de développer la méthodologie et les outils d'évaluation de façon à ce que l'étude de sûreté post-fermeture complète qui appuiera la demande d'autorisation générale remplisse les exigences formulées par l'autorité de surveillance. L'évaluation prend en compte les résultats de nombreux travaux qui sont décrits dans les paragraphes précédents, mais la méthodologie en elle-même nécessite également certaines activités de RD&D. Les différents aspects de ces travaux de développement incluent la gestion des propriétés, des événements et des processus (en anglais Features, Events and Processes ou FEP) et le développement de scénarios ainsi que les méthodes et outils probabilistes pour les analyses de sûreté et de sensibilité. L'accent sera mis sur un traitement cohérent des incertitudes et des risques. Le traitement amélioré des conséquences d'une intrusion humaine, les impacts de l'érosion glaciaire et la mise à découvert d'un dépôt ainsi qu'une modélisation de la biosphère selon l'état de l'art font partie des travaux envisagés.

Sur le plan de la sûreté en exploitation, les activités prévues ont pour objectif global de développer davantage la méthodologie et les outils d'évaluation associés en se concentrant sur une évaluation systématique des accidents, un concept de classification des déchets radioactifs adapté aux besoins d'évaluation de la sûreté opérationnelle, et le développement de concepts de sûreté et des exigences associées en vue de minimiser ou exclure les dysfonctionnements et les accidents. Il convient de noter que, dans le domaine de la sûreté en exploitation, des méthodes abouties et très adaptées, un savoir-faire et une expérience vaste existent déjà au sein de la communauté nucléaire.

Développement d'un concept pour la surveillance des dépôts

L'objectif est le développement d'un concept et à terme de méthodes détaillées et de techniques permettant une surveillance fiable du dépôt souterrain à partir de la surface et in-situ. Le premier concept de surveillance à développer portera sur l'état initial de référence, la construction des ouvrages d'accès et des installations souterraines dédiées aux reconnaissances géologiques et les plans de surveillance des installations pilotes. Sur les aspects stratégiques, la participation à des projets de recherche internationaux avec des partenaires plus avancés dans leurs projets de stockage est en cours. Cette participation permettra de bénéficier de leur retour d'expérience. Plusieurs expérimentations qui ont été initiées ou qui vont l'être dans les laboratoires souterrains en Suisse laissent présumer des avancées en matière de développements techniques et méthodologiques ainsi que sur la faisabilité de la surveillance des dépôts. Pour la surveillance des mouvements de terrain depuis la surface et de la sismicité, un système de positionnement par satellites (en anglais GNSS pour Global Navigation Satellite System) et des stations sismiques sont déjà en place dans les régions d'implantation et des stations supplémentaires ainsi que des systèmes de mesure à distance pourront être ajoutés sur le(s) site(s) sélectionné(s).

Le chapitre 8 décrit l'évolution du programme de RD&D anticipée au-delà de la demande d'autorisation générale. Dans un premier temps, l'accent sera mis sur la poursuite du programme entre le moment où la demande d'autorisation sera soumise et celui où elle sera validée, suite à son examen par l'autorité de sûreté et son approbation par le gouvernement fédéral. La durée de cette période est estimée à 7 ans (Nagra 2016a). Durant ce laps de temps, la demande d'autorisation les installations destinées aux études géologiques souterraines sera préparée. Une fois l'autorisation générale obtenue, le programme de RD&D entrera dans une nouvelle phase, au cours de laquelle les développements techniques et l'ingénierie prendront une part prépondérante, de même que la caractérisation du sous-sol et les programmes scientifiques menés dans les installations pour études géologiques souterraines.

Le temps nécessaire à la construction des ouvrages d'accès (puits et/ou tunnel d'exploration) qui mèneront à l'installation pour études géologiques souterraines sera mis à profit pour caractériser les roches et mettre à jour les données et les modèles. Une fois la profondeur du dépôt atteinte, les installations pour les études géologiques souterraines pourront être construites, probablement en deux phases, afin d'héberger les expérimentations planifiées. Les objectifs de ces activités sont une caractérisation améliorée des roches, la confirmation de la performance des roches vis-à-vis de la sûreté post-fermeture (auto-cicatrisation, transfert de gaz, migration des radio-nucléides, impact thermique), le test et l'optimisation des aspects techniques (construction et soutènement des tunnels et des chambres) et des composants (test des scellements) et la surveillance (concepts et techniques).

En plus de la poursuite des développements dans d'autres domaines permettant d'affiner la démonstration de sûreté, la conception et le développement technique dans l'optique de l'autorisation de construire deviendront importants, englobant de nombreux domaines tels que :

- Le perfectionnement de la conception et la démonstration en taille réelle de la conception des tunnels (incluant leur revêtement) basé sur la caractérisation in-situ de la performance de la roche
- La sélection de la conception définitive des conteneurs EC/DHA et de leur matériau ainsi que le développement et le test de prototypes en taille réelle
- Le test, la sélection définitive et l'optimisation des matériaux de remblayage, incluant leur caractérisation détaillée
- La conception et le test des techniques de remblayage à une échelle industrielle, portée sur la robustesse de la conception et la mécanisation du procédé de remblayage
- Le développement et le test des équipements de manutention des conteneurs EC/DHA et DFMA au sein des installations de surface et des ouvrages souterrains et de leur mise en place dans les dépôts, incluant la conception et le test de méthodes contrôlées à distance satisfaisant aux exigences de radioprotection.

Dans la perspective de l'autorisation d'exploitation, alors que les techniques de mise en place et de récupération auront déjà été développées, elles devront être démontrées avec plus de précision. La constructibilité des éléments de scellement sera également démontrée et les retours d'expérience contribueront à la spécification et au perfectionnement des méthodes de construction. Des procédés mécanisés innovants seront envisagés dans le but d'accroître la sécurité du travail et d'optimiser l'efficacité de la construction et de la mise en place des déchets.

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1 Introduction

1.1 Background and positioning of the report

1.1.1 Nagra's mission and strategy

Nagra's objective is to implement safe deep geological repositories (DGR) for all radioactive waste arising from the use of nuclear energy and from medicine, industry and research. This should occur in a timely manner, in compliance with the regulations and at justifiable cost. In doing so, Nagra must develop the plans for repository implementation and the scientific and technical basis for evaluating their safety and must also assess the overall costs. The planning strategy involves developing proposals for siting two types of repository, one for spent fuel (SF), vitrified high-level waste (HLW) and possibly long-lived intermediate-level waste (ILW), referred to hereafter as the HLW repository, and one for low- and intermediate-level waste (L/ILW repository), and preparing corresponding general licence applications according to the foreseen timetable. Provided the general licences are granted, underground exploration will take place, including the implementation of facilities for underground geological investigations that will lead to nuclear construction and later to operating licences. The two types of repository may be at separate sites or co-located at the same site ("combined" repository).

After almost 30 years of work by Nagra aimed at developing the scientific basis for safe geological repositories¹, the Swiss Federal Government accepted in June 2006 that Nagra had successfully shown with *Project Entsorgungsnachweis* (Nagra 2002a, b and c) that disposal of SF, HLW and long-lived ILW in Switzerland is technically feasible; the demonstration by Nagra of the technical feasibility of disposal of L/ILW had already been accepted by the Federal Government in 1988.

In April 2008, the Federal Government approved the details of the Sectoral Plan for Deep Geological Repositories (*Sachplan geologische Tiefenlager*) (SFOE 2008). The Sectoral Plan defines the process for selection of sites for repositories for deep geological disposal of radioactive wastes for which general licence applications will be prepared, the next major milestone in the RD&D Plan. It clearly defines the roles of the different stakeholders based on the Nuclear Energy Act (KEG 2003), as well as the decision-making process and the input needed for decision-making. The present status of the Sectoral Plan is discussed in section 1.3.

The basic elements of waste management in Switzerland are illustrated schematically in Fig. 1-1.

The present report outlines both a strategic plan for Nagra's RD&D for implementation of the HLW and L/ILW repositories and a programme of technical work consistent with the strategic objectives, with the general licence application as its main focus.

¹ This includes the development of repository concepts and the underlying safety concepts, the development of the corresponding syntheses and documentation (safety cases, geological syntheses, descriptions of design concepts), an evaluation of potential host rocks and their occurrence and establishment of an experienced team and the necessary infrastructure.

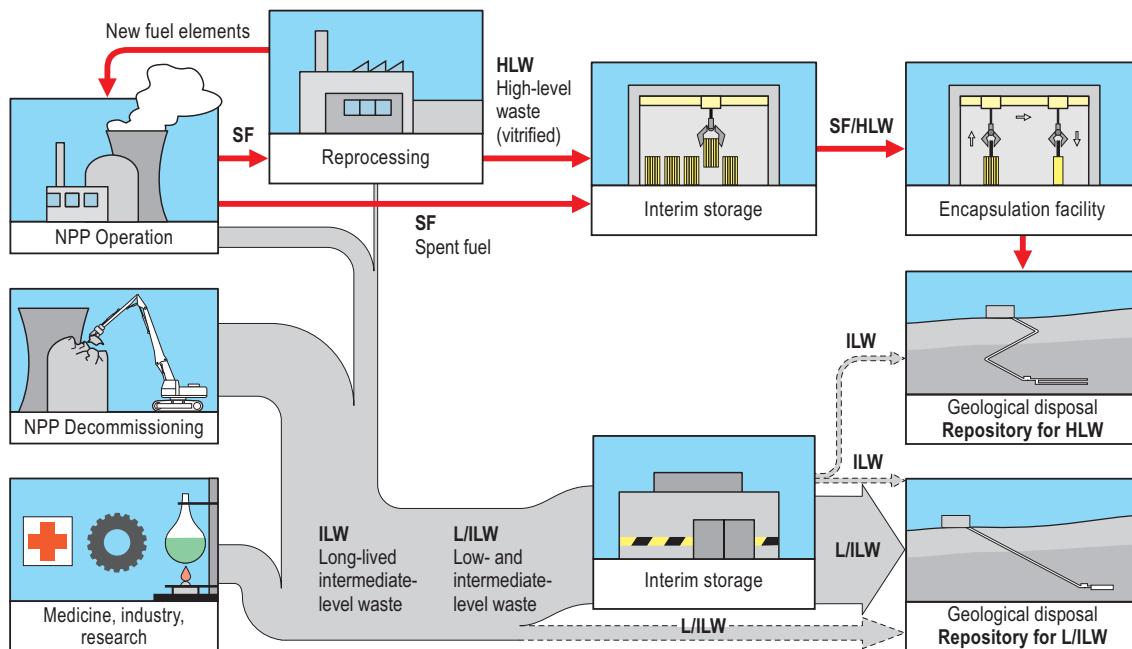


Fig. 1-1: Schematic illustration of the basic elements of radioactive waste management in Switzerland.

Combined repository not shown.

1.1.2 The Waste Management Programme, the RD&D Plan and the Cost Study

In August 2013, the Federal Government requested Nagra to submit an RD&D Plan in 2016, together with the next Waste Management Programme (Nagra 2016a) and the Cost Study. In this Plan, the objectives, scope, nature and time planning of future RD&D activities are to be documented, as well as how to deal with existing open questions. The present report addresses this requirement of the Federal Government. This RD&D Plan will be updated every 5 years. A translation of the decision of the Federal Council (Government) is included in Appendix 1.

This report is the second RD&D Plan published by Nagra. In 2009, a stand-alone Plan was published (Nagra 2009a) on Nagra's own initiative. This document was not required to be submitted to the authorities for review.

1.2 Scope and objectives of the report

The overall objectives and scope of this report include:

- Discussion of the RD&D requirements related to stepwise implementation of the HLW and LILW repositories and the planning assumptions consistent with these requirements, including the overall long-term (~ 30 to 40 years) plan for repository implementation, with the emphasis on defining the factors that dictate the developments needed at each stage of repository implementation.
- An overview of the steps and requirements of the Sectoral Plan and the subsequent general licence applications, the key reports and deliverables required and the associated RD&D – the Sectoral Plan and the general licence applications define the work over the next ~ 10 years.

- A summary of Nagra's proposals for siting regions for the repositories for HLW and L/ILW (i.e. Nagra's formal proposals for Stage 2 of the Sectoral Plan process (see Chapter 3 and Nagra 2014a)).
- A detailed discussion of the programme of technical work for the next 5 to 10 years, including the general licence application foreseen for 2024, and a discussion of the scope of work in the various areas in the period beyond the general licence application.

The main objective of the RD&D Plan is thus to establish the purpose, scope, nature and timing of various future RD&D activities, starting from the broad planning assumptions presented in the following sections and drawing on various syntheses of earlier and ongoing technical work. The RD&D Plan does not list or discuss arguments contributing to decisions to be taken in the context of the site selection as part of SGT Stage 3.

Given the very broad nature of the activities involved and the need to keep the document sufficiently succinct, the focus is on the major lines of reasoning and the main arguments. It is not possible to substantiate all the arguments in detail. The underlying documents (reports and papers) providing these substantiations are referenced for the specialised reader.

The target audience of this report includes the Swiss authorities and the stakeholders in first instance. The international waste management community, Nagra's partner organisations and collaborators also form an important part of the target audience.

The RD&D Plan focuses on assessing and outlining the work required to further develop Nagra's science and engineering base and to ensure that the technology, data and expertise necessary for achieving future milestones in repository planning and development, including eventual implementation, are acquired in a timely and cost-effective manner. The scope of the report is thus wider than describing activities that are defined as RD&D "sensu stricto".

In the context of Nagra's work, RD&D activities have the main objective of reducing remaining relevant uncertainties in the argumentation for the safety and feasibility cases for the general licence applications to an acceptable level. The general licence application must make the case for the safety and feasibility of the HLW and L/ILW repositories at specific sites. It is recognised that the layout and engineered barrier design concepts under consideration may not be the final versions to be selected in anticipation of the construction licence application. As a result, RD&D studies deal not only with reducing uncertainties in the current concepts and the associated safety assessments, but also with providing alternative concepts that may reduce or eliminate the need to address some of the uncertainties.

RD&D activities thus further contribute to the optimisation process (safety, feasibility but also cost) and the development of alternatives at all levels to ensure flexibility towards including future developments in the concepts.

However, other activities are also described in the RD&D Plan. Examples are the site characterisation programme, preparations for safety assessments and the engineering design. These provide the required context and give an integrated overview of the activities planned for the years to come.

The assumptions underlying the RD&D Plan are derived from the Waste Management Programme (Nagra 2016a). Of particular relevance to the RD&D Plan and the Waste Management Programme is the Nagra strategy underlying the response to the issues set out in Box 1-1.

Box 1-1: Key issues in federal law regarding the Waste Management Programme (KEV 2004, Art. 52).

The waste producers must make proposals in the Waste Management Programme regarding:

- a) the origin, type and quantities of radioactive waste
- b) the required geological repositories including the design concepts
- c) the allocation of the wastes to the repositories
- d) the plan for realisation of the deep geological repositories
- e) the duration and required capacity of facilities for the centralised and decentralised interim storage
- f) the finance plan for work related to disposal up to the time of the end of operation, with proposals for:
 - 1. the necessary work
 - 2. the costs
 - 3. the nature of the financing
- g) the information concept

It is noted that the RD&D work programme is conditioned by the assumption that Nagra's recently submitted proposals (Nagra 2014a) regarding the geological siting regions to be further investigated in Stage 3 and associated host rocks for the repositories will be confirmed in the review process for Stage 2 of the Sectoral Plan. Furthermore, Nagra recognises that the basic strategic assumptions for the RD&D programme will inevitably be revised where necessary when this review process is complete and the repository sites (combined site or two separate sites for repositories for HLW and L/ILW) are proposed. The next RD&D Plan, foreseen for 2021, will incorporate these revisions.

The structure of the report is illustrated in Fig. 1-2. The broader context is provided in Chapters 1 to 5, which describe the history of Nagra's programme, the legal context, the current concepts, the associated requirements and the managerial aspects, including the resources. In Chapter 6, the current status of the RD&D programme, with a summary of the major achievements in recent years, is given. Chapters 7 and 8 focus explicitly on the RD&D activities: how the objectives, scope, nature and time planning of the RD&D activities are determined by the programme stages and their implementation. In Chapter 7, a detailed description of the activities in the next 5 to 10 years, covering the general licence application (foreseen for 2024), is provided for the different areas (geological information, radioactive waste and materials, design and technology development for the repository and the engineered barriers, evolution of the safety-relevant properties and processes in the near-field, safety assessment and monitoring). To be able to relate the activities planned in the coming years to what has been achieved already, the state-of-the-art and the progress since the previous RD&D Plan (Nagra 2009a) is summarised for each topic. Chapter 8 gives a broad overview of the technical work for programme stages beyond the general licence application for each of the areas mentioned above. This includes the main objectives of the planned activities in the facilities for underground geological investigations as well as their approximate timing.

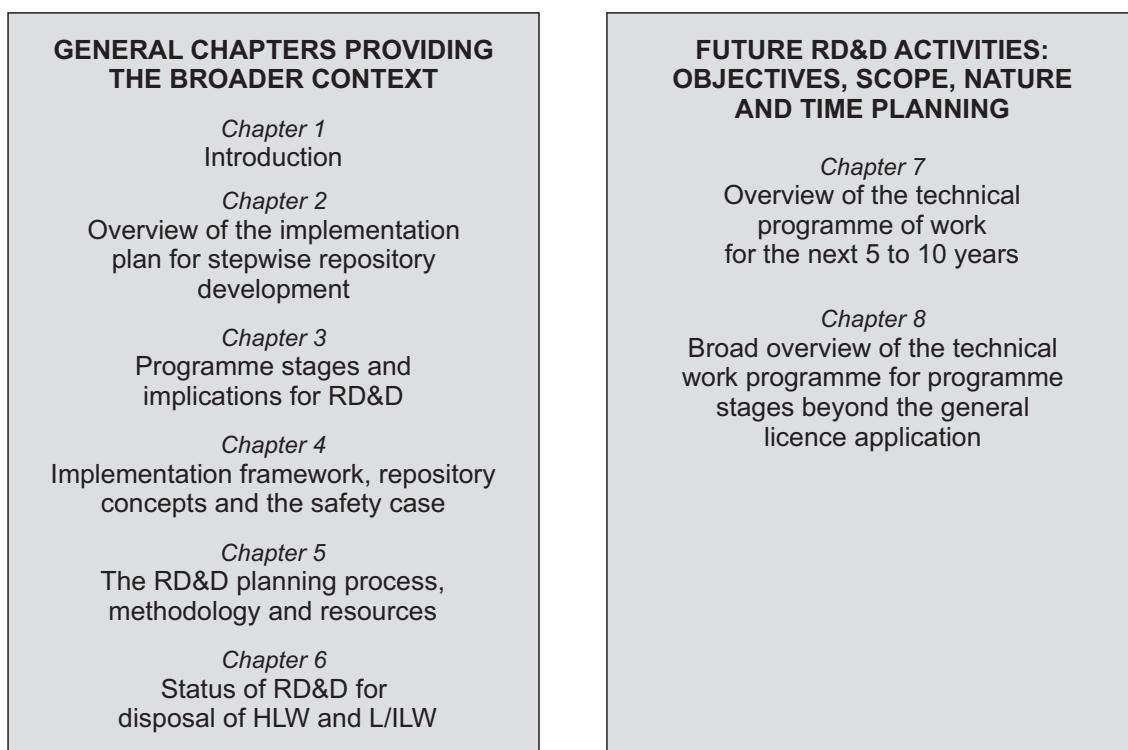


Fig. 1-2: Overview of the Chapters in this report.

1.3 The path to site selection – almost 40 years of research and geoscientific studies including legal and institutional developments

The following provides an overview of the events and decisions leading to the initiation of the Sectoral Plan for Geological Repositories, which serves to select sites for implementing the HLW and the L/ILW repositories.

The legal basis and establishment of Nagra

The management of radioactive waste has been explicitly addressed by the Swiss Federal Government from the very beginning of Switzerland's nuclear programme. The fundamental aspects were first defined in the Atomic Act of 1959 and were further elaborated in the Federal Government Ruling on the Atomic Act (1978) and the Radiological Protection Act (StSG 1991). The 1978 Ruling obliged the producers of radioactive waste to develop waste management solutions and to ensure the funding required for their implementation. Nagra, established as a cooperative of the radioactive waste producers (the electricity utilities and the Swiss Confederation, which is responsible for radioactive waste from medical, industrial and research applications), thus initiated a research and development programme in the late 70s and undertook the exploration of potential host rocks for proposing feasibility projects for geological repositories for the long-term safe disposal of the radioactive waste.

The Government Ruling on the Atomic Act (1978) was accompanied by a very specific requirement to demonstrate that safe disposal of radioactive waste in Switzerland is feasible as a prerequisite to the continued operation of the existing nuclear power plants and the construction of any new nuclear power plants. The demonstration of feasibility included the following three aspects: a) engineering feasibility, i.e. concepts that can be implemented with existing technology; b) long-term safety for humans and the environment; and c) siting feasibility, i.e. that there are formations and locations in Switzerland where a) and b) above can be fulfilled.

Project Gewähr

Nagra initiated a project with the above objectives called "Project Gewähr" and submitted the associated documentation (Nagra 1985a) to the Federal Government in 1985. In order to realise this project, Nagra set up an R&D programme for the development of the basic datasets and the methodologies for the conceptual development and the safety assessment of the geological repositories one for low- and intermediate-level waste (L/ILW) and one for long-lived intermediate-level waste ILW and high-level waste (HLW) – as well for acquiring the supporting fundamental geoscientific data. In 1988 the Federal Government approved Project Gewähr for the L/ILW repository and approved the engineering and long-term safety components for the HLW repository. However, it requested that Nagra extend the considerations for the geological host formations from the crystalline basement to sedimentary formations. Fig. 1-3 shows the extent of the geological formations (for the HLW programme) and specific sites (for the L/ILW programme) investigated by Nagra in the period 1980 to 2002.

L/ILW disposal investigations

For the L/ILW repository, Nagra performed exploratory investigations at the four sites shown in Fig. 1-3 (BDG: Bois de la Glaive; OBS: Oberbauenstock; PPG: Piz Pian Grand; WLB: Wellenberg). Among those, the Wellenberg site was selected as the candidate site for the L/ILW repository, following a detailed site characterisation programme and the assessment of the long-term safety of the overall system (Nagra 1993a). In 1994, Nagra submitted a general licence application, which received a positive review by the safety authorities. Due to a change in the cantonal law, a concession for use of the underground (exploitation of marl), a resource belonging to the Canton, was subjected to a cantonal referendum and Nagra's general licence application was also submitted to the population of the Canton Nidwalden for comment. The cantonal referendum took place in 1995 and the concession was denied by a majority of approx. 51.5 %; the general licence application was also refused.

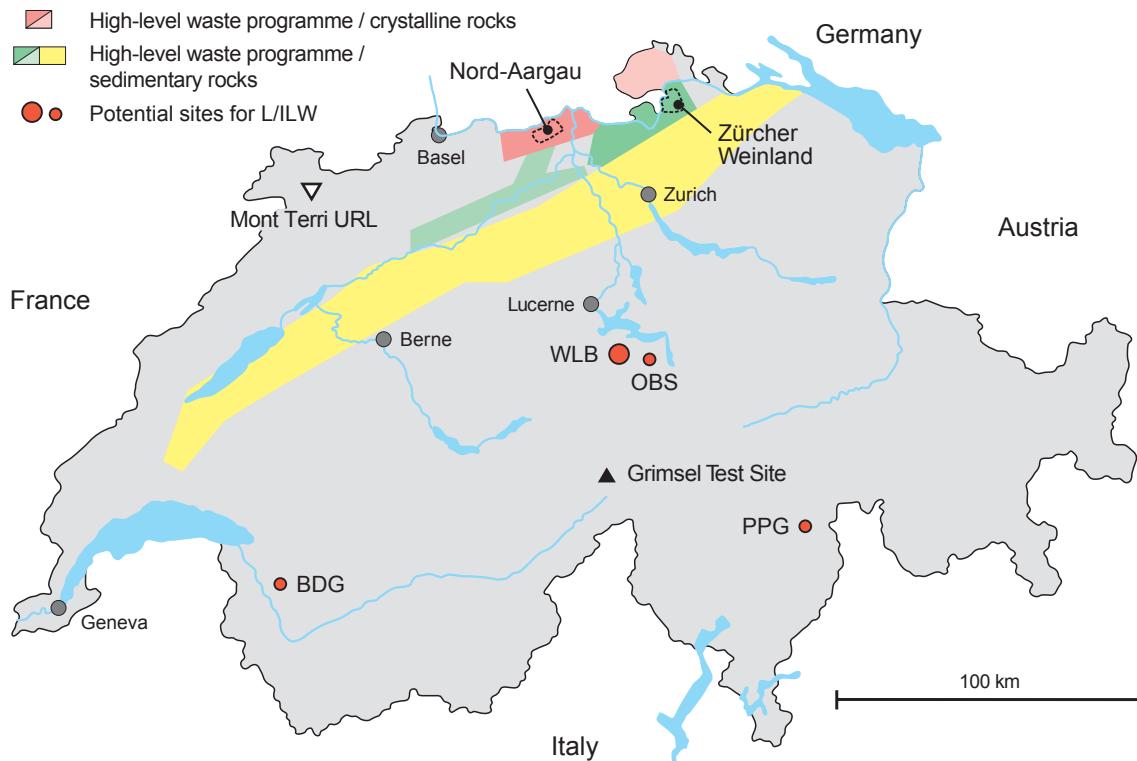


Fig. 1-3: Geological formations, regions and sites investigated by Nagra for the geological disposal of radioactive waste in the period from 1980 to 2002.
 BDG: Bois de la Glaive; OBS: Oberbauenstock; PPG: Piz Pian Grand; WLB: Wellenberg.

Cantonal and federal reviews

The cantonal and federal governments formed different groups to analyse the results and to find a way to proceed. The EKRA² group, established by the Federal Government, proposed adopting the concept of monitored geological disposal (SFOE 2000), as a response to societal wishes concerning monitoring and retrievability. The concept proposed by EKRA foresees stepwise implementation of the repository including the final step, namely closure. A facility for underground geological investigations should first be constructed at the repository horizon to obtain geological and engineering data to aid in construction of the repository. A pilot facility should be constructed as the first part of the actual repository, with geometric and engineering characteristics the same as the actual repository, albeit with a shorter length of the emplacement caverns, and with waste, backfill material, emplacement cavern seals as in the actual repository. This pilot facility should be monitored extensively, while the main repository is being constructed, filled and closed as planned. An extended monitoring period at the end of the emplacement of all the wastes, in addition to several decades of monitoring of the pilot facility, would provide to society at that time a sufficiently long record of observations to decide on final closure. This concept of a pilot facility also became an integral aspect of the HLW repository concept and was incorporated into *Project Entsorgungsnachweis* (Nagra 2002b and c).

² EKRA (Expert Group on Disposal Concepts for Radioactive Waste): An expert group established by the Federal Department of the Environment, Transport, Energy and Communications (DETEC).

The concept for the L/ILW repository was also modified in accordance with these changes, as shown in Fig. 1-4. The new proposal was brought to a cantonal referendum in 2002 – requesting a permit and a concession for the exploratory drift. Despite the favourable evaluation of the proposals and of the entire project by the Nuclear Safety Inspectorate HSK³ (HSK 2001) and by the cantonal technical groups, the requests were denied for a second time in a referendum, leading to a deadlock, although the siting community of Wolfenschiessen accepted the project in all of the public votes.

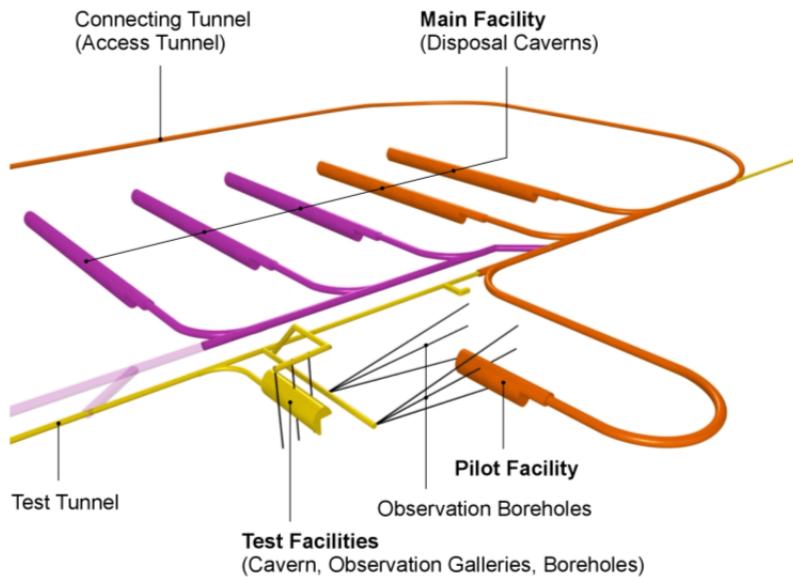


Fig. 1-4: Illustration of the monitored geological repository concept for the L/ILW.

The pilot facility is constructed as the first part of the repository with the same type of waste and engineered barriers as the main facility.

HLW investigations and *Project Entsorgungsnachweis*

Nagra pursued studies related to evaluating sedimentary rocks for disposal of HLW from the mid-1980s through the 1990s and submitted *Project Entsorgungsnachweis* to the Federal Government for review in December 2002. This project, which is based on the Opalinus Clay host rock option and on a potential siting region in the Zürcher Weinland, was an important milestone in the programme for disposal of HLW. The main emphasis was on demonstrating that a site with suitable characteristics could be found and characterised and that, based on its properties, safety and engineering feasibility could be demonstrated. When submitting *Project Entsorgungsnachweis*, due to the excellent results, Nagra also requested the Federal Government to focus future work for implementing the HLW repository on the Opalinus Clay as the host rock and on the Zürcher Weinland as the siting region. During the review by the authorities, Nagra was asked to prepare a report on the different siting options for a HLW repository and this was submitted in August 2005 (Nagra 2005). In the report, the Opalinus Clay is identified as the preferred host rock for a HLW repository, while the crystalline basement in Northern Switzerland and the Lower Freshwater Molasse (USM) are considered as reserve options. The report also discusses the regions suited to siting the HLW repository and qualifies them in broad terms.

³ Since January 1st 2009, HSK has been independent of the licensing authority (Swiss Federal Office of Energy, SFOE) and is now named the Swiss Federal Nuclear Safety Inspectorate (ENSI).

In August 2005, all the extensive reviews of *Project Entsorgungsnachweis* by the Nuclear Safety Inspectorate (HSK; now: Swiss Federal Nuclear Safety Inspectorate, ENSI), the Federal Commission for Nuclear Safety (KSA; now: Federal Nuclear Safety Commission, KNS), the Commission for Nuclear Waste Disposal (KNE; now: Expert Group on Nuclear Waste Disposal, EGT) and the International Review Team (IRT) of the OECD Nuclear Energy Agency were made available. They all came to positive conclusions and HSK recommended to the Federal Government to accept the feasibility demonstration. However, in the reviews many recommendations were made (Nagra 2008b) regarding studies that should be done for future development stages. In June 2006, the Federal Government decided that Nagra had successfully shown that safe disposal of HLW in Switzerland is technically feasible. In the same decision, the Federal Council refused the recommendation to focus further investigations on the Zürcher Weinland and stated that the search for a disposal site should be continued using a sectoral planning process.

The current legal framework and the Sectoral Plan for Deep Geological Repositories

During 2002, two initiatives were formulated at the national level, requesting in essence either a moratorium on new nuclear power plants or the phasing out of nuclear energy in Switzerland. In response to these initiatives, the Federal Government revisited the Atomic Act and, on 21 March 2003, proposed the new Nuclear Energy Act that includes articles on nuclear energy generation as well as radioactive waste management. The national referenda proposing a moratorium or the phasing out of nuclear energy were not approved by the Swiss population and the Nuclear Energy Act and the associated Nuclear Energy Ordinance became effective in 2005.

The following three acts (and the corresponding ordinances) define the major legal framework for geological disposal of radioactive waste (including siting) in Switzerland:

- Nuclear Energy Act (KEG 2003)
- Environmental Protection Act (USG 1983)
- Spatial Planning Act (RPG 1979)

Of particular interest in relation to the disposal programme are the following provisions in the Nuclear Energy Act and the corresponding Nuclear Energy Ordinance:

- The concept of monitored geological disposal, which combines passive safety with a period of monitoring and the possibility of retrieval without excessive effort during the emplacement and monitoring period until final closure of the repository, is required for all types of radioactive waste (based on the proposal by EKRA, SFOE 2000)
- National responsibility: Licensing of site characterisation work, construction, operation and closure of a repository is the responsibility of the Federal Government (general licence: approved by the Federal Assembly and subject to an optional national referendum)
- Stronger commitment of the Federal Government by approving a Waste Management Programme prepared by Nagra on behalf of the waste producers
- Disposal in principle within Switzerland; export (and import) possible for disposal only as an exception under certain conditions
- Overall objectives and requirements related to deep geological disposal and site selection to be based on a Sectoral Plan (a land use planning instrument under the Spatial Planning Act) under the leadership of the Federal Government

- Mandate to the Swiss regulator (ENSI) to specify detailed design principles for deep geological repositories in guidelines, which resulted in the Guideline ENSI-G03 (ENSI 2009)
- Reprocessing: a 10-year moratorium ended in 2016 and has been extended for 4 years.

The legislation thus introduced the need for a Sectoral Plan for the site selection process as defined in the Spatial Planning Act; Sectoral Plans have in the past been defined for other infrastructure projects or installations of national importance, for example transportation corridors, airports, etc. Because the definition of "land use" for such projects has to be harmonised and included in spatial planning at the federal, cantonal and community level, the Sectoral Plan is an appropriate tool for addressing the site selection procedure. The lead role in this procedure lies with the Federal Government and in particular with the Swiss Federal Office of Energy (SFOE) – an office of the Federal Department of the Environment, Transportation, Energy and Communications (DETEC). The full Sectoral Plan document is available from the SFOE (SFOE 2008).

The Sectoral Plan is divided into two parts. The first conceptual part has to be defined for the particular issue in hand, in this case a deep geological repository. This part includes the procedure and the roles of the various participants in the process as well as the criteria that have to be applied at the various decision points and the timing and sequence of the activities.

The first draft of the conceptual part of the Sectoral Plan was developed by the SFOE during 2006 following discussions and intensive participatory workshops, the latter covering a wide spectrum of stakeholders. The draft was circulated for comment to other federal and cantonal departments, authorities and their advisory committees, as well as to the waste producers, Nagra and various interest groups and the general public. In January 2007, a revised version was produced and circulated again for comment. At the beginning of 2008, the final version was prepared and circulated in the federal departments for any final comments. On 2nd April 2008, the Federal Government approved the conceptual part of the Sectoral Plan, which allowed the initiation of the second implementation part that will lead to the general licence applications for one deep geological repository for HLW and one for L/ILW (or a combined repository).

In October 2008, Nagra submitted a proposal with six siting regions that were to be further considered (Nagra 2008c). These proposals were accepted by the Federal Government on 30 November 2011, based on a review by the safety authorities and a broad public consultation. The proposals and the main comments of the authorities are discussed in Chapter 3, with specific emphasis on Nagra's role in the implementation and the implications for RD&D.

Nagra's proposals for Stage 2 of the Sectoral Plan were submitted at the beginning of 2015 and are presently under review by the authorities. These proposals are also summarised in Chapter 3.

2 Overview of the implementation plan for stepwise repository development⁴

2.1 Implementation plan

As discussed in Chapter 1, implementation of the deep geological repositories for SF/HLW/ILW and L/ILW in Switzerland involves a staged process. The site selection process has been regulated since 2008 by the Sectoral Plan for Deep Geological Repositories (SGT).

As part of Stage 1 of the process, Nagra proposed six potential siting regions and these were confirmed by the Federal Council in 2011. In Stage 2, working together with the siting regions, Nagra identified siting areas for the repository surface facilities. The geological knowledge base was expanded by further investigations and the siting regions were narrowed down further based on this and according to the criteria set out in the Sectoral Plan. At the beginning of 2015, Nagra submitted its proposals for at least two siting regions for each repository type to the Swiss Federal Office of Energy, with the regions Jura Ost and Zürich Nordost being proposed for further investigation in Stage 3⁵.

Timetables were prepared by the Swiss Federal Office of Energy (SFOE 2014a and 2016), based on an estimate of the time required for carrying out the technical work and the regulatory and licensing procedures. The duration of the three stages of the Sectoral Plan process was originally estimated to be around 10 years. Experience in the meantime has shown that the original assumptions were on the optimistic side, mainly because of the complex pioneering nature of the process. From a current perspective, it is expected that the process will last twice as long as originally expected. This means that valid general licences will be granted by 2031, that the L/ILW repository will start operation in 2050 and the HLW repository in 2060. It is also assumed that there will be no time-consuming appeal procedures and that the technical work will proceed without any significant delay.

For implementation of the HLW repository, the steps are defined according to the schedule illustrated in Fig. 2-1 (Nagra 2016a), which is based on the assumption of a nuclear programme with only the existing nuclear power plants operating for 50 years (apart from NPP Mühleberg which is planned to operate for 47 years). These assumptions provide the basis for the cost estimates for decommissioning and deep geological disposal and thus for the contributions to be made by the operators to the Waste Disposal and Decommissioning Funds.

The overall schedule for L/ILW disposal for a nuclear programme with only the existing nuclear power plants and an assumption that they will operate for 50 years (except for Mühleberg) is shown in Fig. 2-2. Again, the schedule is driven by the duration of the consultation and approval steps for the various stages and the time required for underground geological investigations and construction and operation of the repository. The background assumptions for both the L/ILW and HLW repository schedules regarding NPP operation and waste arisings, including interim storage, are also shown in Fig. 2-1 for HLW and Fig. 2-2 for L/ILW.

⁴ This Chapter is included to provide a broader context for non-German readers. Information has been extracted and translated from the Waste Management Programme (Nagra 2016a; published in German only) and is not intended as a legally binding translation.

⁵ As part of the evaluation of the submitted documentation, it is currently being discussed whether the Nördlich Lägern siting region should be carried forward to Stage 3.

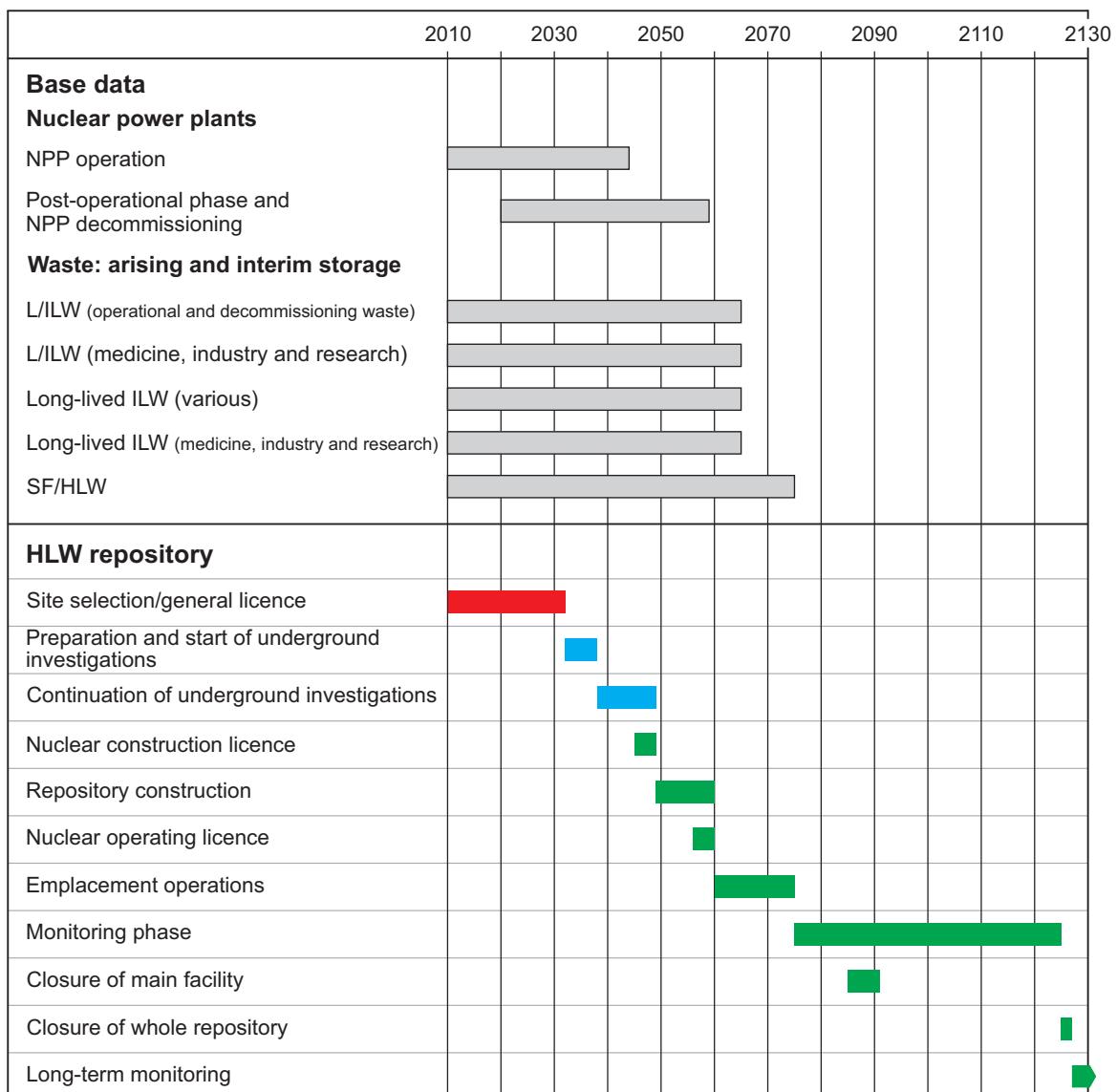


Fig. 2-1: Time plan for implementation of the HLW repository for a nuclear programme according to today's planning (Nagra 2016a).

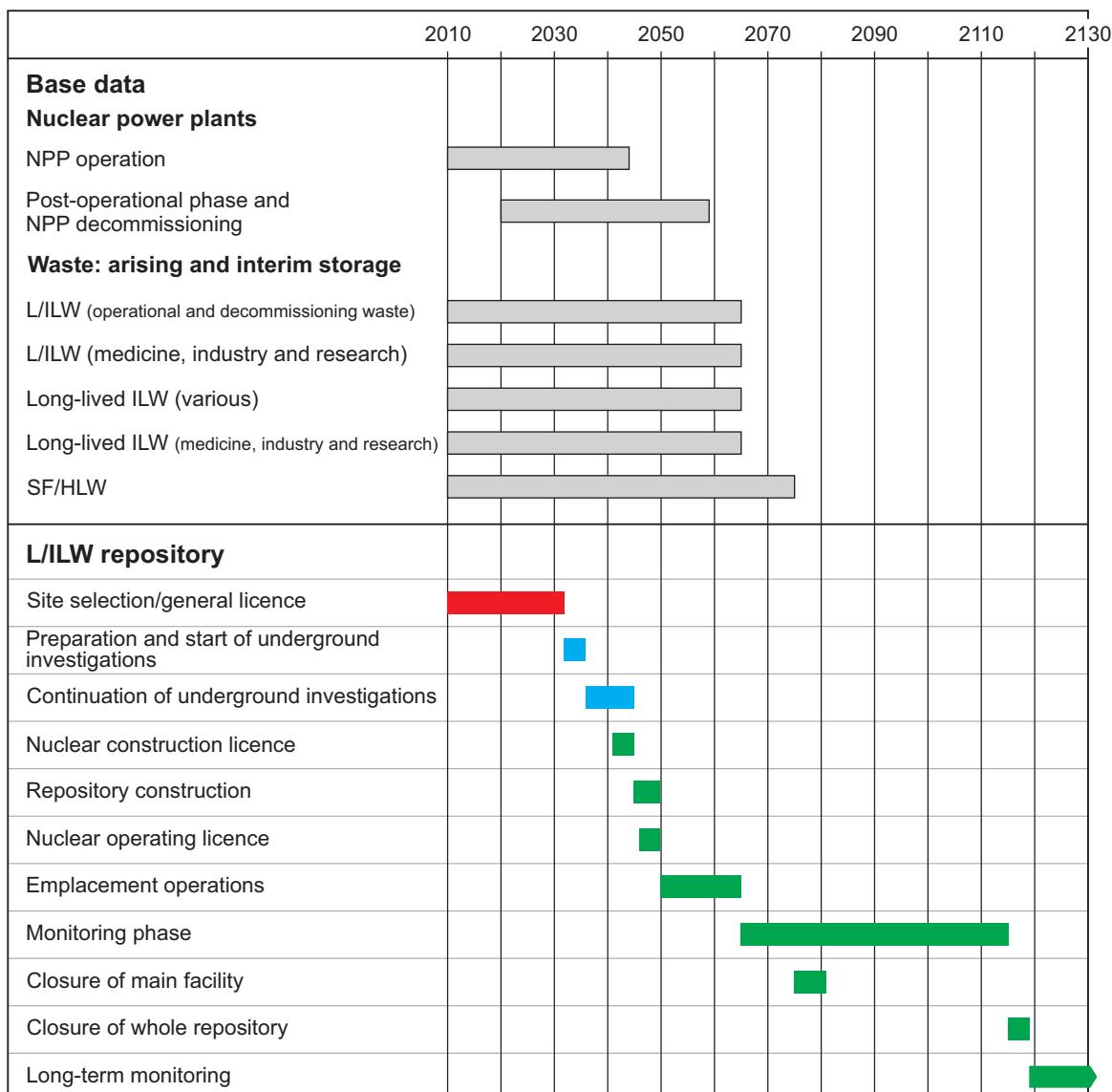


Fig. 2-2: Time plan for implementation of the L/ILW repository for a nuclear programme according to today's planning (Nagra 2016a).

The work programme for the coming years is clearly defined. Significant progress is expected by the time the Waste Management Programme is next updated in 2021. The decision of the Federal Council on the siting regions to be carried forward to Stage 3 is expected in 2018. Field work will be carried out in Stage 3 (including 3D seismics, exploratory boreholes and Quaternary investigations). Around 2021, Nagra will then announce the sites (or site for a combined repository) for which a general licence application will be prepared and submitted. The surface infrastructure (e.g. placing of the shaft head installations) will be decided in cooperation with the siting regions. The current realisation plan assumes that the general licence applications will be submitted to the SFOE in 2024.

2.2 Financing of waste management

The producers of radioactive waste are obliged by law to dispose of the waste safely in deep geological repositories at their own cost. The waste management costs that arise during the operation of the nuclear power plants (e.g. for reprocessing of spent fuel, investigations by Nagra, construction of interim storage facilities) are paid on an ongoing basis. The decommissioning costs and the costs of radioactive waste disposal arising after the nuclear power plants cease operation are secured by payments made by the owners into two independent funds, the Decommissioning Fund and the Waste Disposal Fund.

In order to fix the contributions to the Decommissioning and Waste Disposal Funds and the level of reserves in the Funds, the expected decommissioning and waste disposal costs are recalculated every five years. The plant owners provide the required information and Nagra uses this to calculate the costs of the deep geological repositories. The information provided by the NPP owners is also reviewed by ENSI.

The last estimate of the decommissioning and waste disposal costs was carried out in 2011. According to a requirement attached to the review of the 2008 Waste Management Programme by the Federal Government, the 2016 Cost Study has to be submitted simultaneously with the 2016 Waste Management Programme. The Cost Study of 2016 specifies the annual contributions for the period 2017 to 2021.

2.2.1 Decommissioning Fund for nuclear installations

The Decommissioning Fund for nuclear installations was set up on 1st January 1984. The main purpose of the Fund is to cover the costs of decommissioning and dismantling of disused nuclear facilities and disposing of the waste arising from these activities. The operators of the Beznau 1 and 2, Mühleberg, Gösgen and Leibstadt nuclear power plants and of the ZWILAG interim storage facility in Würenlingen are obliged to make contributions to the Fund. The base scenario assumed for calculating the decommissioning costs and the amount of the contributions to the Fund is an operating lifetime of the facilities of 50 years, while an alternative scenario assumes an operating lifetime of 60 years. The Mühleberg nuclear power plant will shut down after 47 years of operation. According to Article 8 of the Funds Ordinance of 2007, the operating period for waste management facilities is defined in the Waste Management Programme. The objective is to ensure that the presumed costs of decommissioning will be covered when a nuclear facility is taken out of operation and to distribute the contributions to the Fund as evenly as possible over the time period mentioned. Decommissioning includes the dismantling of all technical installations and buildings of a nuclear power plant.

The decommissioning costs for the five nuclear power plants and for ZWILAG have been recently updated (Nagra 2016a).

2.2.2 Waste Disposal Fund for nuclear power plants

The Waste Disposal Fund for nuclear power plants was set up on 1st April 2000. The purpose of the Fund is to cover the costs of managing operational waste and spent fuel after the nuclear power plants have ceased operation. The operators of the Beznau 1 and 2, Mühleberg, Gösgen and Leibstadt nuclear power plants are obliged to make contributions to the Fund. The first contributions were made by the power plant operators in 2001.

Waste disposal comprises all the activities leading up to the emplacement of the waste in a deep geological repository, as well as the activities associated with the monitoring phase and closure of the repository. Costs are generated by waste treatment, reprocessing⁶ of spent fuel and interim storage and final disposal.

The costs estimations are updated every 5 years by Nagra, the outcomes of the latest update in 2016 is published in Nagra (2016a).

2.2.3 Revision of the Funds Ordinance

Key revisions to the Funds Ordinance of 2007 came into force in January 2015. The main changes included modification of the basis for calculating the contributions to the Funds by the operators (longer contribution period). A "safety surcharge" of 30 % will also be added to the calculated decommissioning and waste disposal costs and changes were made to the assumed return on investment and the inflation rate. The calculations now assume a return on investment of 3.5 % (previously 5 %) and an inflation rate of 1.5 % (previously 3 %).

2.3 Types and volumes of radioactive waste

In Switzerland, radioactive wastes and materials arise from the use of nuclear energy and the application of radioactive materials in the fields of medicine, industry and research. For the purpose of disposal, the Nuclear Energy Ordinance (Article 51) divides radioactive waste into the following categories:

- High-level waste (HLW)
 - Spent fuel assemblies (SF) not destined for reprocessing
 - Vitrified fission product solutions from reprocessing of spent fuel (HLW)
- Alpha-toxic waste (ATW)
 - Waste with a content of alpha-emitters exceeding a value of 20,000 Becquerels per gram of conditioned waste
- Low- and intermediate-level waste (L/ILW)
 - All other radioactive waste from operation of the nuclear power plants, future decommissioning of nuclear power plants and other nuclear facilities, hospitals, non-nuclear industries, and research

In terms of waste production, there are key differences between the Waste Management Programme 2008 (Nagra 2008a) and the Waste Management Programme 2016 (Nagra 2016a). In 2008, the assumption for the waste volumes was 50-year operation of the existing NPPs. In 2016, the decommissioning of the Mühleberg NPP foreseen for 2019 is taken into account. Four scenarios for waste production are considered in the Waste Management Programme 2016 that take into account different operating times and a revision of the Radiological Protection Ordinance. Information on conditioning, characterisation and inventorying is unchanged. No statements on reprocessing are made.

⁶ Currently there is a moratorium on reprocessing in Switzerland which was recently extended for four years.

The four scenarios for waste production are:

- *Scenario 1a*: 50-year operation of the NPPs Beznau, Gösgen and Leibstadt and 47-year operation of Mühleberg. The nuclide-specific clearance limits in the existing Radiological Protection Ordinance are assumed.
- *Scenario 1b*: Operating times as in Scenario 1a, but taking into consideration the expected new nuclide-specific clearance limits in a revised Radiological Protection Ordinance, as well as a 30-year decay storage period for radioactive materials up to the time when a decision is made on clearance/re-use or disposal as radioactive waste.
- *Scenario 2a*: 60-year operation of the NPPs Beznau, Gösgen and Leibstadt, otherwise as for Scenario 1a.
- *Scenario 2b*: Operating times as in Scenario 2a, but taking into consideration the expected new nuclide-specific clearance limits in a revised Radiological Protection Ordinance, as well as a 30-year decay storage period for radioactive materials up to the time when a decision is made on clearance/re-use or disposal as radioactive waste.

According to the Sectoral Plan (SFOE 2008), the siting process should lead to geological repositories that can accommodate the waste from the existing NPPs, their decommissioning and dismantling and the waste from medicine, industry and research. The maximum capacities of the repositories will be defined in the general licences.

For the radiological inventories and waste volumes to be accommodated in the interim storage facilities and the deep geological repositories, the Waste Management Programme assumes Scenario 2b. In terms of the nuclear fuel cycle, the Swiss disposal concept considers both reprocessing and direct disposal: around 1,140 t of fuel (uranium/heavy metal, tU) have been sent for reprocessing and the remaining fuel (around 2,930 tU) is destined for direct disposal. For the waste from medicine, industry and research, a collection period up to the end of emplacement of waste from the existing NPPs in the L/ILW repository (up to 2065) is assumed. This includes waste from small producers as well as from large research facilities (e.g. Paul Scherrer Institute (PSI), CERN) and decommissioning waste from research reactors.

The waste volumes for Scenarios 1a – 2b are shown in Tables 2-1a to d. These give the volumes of conditioned waste. As waste is generally packaged in disposal containers before emplacement in the repository, the volume for packaged waste is also given.

Tab. 2-1a: Waste volumes in cubic metres for 50 years operation (Beznau, Gösgen, Leibstadt NPPs) and 47 years for NPP Mühleberg for the currently valid version of the Radiological Protection Ordinance (Scenario 1a).

Explanation for Scenarios 1a – 2b: Volumes of delivered and conditioned waste and volumes packaged in disposal containers (numbers in brackets). The data are divided according to the waste categories specified in the Nuclear Energy Ordinance (KEV 2004) with HLW = high-level waste, ATW = alpha-toxic waste, L/ILW = low- and intermediate-level waste. Additional classification according to origin with SF: spent fuel assemblies; WA: reprocessing waste; BA: operational waste from the NPPs and ZWILAG; RA: reactor waste from the NPPs; SA: Decommissioning waste from the NPPs and ZWILAG, including waste from Lucens; MIR: waste from medicine, industry and research, including waste from CERN; BEVA: waste from the operation and decommissioning of the waste encapsulation plants and disposal of the transport and storage casks for SF taking into account certain reserves from the remaining surface facilities.

Non-reprocessed SF is packaged without further treatment in disposal containers before emplacement in the HLW repository. The first number relates to unpackaged SF and the number in brackets to packaged volumes, whereby some empty positions in the containers have to be considered for restricting the maximum heat production of the containers.

| | | Origin | | | | | | Total |
|----------------------|--------------|--------------------------------|----------------------------|-------------------|----------------|--------------------|---------------------------------|-----------------------------------|
| | | SF (NPP) | WA (NPP) | BA (NPP) | RA (NPP) | SA (NPP) | MIR | |
| Category acc. to KEV | HLW | 1,126 ¹⁾ (7,129) | 114 ²⁾ (398) | | | | 8 ⁴⁾ (8) | 1,248 (7,536) |
| | ATW | | 99 ²⁾ (414) | | | 24 (24) | 154 (573) | 277 (1,011) |
| | L/ILW | | | 7,352 (28,094) | 416 (1,595) | 17,847 (26,006) | 9,755 (14,478) ⁵⁾ | 567 (1,968) 35,937 (72,141) |
| | Total | 1,126 ³⁾ (7,129) | 213 (812) | 7,352 (28,094) | 416 (1,595) | 17,871 (26,030) | 9,917 (15,059) | 567 (1,968) 37,462 (80,687) |

¹⁾ Corresponds to 2,433 tU.

²⁾ Waste resulting from reprocessing of 1,139 tU.

³⁾ Full loading of the disposal containers (no empty positions considered) would result in a volume of 6,455 m³.

⁴⁾ Fuel assemblies from the DIORIT reactor. Assumption: packaged in two disposal containers.

⁵⁾ Including 4'014 m³ waste from the CERN reactor.

Tab. 2-1b: Waste volumes in cubic metres for 50 years operation (Beznau, Gösgen, Leibstadt NPPs) and 47 years for NPP Mühleberg taking into account the planned revision of the Radiological Protection Ordinance (Scenario 1b).

Explanation see Tab. 2-1.

| | | Origin | | | | | | Total |
|-----------------------------|--------------|--------------------------------|----------------------------|-------------------|----------------|------------------------|----------------------------------|--------------------|
| | | SF (NPP) | WA (NPP) | BA (NPP) | RA (NPP) | SA (NPP) | MIR | |
| Category acc. to KEV | HLW | 1,126 ¹⁾ (7,129) | 114 ²⁾ (398) | | | 8 ⁴⁾ (8) | | 1,248 (7,536) |
| | ATW | | 99 ²⁾ (414) | | | 24 (24) | 154 (573) | 277 (1,011) |
| | L/ILW | | | 7,473 (28,260) | 416 (1,595) | 18,839 (27,366) | 14,213 (18,972) | 567 (1,968) |
| | Total | 1,126 ³⁾ (7,129) | 213 (812) | 7,473 (28,260) | 416 (1,595) | 18,863 (27,390) | 14,375 (19,553) ⁵⁾ | 567 (1,968) |
| | | | | | | | | 43,033 (86,708) |

¹⁾ Corresponds to 2,433 tU.

²⁾ Waste resulting from reprocessing of 1,139 tU.

³⁾ Full loading of the disposal containers (no empty positions considered) would result in a volume of 6,455 m³.

⁴⁾ Fuel assemblies from the DIORIT reactor. Assumption: packaged in two disposal containers.

⁵⁾ Including 4'883 m³ waste from the CERN reactor.

Tab. 2-1c: Waste volumes in cubic metres for 60 years operation (Beznau, Gösgen, Leibstadt NPPs) and 47 years for NPP Mühleberg for the currently valid version of the Radiological Protection Ordinance (Scenario 2a).

Explanation see Tab. 2-1.

| | | Origin | | | | | | Total |
|-----------------------------|--------------|--------------------------------|----------------------------|-------------------|----------------|------------------------|---------------------------------|--------------------|
| | | SF (NPP) | WA (NPP) | BA (NPP) | RA (NPP) | SA (NPP) | MIR | |
| Category acc. to KEV | HLW | 1,357 ¹⁾ (8,995) | 114 ²⁾ (398) | | | 8 ⁴⁾ (8) | | 1,479 (9,402) |
| | ATW | | 99 ²⁾ (414) | | | 24 (24) | 168(634) | 291 (1,072) |
| | L/ILW | | | 8,167 (31,068) | 478 (1,811) | 17,847 (26,006) | 9,776 (14,563) ⁵⁾ | 651 (2,302) |
| | Total | 1,357 ³⁾ (8,995) | 213 (812) | 8,167 (31,068) | 478 (1,811) | 17,871 (26,030) | 9,952 (15,205) | 38,689 (86,224) |

¹⁾ Corresponds to 2,932 tU.

²⁾ Waste resulting from reprocessing of 1,139 tU.

³⁾ Full loading of the disposal containers (no empty positions considered) would result in a volume of 7,676 m³.

⁴⁾ Fuel assemblies from the DIORIT reactor. Assumption: packaged in two disposal containers.

⁵⁾ Including 4'014 m³ waste from the CERN reactor.

Tab. 2-1d: Waste volumes in cubic metres for 60 years operation (Beznau, Gösgen, Leibstadt NPPs) and 47 years for NPP Mühleberg taking into account the planned revision of the Radiological Protection Ordinance (Scenario 2b).

Explanation see Tab. 2-1.

| | | Origin | | | | | | Total |
|-----------------------------|------------|--------------------------------|----------------------------|-------------------|----------------|--------------------|----------------------------------|--------------------|
| | | SF (NPP) | WA (NPP) | BA (NPP) | RA (NPP) | SA (NPP) | MIR | |
| Category acc. to KEV | HLW | 1,357 ¹⁾ (8,995) | 114 ²⁾ (398) | | | | 8 ⁴⁾ (8) | 1,479 (9,402) |
| | ATW | | 99 ²⁾ (414) | | | 24 (24) | 168 (634) | 291 (1,072) |
| L/ILW | | | | 8,326 (31,271) | 478 (1,811) | 18,839 (27,366) | 14,222 (19,010) | 651 (2,302) |
| Total | | 1,357 ³⁾ (8,995) | 213 (812) | 8,326 (31,271) | 478 (1,811) | 18,863 (27,390) | 14,398 (19,652) ⁵⁾ | 651 (2,302) |
| | | | | | | | | 44,286 (92,233) |

¹⁾ Corresponds to 2,932 tU.

²⁾ Waste resulting from reprocessing of 1,139 tU.

³⁾ Full loading of the disposal containers (no empty positions considered) would result in a volume of 7,676 m³.

⁴⁾ Fuel assemblies from the DIORIT reactor. Assumption: packaged in two disposal containers.

⁵⁾ Including 4'883 m³ waste from the CERN reactor.

Sufficient capacity for interim storage of all the wastes is available in the various facilities in Switzerland. The main centralised interim storage facility is ZWILAG, which has been fully operational since 2002 (see Fig. 2-3). Additional SF storage capacity exists at ZWIBEZ (the SF/HLW waste storage facility at Beznau in operation since 2007) and the wet storage facility at Gösgen (commissioned in 2008). The first storage casks of vitrified HLW arrived at ZWILAG in 2002, in addition to a number of SF casks from the nuclear power plants. Each of the nuclear power plants also has fuel pools and interim storage for L/ILW from operation. In addition, the BZL (*Bundeszwischenlager*) storage facility is operated by the Paul Scherrer Institute (PSI) for waste from medicine, industry and research.



Fig. 2-3: The interim storage facility (ZWILAG) near Würenlingen (top) and a view of storage casks containing SF and HLW (bottom).

3 Programme stages and implications for RD&D

This Chapter provides an overview of the programme stages, with a detailed description of the programme steps as part of the Sectoral Plan up to the general licence application and a brief description of the key activities for the licensing steps after the granting of the general licence. The different licensing steps require continuing concretisation of the repository projects. From an RD&D perspective, it is essential that the topics are explored in sufficient depth that the decisions in the next licensing step can be taken with a high level of confidence. This also means that RD&D and the related decision-making should not be undertaken too early in the licensing process as fixing aspects of the programme at too early a stage might exclude incorporation of future developments and opportunities.

3.1 Overview of the programme stages

The procedural requirements in the Nuclear Energy Act (KEG 2003) and Ordinance (KEV 2004) and the conceptual part of the Sectoral Plan (SFOE 2008) and the Environmental Protection Act (USG 1983) that apply to the implementation of geological repositories are summarised in Nagra (2016a; Tables A.1). The roadmap for implementation that has been derived based on these requirements and the implications for RD&D in the various stages are described in the following sections.

Site selection in accordance with the conceptual part of the Sectoral Plan is carried out in three stages (see section 3.1.1). Once the site and the repository concept have been defined in the general licence, further nuclear licences according to the Nuclear Energy Act and Ordinance follow: the construction licence, the operating licence and – once the operational and monitoring phases are complete – an order for repository closure from the Federal Government. The most important features of the individual nuclear licences are listed below:

- **General licence:** The general licence defines the site and the main features of the project, including the approximate size and location of the main installations, the categories of waste for emplacement and the maximum disposal capacity. The general licence also specifies the suitability criteria to be observed in further repository implementation, as well as concepts for monitoring and closure of the repository. The preliminary protection zone is defined and the first stage of an environmental impact assessment is carried out.
- **Nuclear construction licence:** The construction licence defines the capacity of the repository and the key elements for technical realisation. It also includes a project for the monitoring phase and a plan for closure. The construction licence defines the detailed layout and design of the repository. The definitive protection zone is defined and the second stage of an environmental impact assessment is carried out.
- **Nuclear operating licence:** The operating licence defines the following: the capacity of the repository, measures for monitoring the environment and stages for starting up operation, the start of which requires a clearance from the authorities. It also defines the requirements applying to the wastes, in particular the activity limits.
- **Closure of the repository:** The Federal Government orders the closure work after the monitoring phase is complete, provided the long-term protection of man and the environment can be ensured. After closure, the Federal Government can order a further limited period of monitoring.

3.1.1 Site selection and general licence

Because site selection and the general licence application are the key issues to be addressed in the next years, these are discussed in more detail below.

The conceptual part of the Sectoral Plan was approved by the Swiss Federal Government on 2 April 2008. It clearly defines the roles of the different stakeholders as well as the decision-making process and the input needed for selection of the sites for the two repositories (SFOE 2008). The three main stages of site selection according to the Sectoral Plan are defined as:

- Stage 1: Selection and approval of geological siting regions
- Stage 2: Selection and approval of at least two siting regions for each of the repositories
- Stage 3: Selection of a site for each deep geological repository and preparation of the applications for the general licences

The broad requirements on Nagra's activities for the Sectoral Plan are summarised in Tab. 3-1 and are discussed below.

Tab. 3-1: Nagra's responsibilities for each stage of the Sectoral Plan (after SFOE 2008).

| Stage/main focus | Nagra's responsibilities |
|--|---|
| Stage 1: Selection of geologically suitable regions for the L/ILW and HLW repositories | <p>Propose geological siting regions both for the L/ILW and HLW repository based on existing information</p> <p>Inform, as requested, and respond to questions</p> <p>Contribute to the development of the evaluation methodology with respect to spatial planning</p> <p>Provide information on land use planning for the siting regions proposed</p> |
| Stage 2: Selection of at least 2 siting regions for the L/ILW and HLW repositories | <p>Develop a site-specific layout for the repository surface facility for at least one site within each region in collaboration with the respective Cantons and regions (participatory process)</p> <p>Perform provisional safety analyses</p> <p>Define the activities and initiate preparatory work for the environmental impact assessment</p> <p>Obtain the basic input for the evaluation of spatial planning aspects; contribute to the socio-economic studies, as required</p> <p>Propose at least two siting regions for each of the repositories</p> |
| Stage 3: Selection of one site for each repository | <p>Perform additional geological investigations, as deemed necessary, in the selected siting regions</p> <p>Select one site each for the L/ILW and HLW repository for preparing the general licence application</p> <p>Reach agreement with Canton and region on compensation</p> |
| General licence application | <p>Document the grounds for the site selection</p> <p>Provide a safety report</p> <p>Provide an environmental impact assessment (Stage 1)</p> <p>Provide a report on the agreement with spatial planning</p> <p>Provide further documentation as required</p> |

Stage 1: Selection of geologically suitable regions for L/ILW and HLW

The focus of Stage 1, which started in 2008, was on a scientific screening process leading to the identification of broad geological siting regions. Highest priority was given to post-closure safety, while technical feasibility had to be ensured. Societal aspects were not part of this evaluation. To assess safety and technical feasibility, the Sectoral Plan defines 13 criteria, grouped into four broad areas, namely "Properties of host rock", "Long-term stability", "Reliability of geological information" and "Suitability for construction" (Tab. 3-2). These 13 criteria were supported by 49 indicators (derived by Nagra in step two of Stage 1, see below). For each indicator, the definition included minimum (indispensable) requirements that had to be met (for example, formation thickness) and, in many cases, more stringent ones, which if they were met would have a further favourable impact on the safety and feasibility.

Tab. 3-2: Criteria for site evaluation from the viewpoint of safety and engineering feasibility, as defined in the Sectoral Plan.

| Criteria group | Criteria |
|--|--|
| 1. Properties of the host rock and of the formations contributing to waste isolation | Spatial extent Hydraulic barrier effectiveness Geochemical conditions Release pathways |
| 2. Long-term stability | Geological/tectonic stability Erosion Repository-induced effects Resource conflicts |
| 3. Reliability of the geological database and statements | Ability to characterise the formations Explorability of the spatial conditions Predictability of the long-term changes |
| 4. Engineering suitability | Geomechanical properties and conditions Underground access and management of inflowing water |

The identification of suitable geological siting regions was conducted in five steps. In a first step, the waste inventory was defined (including reserves for future developments) and the various waste types (approx. 120) were allocated to either the HLW or the L/ILW repository. In a second step, the barrier and safety concepts for the two repositories were defined and – with a view to the evaluation of the geological siting possibilities – quantitative and qualitative requirements on geology were derived. These related to geometric requirements on the host rocks (e.g. lateral extent and depth of intact rock blocks), the barrier properties of the host rock (e.g. thickness, hydraulic conductivity), long-term stability (uplift/erosion, differential movements, etc. for the timescales of concern), the reliability of geological findings (spatial explorability and temporal predictability) and engineering feasibility (e.g. rock strength).

Steps three to five covered the evaluation of the geological siting options. The geological information base available in Switzerland is fairly extensive and includes data and information from investigations performed by Nagra over a period of 30 years as part of its geological disposal programme, as well as the analysis and interpretation of data gathered by other parties

(Fig. 3-1). The latter include, for example, deep boreholes and seismic campaigns for oil and gas prospecting and for geothermal energy, shallower boreholes, surface geological and tunnel mapping, high precision geodetic monitoring, etc.

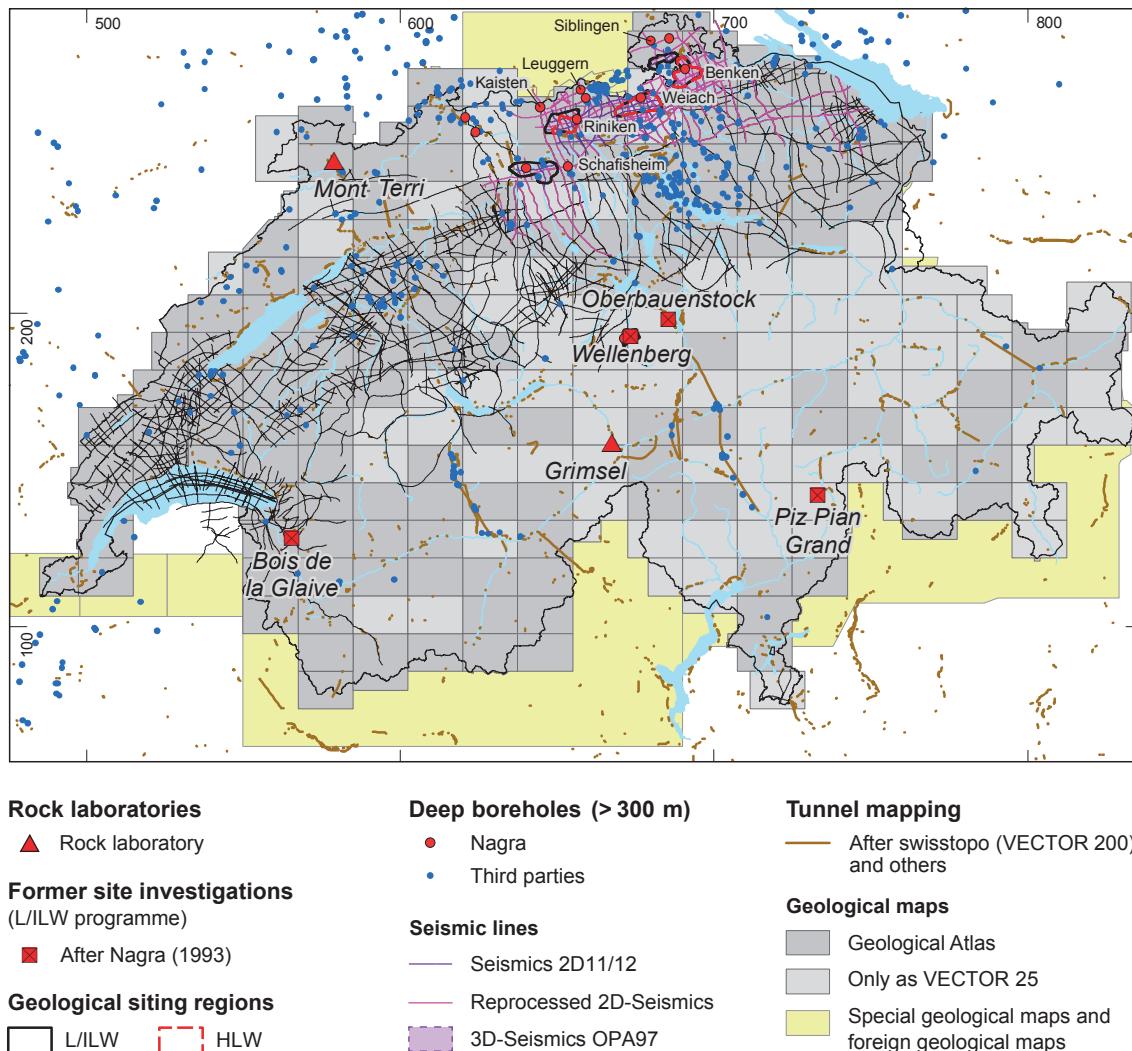


Fig. 3-1: An overview of the sources of geoscientific information used in Stage 1 of the Sectoral Plan (SFOE 2008).

In step three, the large-scale geotectonic setting was assessed and potentially suitable large-scale areas were identified from the viewpoint of long-term stability (uplift and erosion, differential movements) and spatial conditions (size of not significantly disturbed blocks of rock, explorability of spatial conditions). The evaluation showed that all large-scale geotectonic areas in Switzerland could in principle be taken into consideration for the L/ILW repository, whereas for the HLW repository the Alps, the Folded Jura, the western Tabular Jura and a small part of the Molasse Basin (western sub-Jurassic zone) had to be excluded.

Step four involved selecting the preferred host rock formations within the large-scale areas still under consideration. This was done in several sub-steps and led to the following results: for the L/ILW repository the Opalinus Clay with its confining units, the claystone-dominated unit 'Brauner Dogger' with its confining units, the marly-calcareous Effingen Member and the

Helvetic marls (a tectonic accumulation of low-permeability marly rocks in the Alps) were proposed. For the HLW repository, the Opalinus Clay with its confining units was the only host formation proposed.

The configurations of the preferred host rocks within the large-scale areas under consideration were evaluated in step five. Taking into account the presence of regional geological features (regional fault zones, overdeepened valleys resulting from deep glacial erosion, zones with indications of small-scale tectonic dissection, other zones to be avoided for reasons of neotectonics), preferred areas were identified within which the preferred host rocks could be found at suitable depth and with sufficient thickness and lateral extent. The preferred areas were used as the basis for delimiting the geological siting regions. Some siting regions contained several preferred areas and, for L/ILW, sometimes more than one host rock type.

This systematic approach was developed to ensure that the identification and selection of the proposals for the geological siting regions were performed in a fully transparent manner; the detailed documentation was elaborated to deliver a clear answer to the question "why here and not there?" from the point of view of safety. This is also considered to be of importance in view of gaining acceptance and support.

In October 2008, Nagra (Nagra 2008c) proposed three geological siting regions for the HLW repository and six for the L/ILW repository (Fig. 3-2). Three of the siting regions for the latter are almost identical with the ones for the HLW repository. The geological basis and rationale for the site selection is documented in Nagra (2008d).

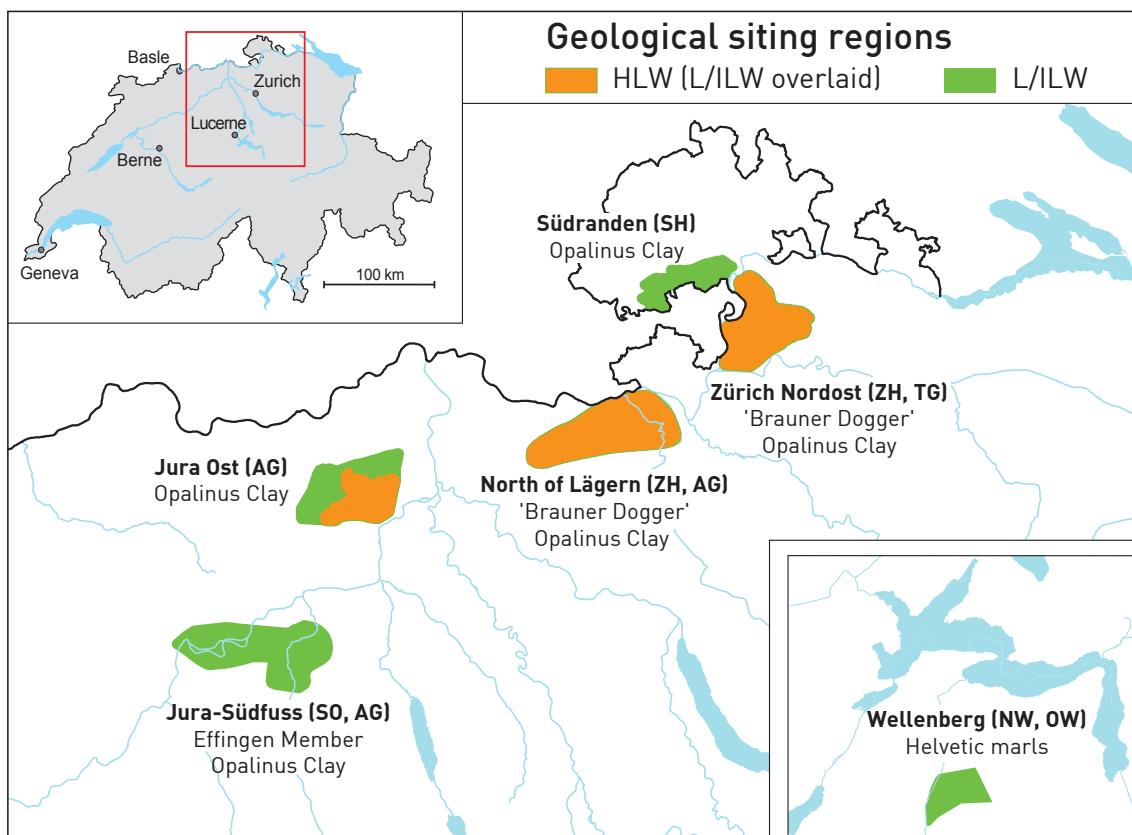


Fig. 3-2: The proposed siting regions (Cantons in brackets) and the respective host rocks (Nagra 2008c).

While Nagra's proposals were being reviewed by the authorities, under the auspices of the SFOE the communities potentially affected in each of the geological siting regions were identified and development of the organisational structure for the participatory process – to begin in Stage 2 – was initiated. The size of the communities that needed to be involved in the participatory process in each of the regions had to be determined. For this purpose, the areas that would, in principle, be available for siting the surface facilities were taken into account, i.e. the geological siting regions with an added 5 km to take into account the possible offset of the surface facility from the geological siting region when using a ramp/access tunnel from the surface site to the underground facilities. Clear "no go" areas from the point of view of land use planning were excluded. A regional participation group (so-called "regional conference") was thus proposed for each of the siting regions.

After an extensive review by the authorities and a public consultation phase, Nagra's proposals for the geological siting regions were approved by the Federal Government in November 2011. This completed Stage 1 of the Sectoral Plan process.

Stage 2: Selection of at least two siting regions for the L/ILW and HLW repositories

The ongoing Stage 2 of the Sectoral Plan process has two main goals: firstly, to select at least one site for the surface facilities with the main access to underground in each of the geological siting regions and, secondly, to narrow down the number of siting regions to at least two for each repository type.

For the selection of sites for the surface facilities, Nagra had – as a first step in Stage 2 – to submit proposals as a starting-point for the discussions with the siting regions. The proposals were based on a conceptual design of the surface facilities and took into account the following primary objectives proposed by Nagra: (i) ensure safety and engineering feasibility of the surface facilities and of the connection to the underground facilities of the deep geological repository; (ii) ensure compatibility with spatial planning and environmental planning in order to minimise environmental impact; (iii) ensure optimum integration of the surface facilities into the region. For each of these objectives, criteria were developed by Nagra, each being supported by more detailed indicators. The development of the proposals for the sites for the surface facilities showed that, due to the high population density and the intense land use in the regions considered, there was hardly any location where no conflict with at least one of the criteria/indicators occurred. Thus, the weighting and setting of priorities for the different criteria/indicators became a critical issue.

In January 2012, Nagra's twenty proposals were published as the starting-point of an intense phase of interaction with the regional conferences and their working groups within each of the siting regions. By applying a different weighting of criteria and indicators, the regional conferences identified additional sites for the surface facilities, which they requested Nagra to evaluate. A total of 32 potential sites were thus considered. By the end of January 2014, all the siting regions had issued their evaluation of the potential sites for the surface facilities and the preparation of the corresponding planning studies was completed by the end of May 2014.

As a second goal of Stage 2, Nagra had to narrow down the number of geological siting regions to at least two for each repository type. At an earlier date, in preparation for Stage 2, Nagra had to evaluate the available geological information and assess the impact of uncertainties with respect to decision-making. This evaluation led to the decision to collect additional geological data in some of the siting regions (e.g. through 2D seismics, analyses of data from third party boreholes, geophysical logging in geothermal boreholes, etc.).

The proposals for the regions to be further investigated in Stage 3 were prepared in five steps. Firstly, in step 1, the methodology used in Stage 1 was adapted to address the changes in boundary conditions and take into account requirements and suggestions put forward by the authorities and the various stakeholders. In a second step, in the siting regions proposed for the L/ILW repository with more than one host rock, a safety-based comparison of the host rocks led to identification of Opalinus Clay as the "priority host rock" that would be used for the following steps. This step was not required for the HLW repository as only the Opalinus Clay was identified as a host rock in Stage 1. When comparing the screened-out sedimentary host rocks to the Opalinus Clay, clear disadvantages appeared, such as intercalations of potentially water-conducting sandy-calcareous or calcareous beds, reduced self-sealing capacity due to the lower clay content and limitations with respect to exploration and characterisation of safety-relevant properties.

Hydraulic tests in the Opalinus Clay in boreholes in Northern Switzerland indicate horizontal hydraulic conductivities $\leq 5 \times 10^{-13}$ m/s (Fig. 3-3). The in-situ packer test data generally show good agreement with hydraulic testing of the rock matrix in drillcores, which supports the assumption of a (anisotropic) homogeneous medium. Various observations highlight the good self-sealing properties of Opalinus Clay (e.g. Bock et al. 2010) and natural tracer profiles provide independent evidence for a diffusion-dominated transport regime (e.g. Mazurek et al. 2009 and 2011).

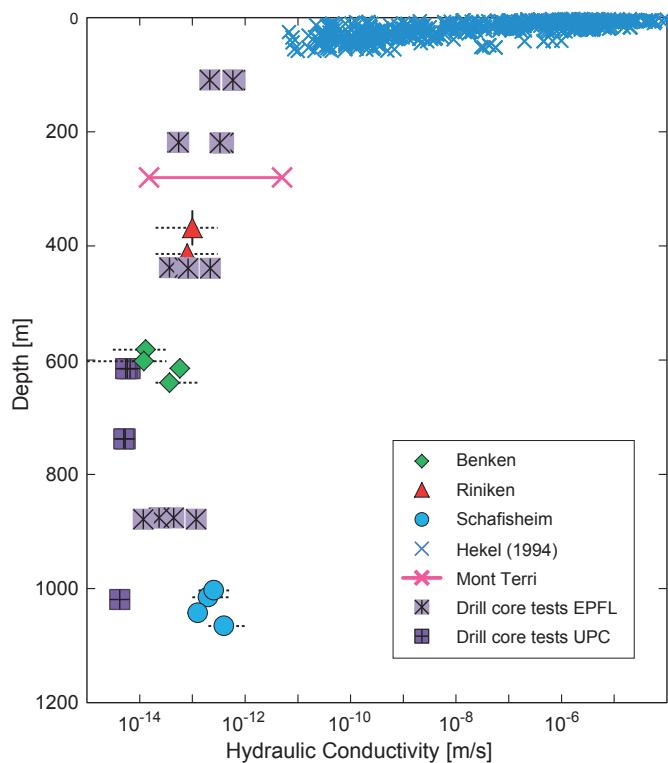


Fig. 3-3: Hydraulic conductivity of the Opalinus Clay as a function of depth.

Packer test data indicate best estimates and ranges. Data from drillcores recalculated to depth based on average confining pressure (after Nagra 2014b, slightly modified).

The third step led to the selection of an optimised spatial configuration of the priority host rock within the siting regions identified in Stage 1 (so-called disposal perimeters). In the fourth step, the suitability of the geological siting regions and the associated disposal perimeters in terms of safety were reviewed, on the one hand using dose calculations (so-called "characteristic dose intervals", see Nagra 2014c) and, on the other hand, through a qualitative assessment using the criteria relating to safety and technical feasibility set out in the Sectoral Plan. Finally, the fifth step involved a safety-based comparison and overall comparative assessment of the geological siting regions and the associated disposal perimeters based on the relevant features specified by ENSI (identification of siting regions with "clear disadvantages" in comparison with other siting regions), see Tab. 3-3.

Nagra's proposals were submitted and published by the SFOE in December 2014 (Nagra 2014a, b and c): of the six L/ILW siting regions and three HLW siting regions identified in Stage 1, Nagra has proposed the two regions "Jura Ost" and "Zürich Nordost" for further investigation (Fig. 3-2); the other four siting regions are proposed to be placed in reserve. Nagra stated that all six regions would meet the safety requirements, but that the regions that have been temporarily placed in reserve show clear disadvantages from a safety viewpoint compared to the two regions mentioned above. Both regions are suitable for the disposal of L/ILW and HLW, as well as for constructing a so-called combined repository for both waste categories. Nagra's proposals are currently being reviewed by the safety authorities and commissions and will be submitted to a broad public consultation before the Federal Council decides on the result of Stage 2. In autumn 2015, ENSI requested additional information from Nagra regarding the justification of certain aspects of the selection process. This was submitted by Nagra in July 2016 (Nagra 2016b), whereby Nagra confirmed its earlier proposals. ENSI's review, a crucial basis for the government's decision, is expected to be completed in 2017⁷.

⁷ At the time of publication of the report, it was undecided if Nördlich Lägern will be included as a third site in Stage 3 of the Sectoral Plan, as the arguments provided by Nagra to place it in reserve might not be supported by the regulator.

Tab. 3-3: Safety-based comparison of the geological siting regions: Evaluation of decision-relevant features and indicators (after Nagra 2014a).

| Decision-relevant features / Decision-relevant indicators | HLW repository | | | | L/ILW repository | | | | |
|--|----------------|-----------------|----------|-----------|------------------|-----------------|----------|--------------|------------|
| | Zürich Nordost | Nördlich Lägern | Jura Ost | Südranden | Zürich Nordost | Nördlich Lägern | Jura Ost | Jura-Südfuss | Wellenberg |
| Effectiveness of the geological barrier (E) | | | | | | | | | |
| Hydraulic conductivity | | | | | | | | | |
| Type of transport pathways and structure of the pore space | | | | | | | | | |
| Transmissivity of preferential release pathways | | | | | | | | | |
| Self-sealing capacity | | | | | | | | | |
| Homogeneity of the rock structure | | | | | | | | | |
| Thickness | | | | | | | | | |
| Length of critical release pathways | | | | | | | | | |
| Colloids | | | | | | | | | |
| Long-term stability of the geological barrier (S) | | | | | | | | | |
| Conceptual models of long-term evolution (geodynamics and neotectonics; other processes) | | | | | | | | | |
| Self-sealing capacity | | | | | | | | | |
| Potential for formation of new water flowpaths (karstification) | | | | | | | | | |
| Erosion during the time period under consideration | | | | | | | | | |
| Depth below the local erosion base level as relevant for formation of new ice-marginal drainage channels | | | | | | | | | |
| Depth below terrain as relevant for rock decompaction | | | | | | | | | |
| Depth below top bedrock as relevant for glacial overdeepening | | | | | | | | | |
| Seismicity | | | | | | | | | |
| Explorability and ease of characterisation of the geological barrier in the siting region (C) | | | | | | | | | |
| Variability of the rock properties as relevant for their ease of characterisation | | | | | | | | | |
| Exploration conditions in the geological underground | | | | | | | | | |
| Engineering feasibility (F) | | | | | | | | | |
| Depth with respect to engineering feasibility (considering rock strength and deformation properties) | | | | | | | | | |
| Geotechnical and hydrogeological conditions in overlying rock formations | | | | | | | | | |
| Available space underground | | | | | | | | | |

 Very suitable
  Suitable
  Limited suitability
  Less suitable

Stage 3: Selection of one site for each repository and preparing the general licence application

In Stage 3, the sites approved at the end of Stage 2 are subjected to a more detailed examination and, where necessary, supplementary geological investigations from the surface (see section 7.2.1) will be performed. This will aid in providing the basis for Nagra to select, for each of the repositories, the site for which the general licence application will be prepared.

For the sites selected, the project for the repository is then defined in greater detail in collaboration with the regional consultation bodies and the socio-economic aspects are subjected to closer scrutiny. The work and the activities in Stage 3 also provide the basis for the first stage of the environmental impact assessment.

General licence application

The general licence application must cover a broad range of issues (Tab. 3-4), most of them at the conceptual level. Because some of the information to be submitted is not directly dependent upon site-specific information, work on these issues will begin well before the start of Stage 3 of the Sectoral Plan or the selection of the sites in Stage 3.

Tab. 3-4: Information to be provided in the general licence application for each of the repositories (Nagra 2016a – Tab. A.1-3).

| |
|--|
| Properties of the site (geological synthesis) |
| Purpose and outline of the project |
| Anticipated exposure to radiation in the vicinity of the installation |
| Important information regarding organisation and personnel |
| Safety for the post-closure phase |
| Environmental impact assessment |
| Compatibility with spatial planning requirements |
| Concept for the monitoring phase and closure |
| Comparison of the options with respect to safety of the planned repository |
| Evaluation of the features of the site relevant for its selection |
| Cost estimate |

After Nagra's submission of the general licence application, it will be evaluated by the responsible federal authorities. The general licence specifies criteria which, if not fully met, lead to the exclusion of a planned disposal zone due to lack of suitability. Stage 3 is completed after the site has been specified in the Sectoral Plan and the Federal Council has granted the general licence. Subsequent steps involve the approval of the general licence by the Federal Assembly, which is subject to an optional national referendum.

3.1.2 Programme stages after granting of the general licence

After the granting of the general licence by the federal authorities, the following programme stages are envisaged:

- Construction and operation of a facility for underground geological investigations at the chosen site(s)
- Construction of the repository
- Operation of the repository
- Closure of the repository

The objectives of the work and key activities associated with these later stages are described in detail in Tab. 3-5.

Tab. 3-5: Key activities in the different programme stages after granting of the general licence using the example of the HLW repository.

| Phase | Objective | Brief description of key activities |
|--|---|--|
| Facility for underground geological investigations | Licence for the facility for underground geological investigations | Licensing procedure for construction and investigations (underground geological investigations and additional surface-based investigations) |
| | Construction of the facility | Supplemented by investigations from the surface, facility construction (exploration tunnel/shaft, experiment tunnels), construction-parallel characterisation, underground investigations, additional surface-based investigations |
| | Activities in the facility | Initiation of experiments, performing experiments and monitoring, synthesis of results, preparing documentation for the nuclear construction licence |
| Repository construction | Nuclear construction licence | Detailed design of surface and underground facilities; preparing documentation for review by the authorities; decision by DETEC |
| | Repository construction | Construction of surface and underground facilities, preparing documentation for the nuclear operating licence |
| | Nuclear operating licence | Review of documentation by the authorities, decision by DETEC |
| Operation of repository until closure | Repository operation | Emplacing wastes in the pilot facility and measurements, packaging/emplacement of waste, continuous backfilling of SF/HLW tunnels, constructing new tunnels for SF/HLW, periodic safety assessment and reporting |
| | Monitoring phase | Continuing measurements in pilot facility, other monitoring activities, periodic reporting |
| | Decommissioning of the nuclear parts of the surface facilities | Decommissioning and dismantling of the encapsulation facility |
| | Closure of the repository and partial dismantling of the surface facilities | Closure of the repository and the pilot facility, backfilling of the main access tunnels, dismantling of the surface facilities (conventional parts) |
| | Closure of the entire facility | Preparatory activities, backfilling and sealing of the subsurface facilities, complete dismantling of the surface facilities, greenfield |

3.2 Objectives and timing of RD&D activities supporting the programme stages

The RD&D programme is designed to provide all the information needed to address the requirements of the Sectoral Plan (Tab. 3-1), as well as to provide the basis for designing, developing and assessing the operational and post-closure safety of the repositories for SF/HLW/ILW and L/ILW.

The broad categories of work are:

- Geological information
- Radioactive waste and materials
- Safety assessment
- Design and technology development for the repository and the engineered barriers
- Evolution of safety-relevant properties and processes in the near-field, including the engineered barriers
- Development of the concept for repository monitoring

The work related to design, technology development and safety assessment is structured and planned so as to support the needs of stepwise repository development (see Tab. 3-5). This means that RD&D proceeds in all areas of study, but with different levels of depth and detail depending on the requirements for each programme stage.

Within the Sectoral Plan, there is a strong emphasis on geological investigations and safety assessment, as the principal objectives are to characterise and compare and select sites. In relation to the safety and barrier concepts for both the HLW and the L/ILW repositories, this requires a substantial contribution of the host rock to radionuclide retention. For this reason, the Opalinus Clay host rock has been proposed by Nagra in SGT Stage 2. Thus, in the RD&D programme further work will be performed to confirm the understanding of radionuclide retention in the Opalinus Clay and the adjacent confining units and to further evaluate the potential effect of perturbing processes (e.g. excavation damage, gas generation, heat generated in the HLW repository, decompaction of the host rock as a consequence of erosion processes, etc.) on host rock performance. This may also provide input to potential modifications of the current concept aimed at keeping perturbations at an acceptable level. Another domain of significant importance will be assessing the construction feasibility of the repository components taking into account the site-specific conditions and the geomechanical properties of the clay host rock at the selected sites.

For the general licence application, there are additional requirements (Tab. 3-4), which imply an increased need for information in a broader range of areas, e.g. monitoring, description of the waste types, barrier performance, contributing to the development of a full safety case. Furthermore, Nagra will implement the activities planned (Nagra 2008a) to address uncertainties that were identified in the safety assessments developed for *Project Entsorgungsnachweis* (Nagra 2008e) and address comments formulated by the regulator in connection with the assessment of the SGT Stage 1 and Stage 2 proposals. Most of these, apart from the latter, have been integrated into the previous RD&D Plan (Nagra 2009a) and the current document.

With the granting of the general licences, the sites for the respective repositories are fixed. This includes the approximate size and location of the most important constructions as well as the waste categories and the maximum disposal capacity. It requires a comprehensive synthesis of

RD&D findings in all areas related to post-closure safety and technical feasibility of construction, operation and closure of the repository. However, for the general licence the layout of the repository is only required to be at the conceptual level and, wherever appropriate, alternative concepts will be maintained for different elements of the repository. In addition, for the general licence there is also a need to provide information in some areas that are considered to have a more limited RD&D component, e.g. environmental impact assessment and programme cost estimates.

The detailed repository design, including the allocation of emplacement caverns and their detailed design as well as the detailed layout of the engineered barrier system, will take place only after exploration from the underground (including results from the facilities for underground geological investigations). This will be done in conjunction with the nuclear construction licence. In anticipation of the construction licence, the materials for the engineered barriers will be finally selected. Up to that point, feasible reference materials will have been selected, but various options will continue to be evaluated in order to achieve the maximum gain from future technological developments. This includes the materials for the disposal canister for SF/HLW and the backfill.

Chapter 7 describes the main requirements and the planned activities for the next 5-10 years, including the general licence application foreseen for 2024. For later programme stages (see Tab. 3-5), Chapter 8 presents an overview of the broad requirements for each stage and the areas of work foreseen.

4 Implementation framework, repository concepts and the safety case

While the purpose and the history of the Nagra work programme are described in Chapter 1 and the boundary conditions at the highest level are outlined in Chapter 2 (realisation plans, financing and the inventory to be disposed of), this chapter provides the framework and the main principles that allow the repository concepts for deep geological disposal to be developed and supported. The concepts currently considered are described; these form a basic element for the development of the safety case for the general licence applications. The components of a safety case are then briefly discussed, as well as the strategy for dealing with uncertainties during repository implementation, illustrated by some examples. This chapter thus determines the RD&D programme described in Chapters 6 to 8 in that it defines the areas that need to be addressed by RD&D to allow the development of requirements and to ensure that these can be met. It also defines the level of understanding that needs to be acquired to deal with remaining uncertainties.

4.1 Implementation framework for deep geological disposal

Context

Nagra's work programme for developing deep geological disposal facilities for HLW and L/ILW is subject to a set of external (stakeholder) requirements, most of which are specific to Switzerland, while others are published by international organisations. External requirements can be grouped into the following broad categories:

- Legal and regulatory requirements (laws, ordinances, regulatory guidelines)
- Recommendations from international organisations such as the OECD/NEA, the ICRP and the IAEA, along with generally accepted codes and standards, both national and international⁸
- Recommendations, requests and obligations set out by the regulatory authorities in the course of stepwise implementation
- Shareholders' (waste producers') needs
- Expectations and objectives of other stakeholders (e.g. politicians, the public, regional bodies, other waste management organisations)

The implementation of deep geological disposal falls under the provisions of the nuclear energy legislation, with the Nuclear Energy Act and the Nuclear Energy Ordinance (KEG 2003, KEV 2004) representing the primary source of external requirements. Licensing of geological investigations for nuclear facilities and licensing of construction, operation and closure of deep geological repositories is the responsibility of the Federal Government (KEV 2004, Art. 5, *cf.* section 1.3). Thus, the Swiss Federal Office of Energy (SFOE) has specified the objectives and criteria for the disposal of radioactive waste in deep geological repositories (including the procedure and criteria for selecting repository sites) in the Sectoral Plan for Deep Geological Repositories (SFOE 2008), the provisions of which are legally binding for all relevant authori-

⁸ According to the KEG (2003, Art. 4), the KEV (2004, Art. 36) and the regulatory Guideline ENSI-G04 (ENSI 2015a, Art. 6.1.1), these types of external requirements are binding for the implementation of deep geological disposal in Switzerland.

ties. Based on the mandate of the KEV (2004, Art. 11, paragraph 3), ENSI has formulated detailed design principles for deep geological repositories and requirements for the safety case in the Guideline ENSI-G03 (ENSI 2009).

The HLW and L/ILW programmes are also subject to external societal, technical and natural constraints (or conditions). Examples of such constraints are the availability of competent research organisations and contractors, the socio-economic situation in potential siting regions, the characteristics of the external infrastructure that will be used by the programmes (e.g. public transport systems, public water supply), the level of readiness of the necessary technology, the natural characteristics of potential sites and the long-term evolution of the conditions at the surface (biosphere). Other constraints arise from the fact that the HLW and L/ILW programmes form an integral part of the nuclear waste management programme in Switzerland (Nagra 2016a). These constraints include the types and inventories of radioactive waste and decommissioning and interim storage activities together with their timing (see Chapters 2 and 3).

External requirements and constraints are subject to uncertainty, possibly including variability with regard to time (e.g. laws and public infrastructure may change) and space (e.g. heterogeneity of geological properties at candidate sites). The HLW and L/ILW programmes have to be implemented in such a way as to be reasonably insensitive to such uncertainties and the associated risks (robustness). Some more details on how uncertainty is addressed with different strategies and methods are given in section 4.4.

Structure and link to RD&D work areas

The implementation of the HLW and L/ILW repositories is a complex task, involving a diversity of elements, such as individuals, organisations, buildings, materials, devices, information, operations, (re-)actions, documents, fees, the sites, the radioactive waste itself and so forth. At the highest level, these elements are organised into main activities⁹, major physical objects (mostly buildings and underground structures) and major systems, which represent combinations of objects and/or activities.

Main activities, such as geological investigations or safety assessment, also include the means (objects) that are needed to perform these activities (e.g. staff, devices, tools, funds, reports, computers). Note that RD&D itself is a main activity within the HLW and L/ILW programmes and that RD&D work areas are directly related to the other main activities of the programmes, with the focus currently being on:

- geological investigations (section 7.2)
- characterisation of radioactive waste and materials (section 7.3)
- development of concepts and technology for repository construction, operation and closure (section 7.4)
- assessment of the safety-relevant properties and processes in the near-field (section 7.5)
- safety assessment and the development of safety cases (sections 4.3 and 7.6)
- development of concepts for repository monitoring (section 7.7)
- other work areas, e.g. socio-economic and environmental impact assessments or development of concepts for long-term knowledge transfer (section 7.8).

⁹ The inclusion of activities such as geological investigations and repository operation extends the earlier implementation framework, which focused on physical components/systems of a deep geological repository and on the functions they deliver (see Nagra 2009a)..

The means, tools and finances for the RD&D activities listed above are broadly described in Chapter 2 and also in Chapter 5.

Major physical objects of a repository are organised into three groups:

- Surface infrastructure (surface facility, shaft heads, etc.)
- Underground access structures (ramp/access tunnel, shafts)
- Underground structures at disposal level (main facility with emplacement rooms, facility for underground investigations, pilot facility, etc.)

Just as the main activities include the objects needed to perform these tasks, the group of major physical objects naturally comprises the actions (or functions) that are performed by these objects (e.g. the safety functions of safety barriers).

Major systems range from purely technical systems (e.g. ventilation, energy supply, engineered gas transport system) to more socio-technical systems involving various technical, constructional, organisational and administrative aspects (e.g. fire protection, radiation protection, security), along with the functions they deliver. Combinations of several elements may also be referred to as installations, facilities (e.g. main facility, pilot facility) or modules.

Concept development and the role of requirements

Implementation of deep geological disposal starts with the development of concepts for the two programmes and the individual elements, while respecting the external requirements and constraints (see section 4.2). The concepts describe broadly how the individual elements of the programmes relate to and interact with each other, thus meeting the overall purpose of Nagra's work programme as outlined in section 1.1.

The concepts are then successively refined in order to arrive at a design or plan with sufficient detail to be implemented successfully. For the general licence application, a brief outline needs to be given for each programme based on a conceptual design that specifies – among other aspects – the approximate size and location of the main buildings (major physical objects as defined above) and the categories of waste to be emplaced, along with the maximum capacity of the repositories (*cf.* KEG 2003, Art. 14).

For each individual element of the programmes, the associated concept is composed of

1. statements and/or visual representations that identify the desired functional, performance or design characteristics of, or constraints on, the element without referring to a specific implementation or solution, and
2. statements and/or visual representations about how the element in question should actually be implemented so that it complies with the information given in 1.

Additionally, each concept may be complemented with references to external requirements, specific analyses, modelling activities and research activities that have led to the formulation of the respective concept (*cf.* below).

It is fundamental to note that both types of information act as requirements (or goals or objectives). The information given in the first part lists the requirements on the given element and the information in the second part sets the requirements on the actual implementation of the

element. Put another way, both types of information trace the decisions (or choices) that are taken during concept and design development, while the above-mentioned external requirements reflect the decisions taken by the associated stakeholders.

At higher levels, the information about the proposed implementation usually identifies a set of sub-elements (or sub-systems or means or components) that together will contribute to meeting the requirements on the respective element, along with the relationships and interactions among the sub-elements. A clear example is the set of passive barriers that together provide the required permanent protection of humans and the environment after closure of a deep geological repository (see further below).

At lower levels, the individual elements may not be further broken down into sub-elements. In this case, the implementation part of a concept typically specifies the properties¹⁰ and/or processes (or internal functions)¹¹ of the proposed implementation, and how these characteristics will meet the requirements on the element itself.

Generally, requirements may be of a qualitative or quantitative nature. In the former case, they may be complemented by more quantifiable (and thus more easily verifiable) requirements expressed in terms of indicators and corresponding values, which in this report are termed criteria¹². Furthermore, some requirements (or associated criteria) must be adhered to by any acceptable implementation or solution (minimal requirements) whereas others may be used for optimisation and evaluation purposes (*cf.* Nagra 2014a).

Concept and design development is not a purely sequential and hierarchical process. Rather, it occurs iteratively (while developing requirements/taking decisions) and recursively (later revisions of requirements/decisions), both within and across hierarchical levels. Changing requirements during concept and design development may affect some or all requirements at lower-ranking levels. Thus, changes at higher levels have more widespread consequences than those affecting lower levels. In this context, it is also worth noting that requirements evolve with regard to their degree of commitment, starting as preliminary requirements / decisions (assumptions), which may be regarded as working hypotheses that are made in lieu of more definitive requirements or decisions to allow the programme to proceed, and ending as final decisions that may be confirmed by e.g. the regulator or the Federal Government in a licensing process.

Once a single element has been implemented (e.g. a site has been selected, a shaft has been constructed or an activity has been completed), the information in the implementation part of the concept is superceded by the actual characteristics of the element (e.g. the characteristics of an object in its "as-built" state), which may then act as constraints on the planning of other elements (e.g. the actual position of a constructed shaft will pose a constraint on the layout of emplacement rooms). Such constraints reduce uncertainty affecting the planning of these other elements, and this planning will thus tend to become more focused and efficient. However, despite increasing constraints, uncertainties will inevitably remain prior to the implementation of an element and so planning needs to retain a degree of flexibility to account for new information and decisions as these become known.

¹⁰ Examples of properties are material type, geometric form, weight, wall thickness, hydraulic conductivity, reliability, mass, cost, etc.

¹¹ Examples of processes are storage, transport, construction, transformation, communication, exchange, control, etc.

¹² Note that the use of the term criterion in this report is different to its use in the Sectoral Plan and the corresponding Nagra documentation, where criteria describe relevant features of a site, thus acting as requirements and constraints. It is, however, consistent with the terminology adopted by other waste management organisations, e.g. with respect to the use of safety function indicator criteria (*cf.* sections 4.4 and 7.5).

Checking that the (proposed) implementation meets the associated requirements occurs before actual implementation of an element (e.g. through physical modelling of an object or numerical modelling and mock-up experiments for systems) and after implementation using various control mechanisms (e.g. inspection, test procedures). Indeed, the information in the implementation part of a concept is often supported by detailed modelling activities and other analyses carried out during an (iterative) optimisation process prior to implementation. A good example of an optimisation process that is supported by a large amount of modelling and analyses is the site selection process as described in Chapters 1 and 3. The required subsurface exploration of the selected sites prior to repository construction illustrates a control mechanism after 'implementation', i.e. after selection of the sites.

Another example of checking adherence to requirements before actual implementation is the development of safety cases at the different programme milestones (see section 4.3). The staged approach to repository implementation with frequent regulatory reviews and broad public consultation, the demonstration of the correct functioning of parts of the total system (e.g. of measures for temporary closure as required in ENSI 2009), concomitant monitoring activities possibly some time beyond repository closure and, finally, the collection of all analyses, arguments and evidence in the safety case (see section 4.3) are intended to provide sufficient confidence that the radioactive waste will be disposed of safely.

RD&D activities are related to requirements, e.g. by demonstrating that requirements on individual elements and their implementation can be met or by increasing the margins by which requirements can be met. In contrast, the outcome of RD&D may also lead to changes in the individual concepts if requirements cannot be shown to be met. Finally, RD&D may also lead to the amendment of requirements e.g. if additional knowledge shows that a requirement is over-cautious in its original form.

High-level requirements

The highest level requirement for deep geological disposal in Switzerland is set out in the Sectoral Plan (SFOE 2008) and the regulatory Guideline ENSI-G03 (ENSI 2009). The so-called protection objective for deep geological disposal states that *deep geological disposal of radioactive waste has to ensure the long-term protection of humans and the environment from the effects of ionising radiation, without imposing undue burdens and obligations on future generations.*

Thus, the main purpose or the main functionality to be fulfilled is the safe disposal of all radioactive waste during operation and post-closure as formulated in Nagra's mission (see section 1.1). The HLW and L/ILW programmes need to be carried out in such a way as to meet this ultimate requirement on radiological safety.

According to the safety principles¹³ in the KEG (2003, Art. 4), the protection objective must be met by preventing the release of impermissible quantities of radioactive substances (confinement) and by protecting humans against impermissible levels of ionising radiation (shielding) during normal operation and in the event of accidents. In addition, preventive and protective

¹³ The confinement and shielding principles may also be regarded as safety functions that the HLW and L/ILW repositories as a whole need to provide (*cf.* the definition of a safety function in the appendix of the regulatory Guideline ENSI-G01, ENSI (2011)). The confinement principle also refers to criteria group 1 and the associated criteria of the Sectoral Plan (see Tab. 3-2).

measures¹⁴ are required in the KEG (Art. 5), e.g. safety barriers, multiple and automated safety systems, as well as measures aimed at preventing any interference with the safety of nuclear installations and nuclear materials through unauthorised acts or the theft of nuclear materials.

These and other provisions in the KEG (2003) and KEV (2004) have been implemented in ENSI (2009) and SFOE (2008) as a set of qualitative guiding principles for deep geological disposal in Switzerland (see Tab. 4-1). The regulatory guiding principles stipulate among other aspects that post-closure safety should be achieved by a system of staged and passive engineered and natural barriers. The requirement for passive safety barriers is founded on the statement in the protection objective that no undue burdens and obligations on future generations should arise. In the same respect, future society should not need to enact any additional preventive and protective measures after closure. Rather, adequate prevention and protection should be provided by the barrier system itself.

Tab. 4-1: Regulatory guiding principles for deep geological disposal in Switzerland according to ENSI (2009) and SFOE (2008) (Original text).

| | Title | Principle |
|---|-------------------------------|---|
| a | Protection of humans | The geological disposal of radioactive waste may result in only low additional radiation exposure to individual members of the population. |
| b | Protection of the environment | As the natural basis for the existence of humans and other living beings, the environment requires to be protected (Art. 1 of KEG 2003). Biodiversity may not be put at risk by geological disposal. |
| c | Transboundary protection | The risks resulting from geological disposal of radioactive waste in Switzerland may not be higher in other countries than is permissible in Switzerland. |
| d | Future protection | Risks arising in the future from geological disposal of radioactive waste may not be greater than those permissible in Switzerland today. |
| e | Long-term safety | A geological repository has to be designed in such a way that, after its closure, no further measures are required to ensure long-term safety. |
| f | Safety barriers | The long-term safety of a geological repository is to be assured by staged, passively functioning natural and engineered barriers (multiple barrier system, Art. 11, paragraph 2b of KEV 2004). |
| g | Monitoring and retrieval | Any measures that would facilitate monitoring and maintenance of a geological repository or retrieval of the waste may not compromise the functioning of the passive safety barriers (Art. 11, paragraph 2c of KEV 2004). |
| h | Freedom from burdens | The responsibility for geological disposal lies with the generation enjoying the benefits of the energy produced. No undue burdens may be placed on future generations. |
| i | Natural resources | The foreseeable future use of natural resources may not be unnecessarily restricted by the presence of a geological repository. |
| k | Optimisation | For decisions that form part of planning, construction and operation (including closure) of a repository, alternatives are to be considered and balanced with a view to optimising operational and long-term safety. |

¹⁴ These provisions are related to criteria group 2 and the associated criteria of the Sectoral Plan (see Tab. 3-2).

In addition, quantitative protection criteria for the post-closure phase with regard to the legal confinement principle and in terms of radiological dose and risk are specified (see section 4.2). The formulation of the protection criteria for the post-closure phase is founded on a number of international recommendations and conventions, notably those of the IAEA (IAEA 2006a and b), as well as on recommendations from the International Commission on Radiological Protection (ICRP 1998, 2006, 2007)¹⁵. Protection criteria for the operational phase are given in the Radiological Protection Ordinance (StSV 1994) and the regulatory Guidelines ENSI-G04 (ENSI 2015a) and ENSI-G15 (ENSI 2010). Compliance with the regulatory protection criteria has to be shown in the framework of a safety case in line with the requirements set forth in ENSI-G03 (ENSI 2009) and other documents (e.g. KEV 2004, StSV 1994).

Along with the regulatory guiding principles and protection criteria, other high-level requirements are represented by:

- additional generic principles currently adhered to by Nagra, which relate to the implementation of deep geological disposal and which are based on various external and internal requirements (see Tab. 4-2),
- specific objectives with regard to conventional safety (e.g. occupational safety and health, structural safety, fire protection), environmental protection, spatial planning, security and safeguards, public relations, socio-economic consequences,
- the overall objectives of the main activities (e.g. the strategic objectives of site exploration activities and of information management), as well as
- the desired functionalities of the major objects and systems (serviceability).

¹⁵ Note that ICRP (2013), which is an update of ICRP (1998) that refers to the latest recommendations in ICRP (2006, 2007), was produced after the publication of ENSI (2009).

Tab. 4-2: Additional generic principles currently adhered to by Nagra for the implementation of deep geological disposal.

These principles complement the regulatory guiding principles in Tab. 4-1. Although they have been derived from various external and internal requirements, they generally do not reproduce the original texts.

| Title | Principle |
|--|---|
| Primacy of safety | Safety, and in particular nuclear safety, is given the necessary priority as far as possible. ¹⁶ |
| Effects of implementation on post-closure safety | The safety functions of the multiple barrier system are not impaired to a significant extent by activities and measures related to repository implementation (e.g. geological investigations at the surface and underground, construction of underground access structures, monitoring, maintenance, retrieval, ventilation, inspection, fire protection, repository extension, handling of accidents, temporary closure, security and safeguards, radiation protection, etc.). |
| Stepwise implementation | Implementation of deep geological disposal is carried out using a stepwise approach with well-defined milestones that conform with legal and regulatory procedures and with the possibility of recursion (i.e. of repeating steps) if needed. |
| Treatment of uncertainties / risks ¹⁷ | Uncertainties and associated risks are identified in a systematic and continuous manner, analysed with respect to their relevance and – if deemed possible and necessary – reduced or avoided by means of research activities, measurements or other methods. |
| Prioritisation and flexibility | Aspects with high uncertainties or risks are addressed with priority and as early as possible; less critical aspects are addressed as early as needed in order to be able to profit from future developments and insights. |
| State-of-the-art / experience | Implementation of deep geological disposal occurs in accordance with the state-of-the-art in science and technology, while considering existing experience with similar facilities. |
| Reserves / margins | Sufficient reserves and margins are provided in order to handle possible threats and/or to make use of potentially arising opportunities. |
| Spatial, temporal and functional separation / modularity | Objectives and functions are attributed to the activities, objects and systems of the programmes in a clear and unambiguous manner ¹⁸ and, if necessary, elements may be spatially separated or carried out at different times. |

¹⁶ The safe disposal of radioactive waste will be achieved if all requirements have been met and verified. In particular, the proposed implementation must be possible from a practical, engineering perspective, otherwise the regulatory protection objective will not be achieved (*cf.* KEG (2003) Art. 4.3b and Section 6.1 in ENSI-G03 (ENSI 2009)).

¹⁷ This requirement is a generalisation of the principle *Zuverlässigkeit der geologischen Aussagen* (reliability of geological information) in Nagra (2008e) and Nagra (2014c). It also refers to criteria group 3 and the associated criteria of the Sectoral Plan (see Tab. 3-2). Note that uncertainty in this report is defined to also include variability in space and time.

¹⁸ This does not apply to safety systems in which the same safety functions are provided by different components (redundancy).

Tab. 4.2: continued

| Title | Principle |
|---|---|
| Established methods and materials | Established, high-quality and sufficiently available materials and technology are used and established methods and organisational structures are applied. |
| Robustness and resilience | Repository implementation shall be insensitive to uncertainties, processes and events and/or, in case of disturbances, the original state or a safe state shall be reached in a short time and maintained. |
| Accessibility | All buildings and rooms of a deep geological repository ¹⁹ are at any time accessible to individuals and any required auxiliary means, or can be made accessible without undue effort. |
| Quality management / quality assurance | A quality management programme is prepared in accordance with international standards and the applied quality assurance measures are documented. |
| Organisation and personnel | A suitable organisation with an adequate number of appropriately qualified personnel is established and a strong safety awareness is fostered. The behaviour of Nagra as an organisation and the behaviour of its personnel are regulated in a code of conduct. |
| Involvement of stakeholders and communication | Repository implementation involves continuous contact with various stakeholders. Stakeholders are informed in a timely, comprehensible and transparent manner and their concerns are accepted and evaluated. |

4.2 Repository concepts currently under consideration

Overview

The concepts for implementing deep geological disposal currently considered in Switzerland are the result of many years of RD&D, as well as of safety, design, cost, site evaluation and other studies performed by Nagra (e.g. Nagra 1985b, 1994a, 1994b, 2002a, 2002c, 2005, 2008c, 2008e, 2011b – e, 2013a – d, 2014a, 2014c) and their reviews by the authorities (e.g. HSK 1986, HSK 1996, HSK 2004, HSK 2005, ENSI 2015b, Nagra 2008b). They also take into account the relevant national legal and regulatory guidance (e.g. KEG 2003, KEV 2004, ENSI 2009), as well as input from international developments.

State-of-the-art technology and procedures for implementing these concepts (e.g. constructing the repositories, handling the wastes, exploring the selected sites, manufacturing/emplacing the engineered barriers) are established, available and affordable. On the other hand, the implementation of deep geological disposal will take considerable time and it is likely that significant technological progress, e.g. in robotics and control, will be made by the time construction begins. Furthermore, the outcome of characterisation activities at the selected sites, which include geological investigations both at the surface and underground over several years, will have a large influence on the concepts finally adopted. As a consequence, the concepts currently under consideration are unlikely to be the final versions that will support a construction licence application and that will be adopted in subsequent programme milestones. Rather, refinement and optimisation will occur in subsequent steps, triggering future RD&D activities in various domains.

¹⁹ With the exception of backfilled underground structures.

This section provides a brief overview of the concepts currently under investigation, with the focus on concepts for the barrier systems that provide for post-closure safety, as well as on concepts for the major physical objects (or facilities) and for the main activities 'repository operation' and 'repository closure'. Where pertinent variants exist, these are mentioned explicitly. Concepts for other main activities (e.g. geological investigations, assessment of safety-relevant properties and processes in the near-field) are mentioned on a case-by-case basis together with associated RD&D activities in Chapter 7.

Post-closure safety concepts

The following paragraphs describe the safety concepts for the post-closure phase based on the corresponding requirements on post-closure safety and the currently proposed implementation. A more detailed description is given in Nagra (2008e) and in Nagra (2014c).

Requirements

The requirements on post-closure safety of a deep geological repository refer to the overall protection objective and the relevant legal and regulatory guiding principles (see section 4.1). The set of post-closure safety requirements is given in Tab. 4-3.

Tab. 4-3: Post-closure safety requirements on which the current concepts are based.

These requirements have been derived from various external requirements, but they generally do not reproduce the original texts.

| Title | Requirement |
|---|---|
| Protection objective | Permanent protection of humans and the environment from the effects of ionising radiation from the emplaced waste must be provided without imposing undue burdens and obligations on future generations. |
| Effective confinement | Radioactive substances must not be released in impermissible quantities. |
| Balanced contributions of safety barriers | The effectiveness of the multiple barrier system may not depend unduly on the effectiveness of one single barrier. |
| Protection criteria | Quantitative protection criteria are used until at most one million years after orderly repository closure to determine whether the protection objective is met. |
| Classification of evolution scenarios | The variants for future evolution of a closed repository that are realistically conceivable are to be classified into likely or less likely and the selected classification has to be justified. |
| Protection objective 1 | For each future evolution classified as likely, the release of radionuclides may not lead to an individual dose exceeding 0.1 mSv per year. |
| Protection objective 2 | Future evolutions classified as less likely that are not considered under protection objective 1 may not, taken together, constitute an additional individual radiological risk of health detriment exceeding one in a million per year. |
| Period of concern | The period during which the multiple barrier system has to provide its safety functions is determined by the radiological hazard potential of the emplaced waste and the predictability of long-term geological evolution. After this period, radiological impacts may not be significantly higher than natural exposure. |

Tab. 4.3: continued

| Title | Principle |
|--|---|
| Protection from natural events and processes ²⁰ | The safety functions of the multiple barrier system must not be impaired to a significant extent by natural events and processes (e.g. erosion, decompaction). |
| Protection from repository-induced effects | The safety functions of the multiple barrier system must not be impaired to a significant extent by repository-induced effects (e.g. thermal load, chemical interactions, gas production, mechanical processes, radiation-induced effects). |
| Protection from inadvertent future human actions | The safety functions of the multiple barrier system must not be impaired to a significant extent by foreseeable future activities related to the exploration or exploitation of the geological environment (e.g. drilling and other investigations from the surface, mining activities, geothermal exploitation, extraction of mineral and geothermal water). |
| Protection from intentional human access | The emplaced radioactive waste must be protected sufficiently and permanently from intentional human access. |
| Preclusion of nuclear criticality | The state of nuclear criticality must be ruled out for all periods and all realistically conceivable situations after closure. |

Proposed implementation

The effective confinement of the emplaced radioactive substances and adherence to further post-closure safety requirements are ensured by avoiding unfavourable interactions and ensuring favourable interactions²¹ between the following sub-elements (components) of the post-closure barrier system with the radioactive waste and the associated radionuclides, with external influences, and with one another:

- The overall geological situation (or environment)
- The spent fuel assemblies and the radioactive waste matrices
- HLW and L/ILW waste containers
- The SF/HLW disposal canisters and the L/ILW disposal containers
- The backfill and seals of the emplacement rooms
- The backfill and seals of other underground structures
- The host rock and possibly additional confining units that provide substantial contributions to the effective confinement of radioactive substances (effective containment zone)

²⁰ The safety requirements that deal with protection from natural events and processes, from repository-induced effects, from inadvertent future human actions and from deliberate human access correspond to the principle *Begrenzung des Einflusses ungünstiger Phänomene, inkl. lagerbedingter Einflüsse* in Nagra (2014c) and also refer to criteria group 2 and the associated criteria of the Sectoral Plan (see Tab. 3-2).

²¹ Of particular relevance are thermal, hydraulic, mechanical, chemical and electrostatic interactions, Examples of which are, respectively, dissipation of decay heat, hydraulic isolation, mechanical support, cement-clay interactions, and sorption.

The lack of unfavourable interactions and the provision of desired interactions are mainly influenced by:

1. the geometric setting, i.e. the repository architecture (e.g. emplacement of radioactive substances deep underground, connectivity and geometry of underground structures), the geometric form of the waste and the technical barriers, and the geometry of the geological barriers (e.g. thickness of individual layers, location and dimensions of faults),
2. the individual materials and their properties (e.g. hydraulic conductivity, mechanical strength, swelling capacity, chemical composition),
3. various state parameters (e.g. pressure, temperature, redox conditions, pH), as well as
4. the long-term evolution of the aspects 1. to 3.

Each barrier performs one or several post-closure safety functions, which are (*cf.* Nagra 2008e, Nagra 2010b, Nagra 2014c):

- **Physical separation of radioactive materials from the human environment (isolation)** – The safety and security of the emplaced radioactive substances, including fissile material, is ensured by placing it deep underground, with all access routes backfilled and sealed, thus isolating it from the human environment and reducing the likelihood of any undesirable intrusion or misapplication of the emplaced materials.
- **Ensuring long-term stability of the barrier system** – The overall geological situation at the selected site in combination with the emplacement of the waste deep underground, the backfilling and sealing of all underground and under-surface access structures, and an appropriate repository design protect the repository from repository-induced effects (temperature, gas pressure build-up) and from any detrimental impacts of processes and events taking place at the earth's surface that would jeopardise the safety of a near-surface repository (e.g. war, civil unrest, future glaciations, erosion, etc.).
- **Containment of radionuclides** – Much of the activity initially present decays while the radionuclides are contained within the individual waste and disposal containers. This is particularly the case for SF and HLW, for which the high-integrity disposal canisters are expected to remain unbreached for at least several thousand years, thus providing complete containment of radionuclides during this period. Even after the waste and disposal containers have largely lost their containment function, they still provide a barrier to radionuclide transport because they limit water access to the waste forms and because of the favourable radionuclide retention properties of canister materials and corrosion products.
- **Slow release of radionuclides from spent fuel assemblies or the waste matrix** – After the waste and disposal containers have lost their containment function, the rate at which radionuclides are released from the spent fuel assemblies or the waste matrices is low, due to favourable geochemical conditions (specifically due to the prevailing reducing conditions). This applies explicitly to SF (stable UO₂/MOX fuel matrix) and to HLW (stable glass matrix), but also to long-lived ILW and L/ILW, where a large fraction of radionuclides are incorporated in slowly corroding steel.
- **Retention of radionuclides** – After release from the waste matrices, radionuclides are transported only very slowly through the further near-field barriers (backfill/seals) and through the host rock and the confining units due to a number of favourable properties of the engineered and geological barriers (e.g. favourable geochemical conditions in the near-field and in the geosphere, low water flow in the engineered barrier system, in the host rock and in the confining units). During transport, radioactive decay takes place, thus further reducing radionuclide release from the repository to the human environment.

- **Dispersion and dilution of radionuclides** – A number of additional processes in the geological environment contribute to low radionuclide concentrations in the human environment. These include notably the spreading of radionuclides by means of diffusion and hydrodynamic dispersion, as well as dilution.

Figs. 4-1 to 4-4 illustrate the currently proposed implementation of the barrier systems for the different waste types and describe how the properties and/or processes of the individual elements of the barrier system contribute to providing the safety functions. Compliance of the proposed implementation with additional post-closure safety requirements (*cf.* Tab. 4-3) is checked within the framework of safety assessment (*cf.* section 7.6) and in making the safety case at each programme milestone (*cf.* section 4.3). In the particular case of the required adequate protection from repository-induced effects, such as the formation of an excavation-damaged zone or gas generation, the case is made through detailed system analyses as described in section 7.5.

The time frames for safety assessment – or periods of concern – were derived in Nagra (2008e) in the context of the Sectoral Plan based on guidance set out in ENSI (2009), and by considering the radiotoxicity of the allocated wastes and its evolution. The time frames for safety assessment are 100,000 years for the L/ILW repository and 1 million years for the HLW repository. Each barrier has its own specific evolution, although – with the exception of the spent fuel assemblies, the waste containers and the disposal canisters/containers – all barriers are expected to provide significant contributions to the overall barrier effect with regard to the release of radionuclides throughout the respective time frames for safety assessment.

The preclusion of nuclear criticality is ensured through various measures (e.g. specification of requirements on minimum burnup for spent fuel assemblies, use of inert fillers in the void space of SF disposal canisters if required, etc., *cf.* Nagra 2002c).

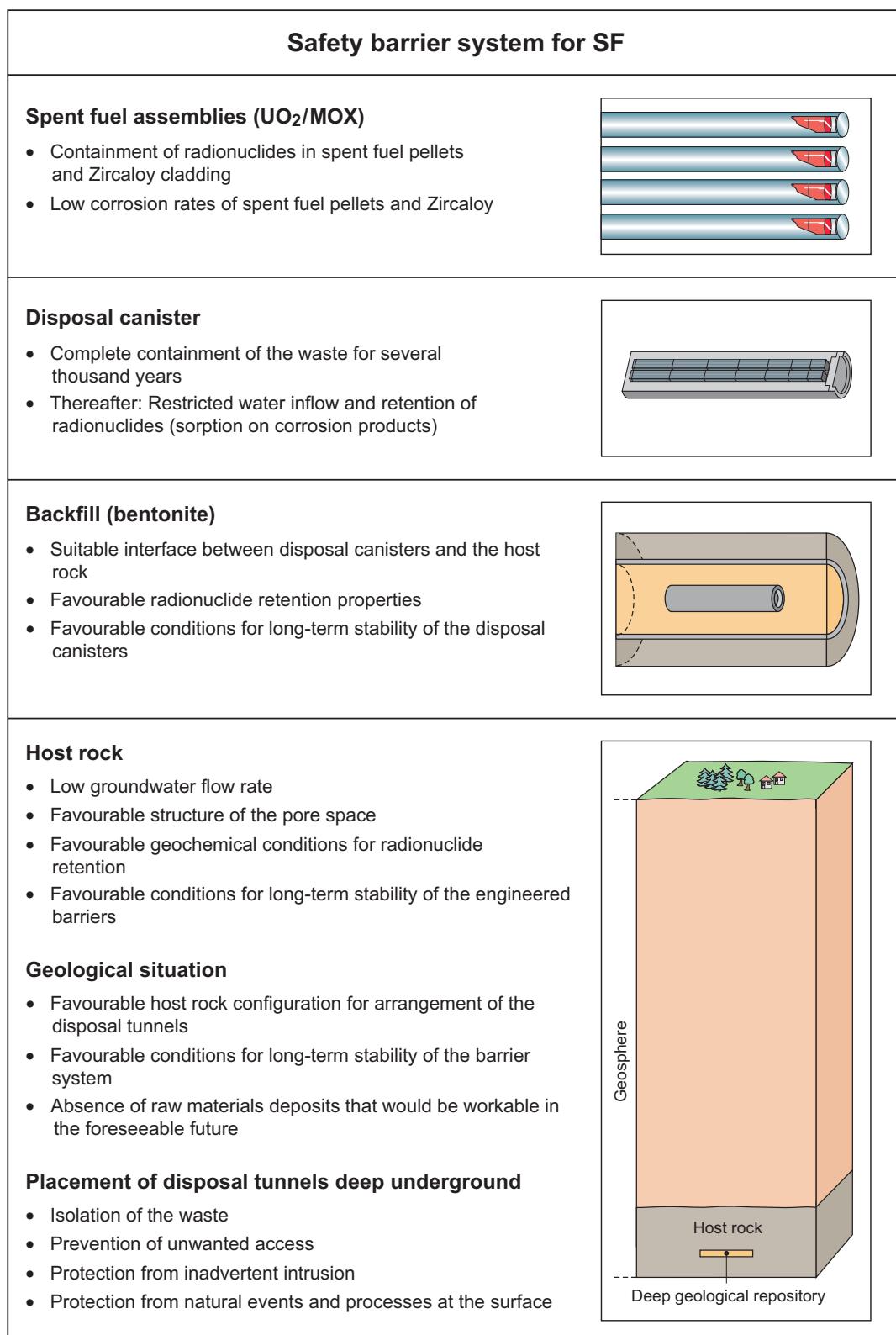


Fig. 4-1: Illustration of the barrier system for SF, which shows how the properties and/or processes of the individual barriers contribute to post-closure safety.

Not to scale, the backfill of other underground structures and the various seals are omitted from this figure.

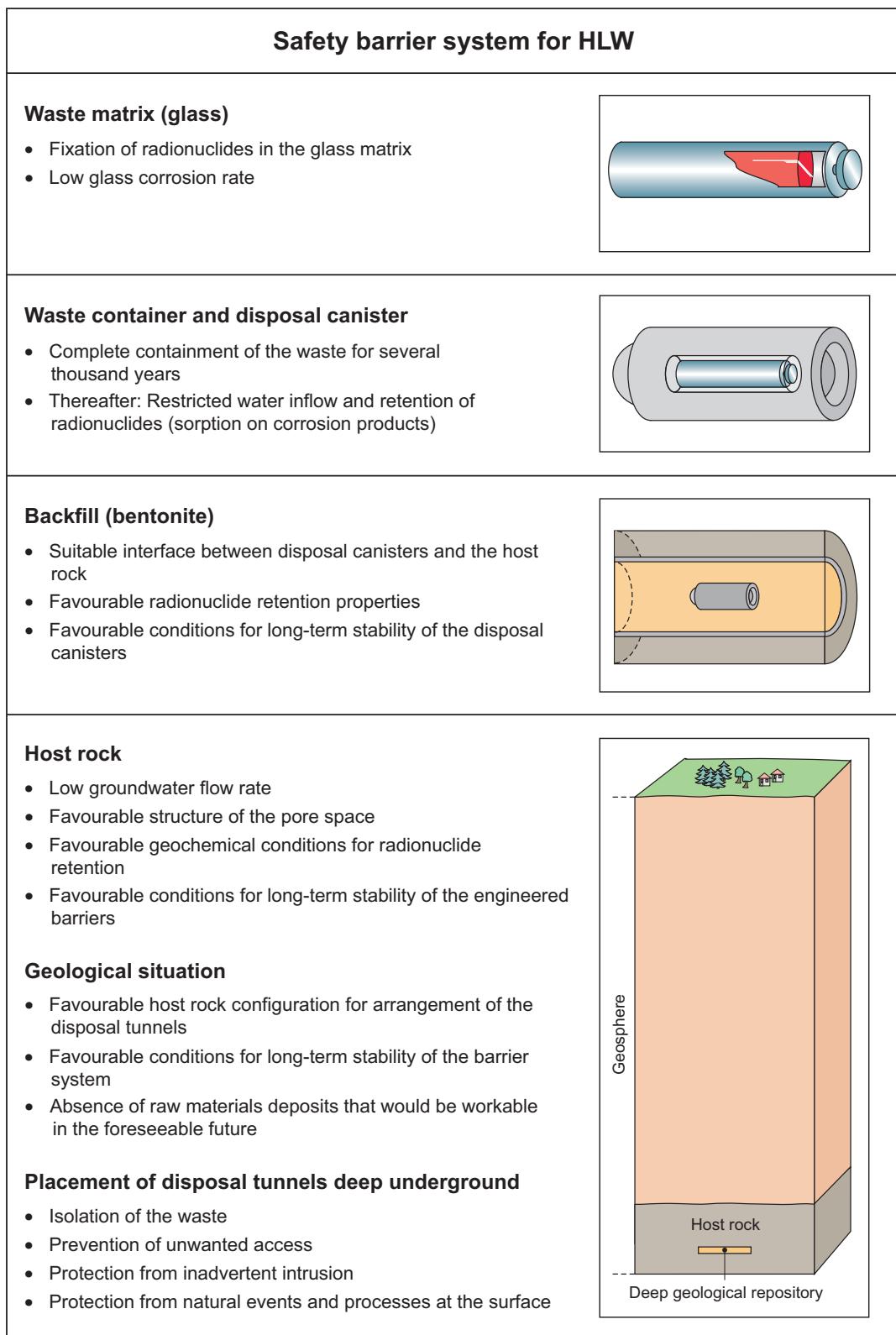


Fig. 4-2: Illustration of the barrier system for HLW, which shows how the properties and/or processes of the individual barriers contribute to post-closure safety.

Not to scale, the backfill of other underground structures and the various seals are omitted from this figure.

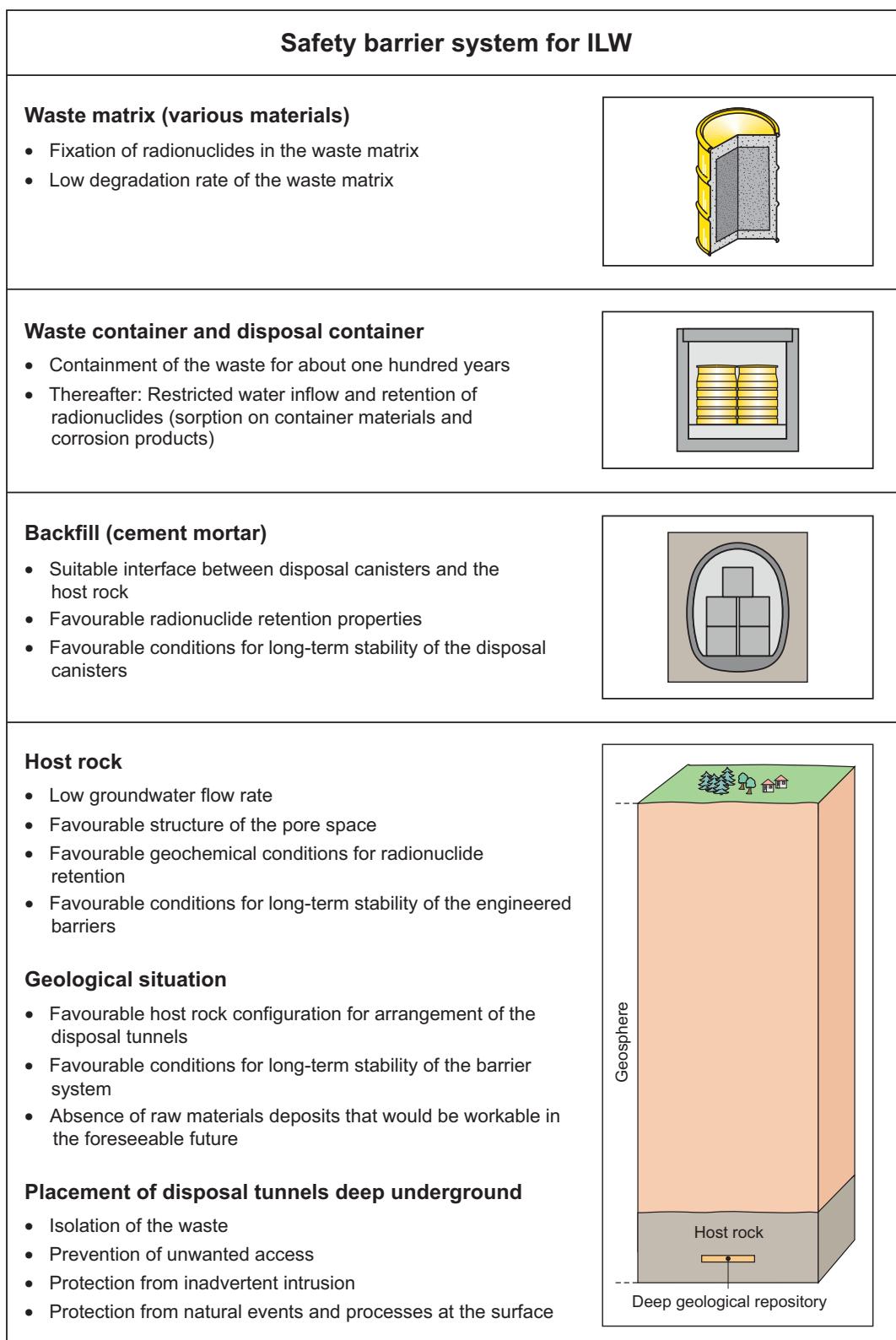


Fig. 4-3: Illustration of the barrier system for ILW, which shows how the properties and/or processes of the individual barriers contribute to post-closure safety.

Not to scale, the backfill of other underground structures and the various seals are omitted from this figure.

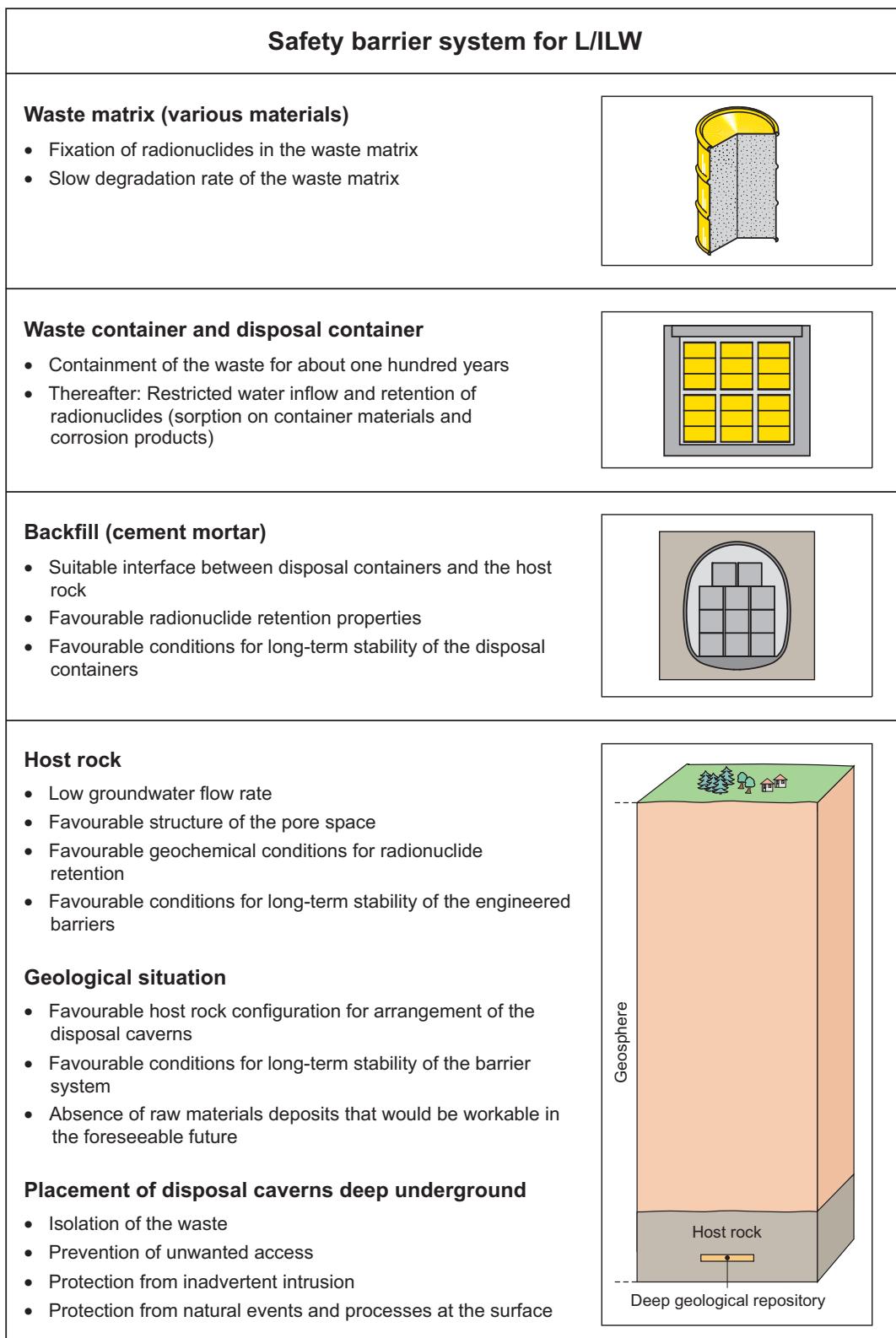


Fig. 4-4: Illustration of the barrier system for L/ILW, which shows how the properties and/or processes of the individual barriers contribute to post-closure safety.

Not to scale, the backfill of other underground structures and the various seals are omitted from this figure.

Facilities and operations/closure concepts

Fig. 4-5 and the subsequent paragraphs outline the currently envisaged concepts for the facilities and operations/closure of the HLW repository with the focus on the currently proposed implementation of the individual facilities and activities.

The surface infrastructure of the HLW repository consists of the required access infrastructure, the surface facility with the waste receiving and handling facilities, the shaft heads, plus temporary sites for the use or storage of excavated, extracted and demolition material.

Access to underground will be provided, during construction, operation and closure, by a ramp (access tunnel) and by shafts (ventilation shaft, construction shaft). As alternatives, any combination of ramps and shafts are in principle possible, thus allowing, for example, for an offset of the surface facility with respect to the underground structures.

The major underground facilities are:

- The SF/HLW main facility, where the majority of all SF and HLW will be disposed of and which will be backfilled and sealed in due time after waste emplacement.
- The ILW facility²².
- The pilot facility, where the behaviour of representative amounts of the different waste types, backfill material and the host rock will be observed until the end of the monitoring period and in which data will be collected to confirm post-closure safety with a view to closure.
- A facility for underground geological investigations, where site-specific data for the safety-relevant properties and processes in the host rock will be acquired and where demonstration activities will be carried out (this facility is later re-designated as the test area of the actual repository once repository construction begins).

The facility for underground geological investigations will be constructed prior to the construction licence for the HLW repository. It is planned that this facility and the associated underground access structures will be integrated into the final repository in order to maximise the available space for the layout of the disposal areas and to minimise perforations of the host rock and the confining units.

The underground facilities of the HLW repository will be constructed in Opalinus Clay at a depth of several hundred metres below ground surface roughly in the middle of the Opalinus Clay stratum or, if the confining units on either side of this stratum exhibit excellent barrier properties, in the middle of the effective containment zone, which consists of the Opalinus Clay stratum plus the confining units.

In order to provide for optimum use of the available space at repository level (constrained by the geometric configuration of the Opalinus Clay host rock and important geological features), the current concept for the SF/HLW main facility allows for several spatially separated disposal areas, each with multiple emplacement rooms, possibly with different lengths. In this way, avoidance of smaller-scale unfavourable geological features can be considered in the layout of the disposal areas and the emplacement rooms, regional fracture zones having already been taken into account when determining the extent of the geological siting regions. In the case of SF/HLW emplacement rooms, even minor unfavourable geological features may be avoided by not using the affected section of an emplacement room for canister emplacement.

²² Given that all the geological siting regions for L/ILW proposed for further investigations in SGT Stage 3 (see Nagra 2014a) are also proposed siting regions for HLW with Opalinus Clay as the host rock, it remains an option to include the ILW in the L/ILW repository rather than in the HLW repository as suggested in Fig. 4-5.

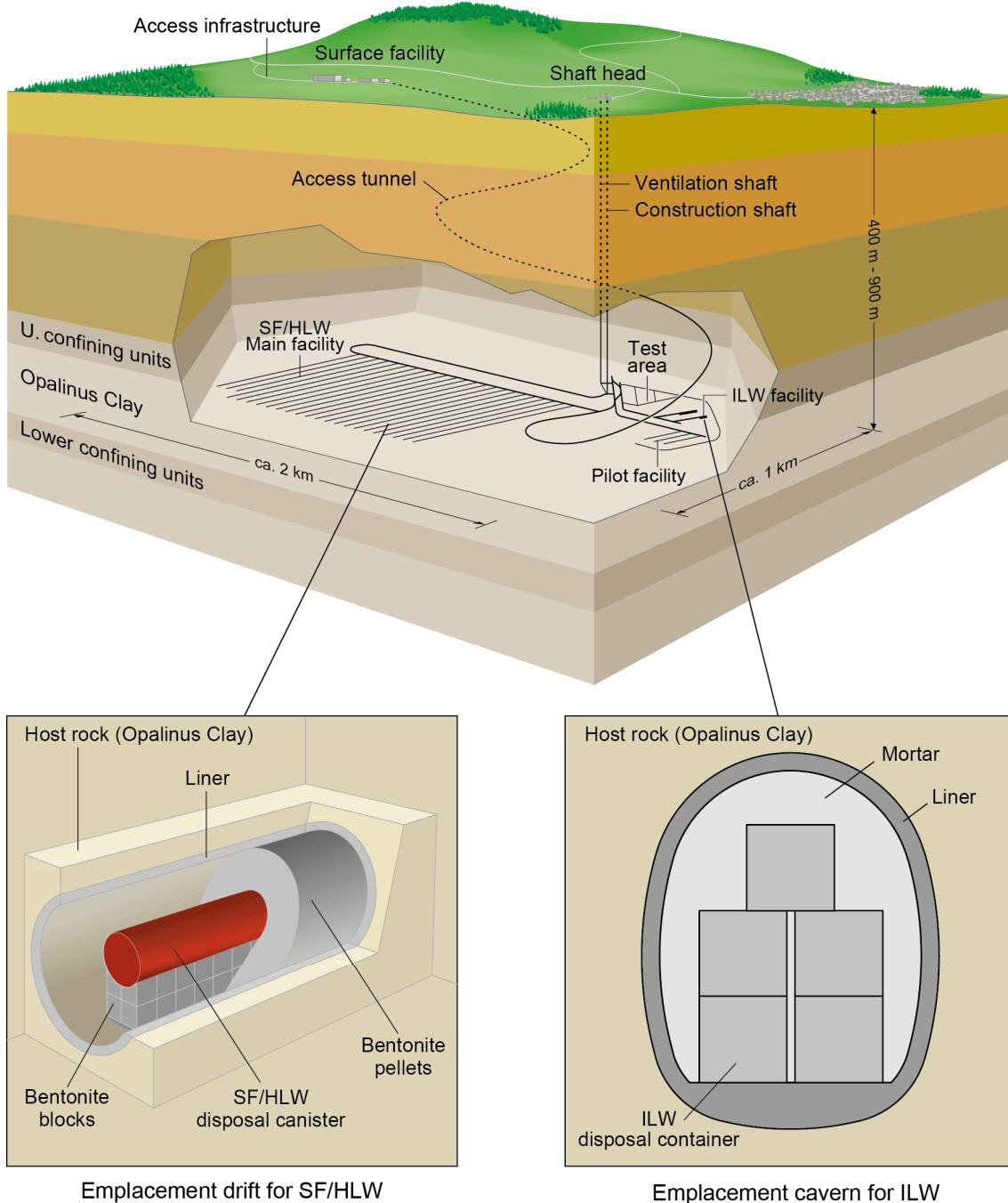


Fig. 4-5: Example layout of the HLW repository with its main features.

Not to scale.

Minimum distances are envisaged between the individual underground structures, as well as between these structures and important geological elements or other features (e.g. existing or future deep boreholes). Access to the disposal areas is provided through the operations and the construction tunnels, which allow for simultaneous waste emplacement and construction activities (for SF and HLW). The current concept for the main facility foresees a dead-end topology, i.e. the connections both from disposal areas and from emplacement rooms to other parts of the repository are single or at least concentrated at single locations.

The emplacement rooms are conceived so as to provide sufficient mechanical stability and suitable conditions for safe and reliable construction, operation (including possibly retrieval) and backfilling/sealing. In addition, the host rock should only be affected by construction and operations of the repository to an extent that does not significantly compromise the performance of the barrier system after closure (e.g. small deformations). Further, the use of materials with detrimental effects on barrier performance should be limited.

The emplacement rooms for SF and HLW (also termed emplacement drifts) have initial internal diameters of about 3 m, with single-shell sprayed concrete lining and lengths restricted to about 1,000 m due to conventional safety and operational considerations. The spacing between individual emplacement rooms is about 40 m in the current concept. The concept also foresees the prior and thus spatially separate emplacement of HLW in order to extend the time available for cooling of SF before emplacement.

The emplacement rooms (also termed caverns) for long-lived ILW in the ILW facility are supported by single-shell sprayed concrete lining. The clearance area of each cavern will depend on the geomechanical conditions encountered underground. The length is restricted to about 400 m due to conventional safety and operational considerations, and the spacing between individual emplacement rooms is about 100 m. To optimise the overall barrier efficiency, ILW with a significant content of materials that may have adverse effects on radionuclide retention in the near-field will be emplaced in separate rooms. Thus, each waste type will belong to a specific waste group that is allocated to specific emplacement rooms.

The pilot facility serves to observe the behaviour of the waste, backfill materials and the host rock until the end of the monitoring phase and to collect data to confirm radiological safety with a view to closure. A concept for monitoring and technologies for retrieval will be developed as part of RD&D (see sections 7.7 and 7.4).

Radioactive waste to be disposed of in the respective repositories will arrive at the surface facility either from one of the interim storage facilities or from the (decommissioned) nuclear power plants. In both cases, waste-specific reusable transport casks will be used. For waste to be accepted, so-called waste acceptance criteria (WAC) need to be fulfilled. The current preliminary waste acceptance criteria will be continuously refined as repository planning proceeds, thus providing continuous feedback to the waste producers and the waste conditioning procedures that are applied.

SF assemblies and fabrication flasks with HLW will be loaded into disposal canisters without further prior treatment in the encapsulation facility²³. SF disposal canisters will be loaded with 4 to 9 fuel assemblies, but alternative configurations are also conceivable (see section 7.4.5). The loading will be carried out with the objective of arriving at a homogeneously distributed thermal load (the current heat output restriction is 1500 W per canister at emplacement), thus providing for optimum use of the available space underground and an optimum emplacement procedure. For this reason, the encapsulation facility needs to feature several input and output docking stations. Aspects determining the thermal pitch (maximum heat output per canister and layout aspects such as tunnel spacing) will be revisited in anticipation of the construction licence when the thermal conditions and parameters at the selected site are confirmed by research in the facility for underground geological investigations. The RD&D activities related to assessing the impact of the heat output of the disposal canisters on the engineered barriers and the host rock are described in section 7.5.

²³ The current overall waste management concept foresees the location of the encapsulation facility within the perimeter of the surface facilities of the HLW repository. However, alternative locations are also possible.

According to the current preliminary design (Patel et al. 2012), the SF/HLW disposal canisters consist of carbon steel and are about 5 (SF) or 3 (HLW²⁴) metres long (alternative canisters are under investigation). They have a diameter of about 1 m (SF) or 0.7 m (HLW) and a wall thickness of about 14 cm. The disposal canisters are designed to be gas-tight and to resist any thermal or mechanical load that may occur in normal operations or in case of accidents. Thus, no release of radionuclides can occur for any design basis accident. In addition, they provide adequate shielding. During the post-closure phase, the disposal canisters provide complete containment for several thousand years.

ILW will be packaged in concrete disposal containers of standard size either in the surface facility of the HLW repository and/or at other locations (e.g. at the nuclear power plants in the course of decommissioning activities). The ILW disposal containers are designed to resist any thermal or mechanical load that may occur in normal operations or in case of accidents. Thus, little or no release of radionuclides can occur for any design basis accident. Packaging takes account of the assignment of individual waste packages to the different waste groups and other aspects may also be considered. The concepts for ILW (and L/ILW) disposal containers are currently under revision in close collaboration with the waste producers and the interim storage facilities (see section 7.4.6).

Transport of the packaged waste to the underground facilities occurs through the main access structure, which is a ramp/access tunnel in the current concept. Transport overpacks, which can be used several times, protect the waste packages from mechanical loads, thermal loads and liquids, and prevent the release of undue quantities of radionuclides in the case of accidents. In addition, they protect the operating personnel from radiation originating from SF and HLW.

The SF/HLW disposal canisters will be emplaced co-axially at intervals along the rooms, supported by pedestals of compacted bentonite blocks. The spacing between adjacent canisters along the rooms is about 3 metres in the current concept. The ILW disposal containers will be stacked in the emplacement rooms using an overhead crane. The current concept foresees different compartments with several horizontal layers inside an emplacement room, thus providing for the possibility to backfill individual compartments and layers immediately after emplacement. Note that regulatory clearance is required prior to the emplacement of each waste type.

Immediately after emplacement of a SF/HLW disposal canister, the respective section of the emplacement drift will be backfilled with highly compacted granular bentonite. The bentonite blocks and granules together form a protective mechanical and chemical buffer around the disposal canisters. Requirements on the bentonite buffer are derived and justified in Leupin & Johnson (2013). They are formulated in terms of safety-relevant buffer properties and preferred values for the indicators that quantify these properties (notably the current requirement (criterion) on hydraulic conductivity is $< 10^{-11} \text{ m s}^{-1}$, see section 7.5). Other backfill materials remain possible; the final decision on the backfill material and its safety-relevant properties will be taken in anticipation of the construction licence.

In order to increase the level of compartmentalisation in the SF/HLW main facility, which contributes to the overall robustness against detrimental phenomena (see Tabs. 4-2 and 4-3), so-called intermediate bentonite seals that provide direct physical contact between the bentonite of the seal and the Opalinus Clay host rock may be installed at frequent intervals along the SF/HLW emplacement rooms. The current requirements on these intermediate seals are also given in Leupin & Johnson (2013). They are identical to those for the buffer, with the exception

²⁴ The length of the HLW disposal canister reflects the assumption of two HLW flasks in a single canister according to Patel et al. (2012). However, current planning assumes three HLW flasks per canister.

that the requirement on hydraulic conductivity is more stringent ($< 10^{-12} \text{ m s}^{-1}$) and that there is clearly no requirement regarding mechanical support of a disposal canister in the case of the intermediate seals.

Shortly after an SF/HLW emplacement room has been completely filled, a final seal consisting of highly compacted granular bentonite in the current concept will be installed. Requirements regarding these seals are still under development and the feasibility of their construction will be demonstrated in anticipation of the construction licence in the facility for underground geological investigations.

The construction of further SF/HLW emplacement rooms occurs in parallel to emplacement. The construction operations will be completely separated from emplacement operations, e.g. by using the construction shaft instead of the access tunnel. The ILW emplacement rooms will all be constructed prior to emplacement.

In the case of ILW, the remaining void spaces between the disposal containers will be backfilled with a specially designed mortar and the caverns will finally be sealed with a gas-permeable sand/bentonite-based seal, which is a key element of the so-called engineered gas transport system (EGTS, see sections 6.2 and 7.5.3.3).

Monitoring activities will be carried out at and from the surface (e.g. measurement of radionuclide concentrations in environmental compartments, continuous measurements of state variables in deep boreholes) and underground, particularly in the pilot facility during the monitoring period. Retrieval of SF and HLW – should the need arise – would make use of the mechanical properties of the proposed bentonite backfill (lower strength compared with the disposal canisters and the tunnel lining), thus facilitating the excavation of the disposal canister to an extent that allows it to be removed safely.

In view of the long timescales involved in repository operation, a concept for maintenance of important installations and replacement of components (e.g. waste receiving and handling facilities, monitoring instrumentation, etc.) will be developed.

Closure of the HLW repository involves stepwise backfilling of all remaining underground structures, the installation of seals within the access structures to the individual disposal areas and within the underground access structures (which also serves to re-establish the permanent hydraulic separation of aquifers) and the installation of durable repository markers. Closure involves all activities that are required for the nuclear and conventional decommissioning of the surface infrastructure, including the disposal of small amounts of radioactive waste that may arise. Technology and procedures for these activities are readily available.

Fig. 4-6 illustrates schematically the concept currently considered for the facilities and operations/closure of the L/ILW repository. The concept is mostly identical to that for the ILW facility in the HLW repository.

One major difference concerns the size and shape of the emplacement rooms. All potential host rocks for the L/ILW repository show – at least partially – a high clay mineral content (consolidated clay rocks and marl), low hydraulic conductivity as well as similar intrinsic geomechanical properties. However, geomechanical conditions may vary between the candidate host rocks as well as between different sites, resulting in different constraints on the dimensions of the rooms. Furthermore, the vertical extent of homogeneous rock blocks with favourable confinement properties (called the host rock in the strict sense) may vary between potential siting regions and between host rocks, which in turn may impose constraints on the vertical size of the rooms.

Another difference concerns the amount of gas-producing materials to be emplaced, or, more accurately, the volume-specific amounts, and how these materials are distributed in the repository. This has led to specific RD&D activities in the field of repository-induced effects (see section 7.5).

The term "combined repository" indicates a concept where both repositories are located at the same site, although the SF/HLW emplacement drifts would be spatially separated from other emplacement rooms. The decision to build two entirely separate repositories or a combined repository will be taken in anticipation of the general licence application(s). The "combined repository" is discussed in greater detail in Nagra (2016a).

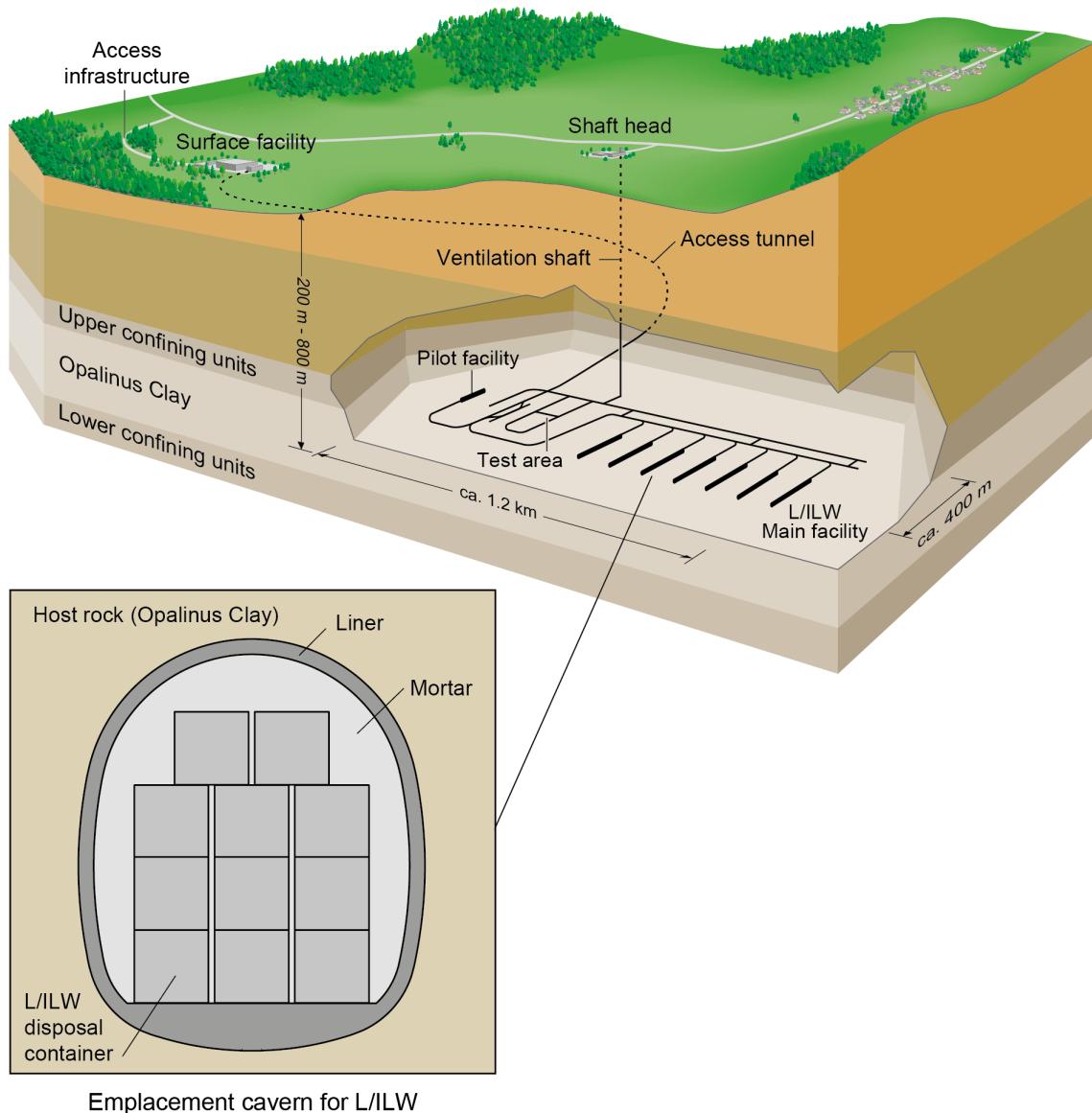


Fig. 4-6: Example layout of the L/ILW repository with its main features.
Not to scale.

Alternative concepts

Repository concepts other than the ones presented above are being considered worldwide. These differ from the current concepts proposed by Nagra – among other aspects – in the overall repository architecture, the type of underground access to the repository, the length and size of the emplacement drifts, the backfilling materials and the canister materials. Specific requirements and constraints inherent to the Swiss context, which include those of a geological nature (such as the limited thickness of the Opalinus Clay) and of a legal nature (such as the requirement that the canisters must provide full isolation for at least 1,000 years in the case of SF and HLW, the requirement for deep geological disposal of L/ILW waste) have led to the conclusion that, for the present stage of the Swiss programme (SGT Stage 2), the current concepts are advantageous for deep geological disposal in Switzerland compared with other concepts being considered elsewhere (Nagra 2016b and c). However, alternatives will continue to be evaluated in the future with the major aim of optimising safety (and thus also feasibility of construction, *cf.* Nagra 2016a). Where alternatives are promising, RD&D is being conducted to reduce the remaining uncertainties related to their suitability. An example is the ongoing and planned work on copper-coated disposal canisters for SF and HLW described in section 7.4.5. The final selection of the engineered barrier materials and the final repository layout will be decided in anticipation of the construction licences (Chapter 8).

4.3 The safety case

A safety case is a formal compilation of evidence, analyses and arguments that quantify and substantiate a claim that a deep geological repository will be safe (OECD/NEA 2013). In other words, the safety case shows that a selected repository concept and design (at early stages) or an implemented repository (with a view to closure) conforms to the regulatory safety requirements mentioned in section 4.1, i.e. to the protection objective, the qualitative guiding principles and the quantitative protection criteria for deep geological disposal set out in SFOE (2008), ENSI (2009) and other regulatory guidelines.

The Guideline ENSI-G03 (ENSI 2009) requires the compilation of operational and post-closure safety cases for all major milestones of the HLW and L/ILW programmes (general licence, construction licence, operating licence). A post-closure safety case is also required for repository closure. ENSI (2009) further contains specific requirements on safety assessment and on the development of a safety case. Both need to be carried out according to the respective state-of-the-art and with a level of detail that corresponds to the particular stage of development of the programmes. The safety case also needs to be documented in a dedicated safety report.

The results of safety assessments and the open issues and residual uncertainties identified in safety cases along with review comments from the authorities provide continuous feedback to repository implementation in subsequent stages. The next safety cases for the HLW and L/ILW programmes are planned in support of the general licence applications. Related RD&D activities are documented in section 7.6.

Post-closure safety

According to the Guideline ENSI-G03 (ENSI 2009), a post-closure safety case describes the evolution of the disposal system after closure, analyses the resulting radiological consequences and substantiates compliance with regulatory safety requirements by means of a comprehensive and systematic safety assessment. This also involves an evaluation of the methods and data applied in safety assessment, the collection of additional arguments and a comprehensive and systematic analysis of relevant uncertainties (see section 4.4).

The most recent post-closure safety case compiled by Nagra was for Project Opalinus Clay in 2002 (Nagra 2002c). It already had all the main elements of a safety case identified in the latest OECD/NEA document *Post-closure Safety Case for Geological Repositories; Nature and Purpose* (OECD/NEA 2013), namely:

- A *safety strategy*, which is the high-level approach adopted for achieving safe disposal
- An *assessment basis* consisting of the information and analysis tools for safety assessment
- A range of *evidence, analyses and arguments* that quantify and substantiate the claim that the repository will be safe, including the results of safety assessment and an evaluation of the impact of uncertainties

The relationship between these elements is illustrated in Fig. 4-7.

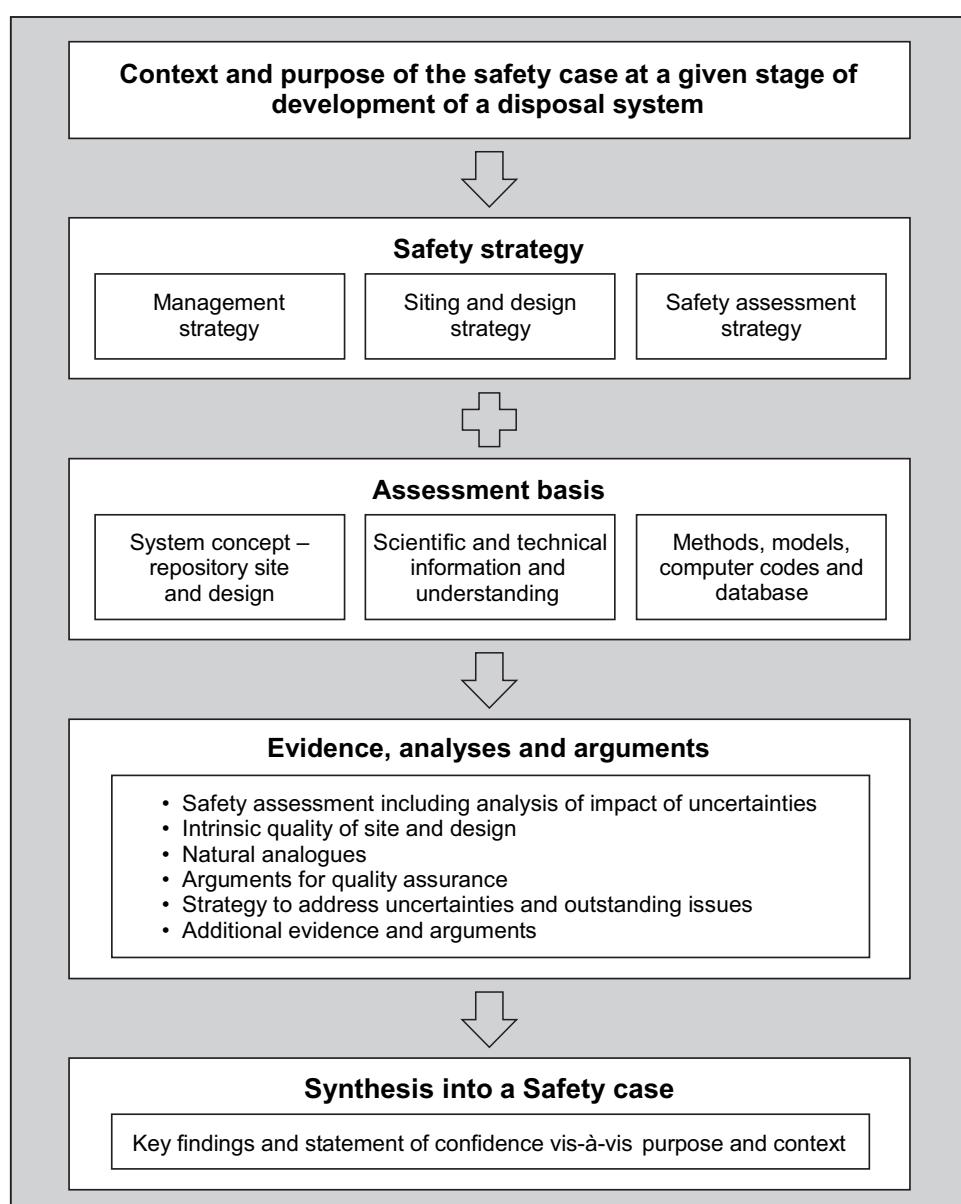


Fig. 4-7: Overview of the relationship between the different elements of a safety case (after Figure 2.1 of OECD/NEA 2013).

There has been no need for Nagra to carry out any further development of its own safety case methodology since Project Opalinus Clay as the focus of the Swiss disposal programme has been on site selection, with specific requirements that are distinct from those of a safety case (see section 7.6.1). Nagra has, however, been involved in several international initiatives, including the above-mentioned document on the nature and purpose of a post-closure safety case published by the OECD/NEA (OECD/NEA 2013), as well as initiatives dealing with more specific issues used in the development of a safety case, such as the EU PAMINA project (Galson & Richardson 2011) and the OECD/NEA MeSA initiative (OECD/NEA 2012a). Specifically, these initiatives have addressed issues such as safety strategy, safety functions, scenario development, modelling strategy, sensitivity analysis, uncertainty management and safety indicators. Nagra has also made substantial progress in its assessment basis. For instance, the safety assessment codes have been developed further to meet specific needs related to the site selection process (*cf.* section 7.6.1). The detailed study of repository-induced effects and the methodology applied in this study (*cf.* section 7.5) provide another example of where Nagra has improved its assessment basis.

Operational safety

The safety case for the operational period of a deep geological repository involves systematic and comprehensive safety assessments both for normal operation and for accidents. Since Project Opalinus Clay (see Nagra 2002a), Nagra has continuously broadened its basis for operational safety assessment (see section 7.6.2). In addition, wide-ranging experience in developing an operational safety case has been acquired for existing national and international nuclear facilities.

4.4 Dealing with uncertainties

As set out in section 4.1, uncertainties (and associated risks) must be considered for all aspects and all lifecycle stages of repository implementation. Thus, a strategy is adopted to deal with uncertainties, key aspects of which are the identification and analysis of uncertainties and the avoidance, mitigation and reduction of uncertainties with potentially adverse effects (threats)²⁵ (see Tab. 4-2). This section provides examples of how avoidance, mitigation and reduction strategies will contribute to reducing uncertainties with potentially adverse consequences, with a focus on the post-closure phase of a deep geological repository and the development of a post-closure safety case. Note that RD&D is itself part of the strategy for dealing with (mostly scientific and technical) uncertainties.

Uncertainties related to Nagra's short- and mid-term activities are addressed using an integrated risk management framework according to ISO 31000:2009. To avoid major uncertainties that are more related to long-term aspects of repository implementation, a minimum and also legal requirement on any acceptable repository concept is that it will be based on proven technology and materials to ensure reliability of implementation (see Tab. 4-2). Further requirements are that operations must be optimised with a view to nuclear safety and that procedures and systems that are intrinsically favourable to safety during normal operations and in operational incident conditions should be selected (see section 4.1 and Tabs. 4-1 and 4-2).

²⁵ See also section 3.4 of the NEA safety case document (OECD/NEA 2013), OECD/NEA (2012a) and Galson & Richardson (2011) along with references therein.

As noted in section 3.1.1, requirements on siting and geological setting have been derived from the criteria in the Sectoral Plan (see Tab. 3-2) to guide Stages 1 and 2. A more detailed examination of these requirements will be performed in Stage 3 for the proposed geological siting regions. Among these requirements are those related to the stability of the underground environment and the need to avoid adverse impacts of phenomena such as seismicity, uplift and erosion (see Tab. 4-3). Others relate to the reduction of uncertainties related to exploitable natural resources within or around the host rock that could attract inadvertent future human intrusion. Still others relate to the long-term predictability of conditions deep underground.

The engineered barrier system must clearly be compatible with the geological environment and complement it in terms of post-closure safety. This means that engineered materials or structures that would introduce significant uncertainties with regard to adverse effects on the safety functions of the host rock are avoided. Similarly, engineered materials must be mutually compatible, so that uncertainties about potential adverse interactions are avoided.

Some potentially detrimental phenomena and their attendant uncertainties cannot be entirely avoided, but their impact can be reduced or mitigated by a suitable choice of concept and design. For example, heat generation is an intrinsic characteristic of radioactive materials, especially SF and HLW. Any potentially adverse impacts on the repository barriers can be mitigated by increasing the storage time of the SF/HLW prior to emplacement in the repository, as well as by the choice of canister loading, canister pitch within the emplacement rooms and the separation of the rooms from one another. Furthermore, the requirement that the disposal canisters for HLW and SF must ensure complete containment of radionuclides for a minimum period of time after emplacement is in part motivated by the need to avoid analysing in detail the comparatively uncertain impacts of repository-generated heat and/or partial saturation on the radionuclide retention and transport characteristics of the surrounding barriers during early evolution.

Similarly, repository-generated gas, which might introduce some uncertainty in repository evolution, cannot entirely be avoided. However, it can be reduced by limiting the use of steel, e.g. in supporting structures, and/or by the use of an engineered gas transport system (EGTS, Nagra 2008g), as envisaged for the ILW emplacement rooms of the HLW repository and for the L/ILW repository; these measures are designed to ensure that gas pressures that could potentially lead to damage to the host rock are never attained. However, this approach gives rise to other second-order uncertainties, such as those related to gas transport properties of seals, which are currently being addressed through more detailed investigations (*cf.* Diomidis et al. 2016).

As a further example, inadvertent future human intrusion cannot be ruled out entirely, but the layout and design of the repositories can be chosen to minimise the likelihood of, and vulnerability to, inadvertent future human intrusion.

Potentially detrimental uncertain phenomena that cannot be entirely avoided or that are not clearly negligible need to be analysed in terms of their impact on post-closure safety, operational safety or feasibility. With regard to post-closure safety, indicators that measure the consequences of potentially detrimental phenomena on post-closure safety functions are derived along with associated criteria that, if met, mean that it can be assumed the safety functions will be provided as intended. If a safety function indicator criterion cannot be formulated, or if the criterion cannot unequivocally be shown to be met, then radionuclide release and transport calculations are carried out (or existing radionuclide transport calculations are re-examined) to evaluate the nature and extent of any detrimental effects and assess the implications in terms of overall safety criteria, principally the regulatory protection criteria. Key products of the RD&D

programme are the fundamental understanding, modelling capability and data needed to evaluate the safety function indicators, as well as the overall safety criteria, and to test whether the respective criteria are satisfied for a given concept and design.

Fundamental understanding, modelling capabilities and data each have their own attendant uncertainties that are taken into account when performing safety, design or other studies. For instance, in the post-closure safety assessments of Project Opalinus Clay (Nagra, 2002c), a distinction was made between:

- *Scenario uncertainty*: uncertainty in the broad evolution of the repository and its environment both with a view to implementation (design and system options) and after closure. In the case of the post-closure period, this can also be considered as the uncertainty related to inclusion, exclusion or alternative realisations of FEPs²⁶ that may affect this broad evolution.
- *Conceptual uncertainty*: uncertainty in the assumptions or conceptual models used to represent a given scenario or set of phenomena.
- *Parameter uncertainty*: uncertainty in parameter values used in a model. Parameter uncertainty can be due to spatial variability and evolution over time of relevant properties and processes, as well as uncertainty in the extrapolation of observations from laboratory or natural system conditions to scales of space and time relevant to the repository safety assessment. Parameter uncertainty can also arise from uncertainty in the models that are used to interpret the raw data and to derive the parameters required for safety assessment.

A range of strategies can be employed to account for such uncertainties, including:

- the use of several conceptual and numerical/analytical models
- the evaluation of a wide range of deterministic calculation cases
- the use of conservative model assumptions and pessimistic parameter values in these cases, provided an unambiguous link can be established between the assumptions/values and their postulated conservative/pessimistic consequences
- the use of probabilistic methods for uncertainty and sensitivity analysis

or a combination of these.

Whatever strategy is adopted, the aim is to identify which, if any, detrimental phenomena and attendant uncertainties could lead to safety requirements and other requirements not being met. A decision must then be taken as to how to address these phenomena/uncertainties. The available approaches are (i) to modify the concept and design to avoid these phenomena and uncertainties, (ii) to mitigate their impact, or (iii) to reduce the uncertainties by further studying the phenomena, developing improved and better substantiated models and collecting more or higher quality data. In this respect, irreducible and reducible uncertainties can be distinguished:

- Reducible uncertainties reflect the state of knowledge about e.g. the appropriate value to use for a parameter assumed to have a fixed (but not precisely known) value. In principle, such uncertainties can be reduced by making more measurements or by carrying out more laboratory experiments.

²⁶ FEPs: Features, Events and Processes.

- Irreducible uncertainties are either concerned with the inherent randomness in events that could occur in the future or are uncertainties which are reducible in principle (e.g. spatial variability), but for which further reduction is not reasonably feasible or justifiable (e.g. due to the efforts this would entail or the need to use destructive measuring methods). These uncertainties are considered intrinsic and need to be addressed by appropriate siting and design.

In either case, RD&D activities aim either to ensure directly that the requirements can be met or to increase the margins by which requirements are met, thus increasing the robustness of a deep geological disposal facility, its implementation and the attendant safety case.

5 The RD&D planning process, methodology and resources

5.1 The RD&D planning process

The RD&D Plan is an integral part of the Nagra Quality Management System (QMS) and is one of the key elements of the strategic long-term planning of Nagra and of the Swiss waste producers.

The RD&D Plan provides input to:

- The annual budget process, by indicating the needs for resources in order to address the priorities identified
- Estimates of the costs of implementing disposal, which are updated every five years as input to the financial planning by the utilities for the Waste Disposal Fund (funds for the disposal of radioactive waste, see Nagra 2016a)
- The strategic planning of resources, including the human resources required by Nagra and by its RD&D platforms (i.e. underground laboratories) and competence centres to carry out various RD&D activities
- Decision-making by Nagra in relation to requirements for the various phases of repository development
- Decision-making with respect to proposals for partner projects, by identifying areas where collaboration would be desirable, e.g. as part of existing or potential EU Horizon 2020 research and innovation projects or initiatives from the Implementing Geological Disposal of Radioactive Waste Technology Platform (IGD-TP), or other multilateral, bilateral or cooperative projects; this also includes identifying areas where commercial work could provide experience that would also be valuable to repository projects in Switzerland.
- Identification of areas where explicit measures are needed to manage knowledge (Knowledge Management Process)

5.2 The RD&D planning methodology

A considerable amount of relevant technology, data and expertise already exists at Nagra and within other waste management organisations worldwide. Further valuable information is available from the wider scientific and technical community and is documented in the corresponding literature. The challenge facing Nagra is to carry out RD&D in a manner that helps to deliver the projects at the required milestones, while making full use of relevant technology, data and expertise that are already available and monitoring relevant developments elsewhere. In doing so, Nagra should use its human and financial resources efficiently and share resources where appropriate. The methodology adopted to meet this challenge includes the following elements:

- The implementation plans for the repositories up to the start of operation (Chapter 2)
- The strategic requirements associated with the various steps involved in planning, licensing and implementing the two types of repositories foreseen in Switzerland (discussed in Chapter 3)
- The broad planning assumptions and strategic requirements to set the overall RD&D priorities and the current concepts and their alternatives (Chapter 4)

- The assessment of the current status of RD&D in Switzerland and worldwide and the identification of any gaps that will need to be addressed in meeting the strategic requirements for the future licensing stages (Chapters 6, 7 and 8)
- The planning of the specific work to be carried out to address each issue; in Chapter 7 the planning is described in detail for the next 5 to 10 years, including the general licence application foreseen for 2024, while a broad indication of the main activities planned beyond the general licence application is provided in Chapter 8.

Interdisciplinarity is a key element in this process. Although many specialists are involved in the activities, a significant number of people involved in the programme should have a broad oversight given the many different scientific disciplines involved.

5.2.1 Approaches for addressing RD&D needs

The general approaches available for addressing the RD&D needs identified by the above methodology are summarised in Tab. 5-1, which also indicates the types of issues for which a particular approach might be appropriate.

The approach adopted can depend on several factors, including:

- The priority assigned to an issue, which may be related to the time at which the information is required as well as its significance and the challenges involved in achieving the required results
- The degree to which full project control over the work related to an issue is required
- The need to maintain core competence at Nagra in areas of site selection and safety methodology and the requirement for Nagra staff to present and explain the results to the authorities, elected representatives and the public
- The need to maintain or develop scientific and engineering competence in particular areas at Nagra and at the competence centres, and the opportunities to resolve some issues because strong scientific competences already exist in certain areas
- The possibility to learn from others and to limit the duplication of work
- Cost effectiveness

Tab. 5-1: Approaches available for resolving outstanding issues and uncertainties.

| Possible approaches | | Issues for which the approach may be appropriate |
|----------------------------|--|--|
| A | To carry out RD&D projects relying on Nagra staff at a technical as well as managerial level | Appropriate for high-level strategic and methodological issues (siting strategy, safety strategy, safety assessment methodology, strategy for URL studies) and technical areas requiring expertise specific to the Swiss programme (e.g. producing the overall syntheses for geoscience, engineering projects and safety; waste inventory definition and associated characteristics). |
| B | To manage RD&D projects for which technical work is undertaken by competence centres external to Nagra | Appropriate if the approaches below (C, E) are unavailable or inadequate, or if the option of "buying in" knowledge (D) is rejected because of a desire to maintain or develop competence in particular areas at the competence centres. An important consideration is the availability of national competence centres. Nagra's management role is confined to the strategic level (definition of work programme areas and requirements), which enhances Nagra's multidisciplinary overview. |
| C | To engage in partner or commercial projects | Appropriate (and cost-effective) for issues requiring RD&D that are of common interest to other organisations, because know-how and knowledge can be pooled. Such projects also enhance acceptance and credibility. |
| D | To "buy in" technology, data and expertise from outside | Appropriate (and cost-effective) where, for example, site characterisation techniques, computer codes, etc. are known to exist, but are not currently available to Nagra, especially if there is no need to develop detailed technical competence in these areas, or if there is uncertainty as to whether Nagra RD&D would deliver the required product in time for the next project milestone. This nevertheless requires the capabilities at Nagra to manage such projects. |
| E | To monitor developments internationally | <p>International developments will of course be monitored in all relevant areas. It may, however, be the <i>sole</i> approach if:</p> <ul style="list-style-type: none"> - no RD&D requirements are identified in the assessment of the current status (such aspects are not dealt with in the RD&D Plan) - an issue is judged to be of low priority for the next milestones - adequate work is being carried out already by other organisations and will be available in the public domain in time for the relevant milestone <p>This nevertheless requires the capabilities at Nagra to oversee the relevant scientific-technological area of work.</p> |

5.3 RD&D resources, competence centres and URLs

This section describes the means for the implementation of the programme as well as the competence centres and the available URLs in Switzerland. Nagra is organised as a project management organisation and has a staff of approximately 100 persons. It is responsible for developing the disposal strategy in cooperation with its Board of Directors, developing the work programmes and managing the technical programme. The staff develops key strategic issues (e.g. siting strategy, safety assessment methodology, geosyntheses, safety reports and waste inventories). Nagra is also responsible for communication with all interest groups. In all these activities Nagra is supported by a wide network of universities, companies, contractors and experts.

In the following sections, some of the important contributions of the competence centres to the Nagra programme achievements of the past ten years are presented; these contributions are further discussed in Chapter 7, where they are integrated into the relevant programme areas. In addition to the RD&D collaboration with competence centres in Switzerland described in this section, Nagra is strongly embedded in the international research community as discussed in section 5.4.

5.3.1 The Mont Terri Rock Laboratory

The Mont Terri Project was established in 1996. It is an international collaborative project run by swisstopo in which currently 16 partner organisations from 8 countries perform experiments in the Opalinus Clay, the selected host rock for the Swiss repositories.

The project runs an underground research laboratory (Mont Terri URL) in the north-west of Switzerland near Saint-Ursanne. Adjacent to a highway tunnel, a security gallery and a newly excavated tunnel for the URL (see Fig. 5-1) allow horizontal access to the rock in the backlimb of the Mont Terri anticline. For the Swiss programme, the Mont Terri URL can be considered an off-site URL. The lithology and mineralogy are very similar to the potential siting regions in northeast Switzerland. Therefore, many safety-relevant features and processes can be readily investigated at Mont Terri (e.g. self-sealing, transport properties, hydrogeology, see Mazurek et al. 2008). However, differences in the burial history and in the actual depth, the considerable tectonic overprint and the inclined position of the Opalinus Clay layer at the location provide challenges for the transferability of geomechanical results to the siting regions in north-east Switzerland.

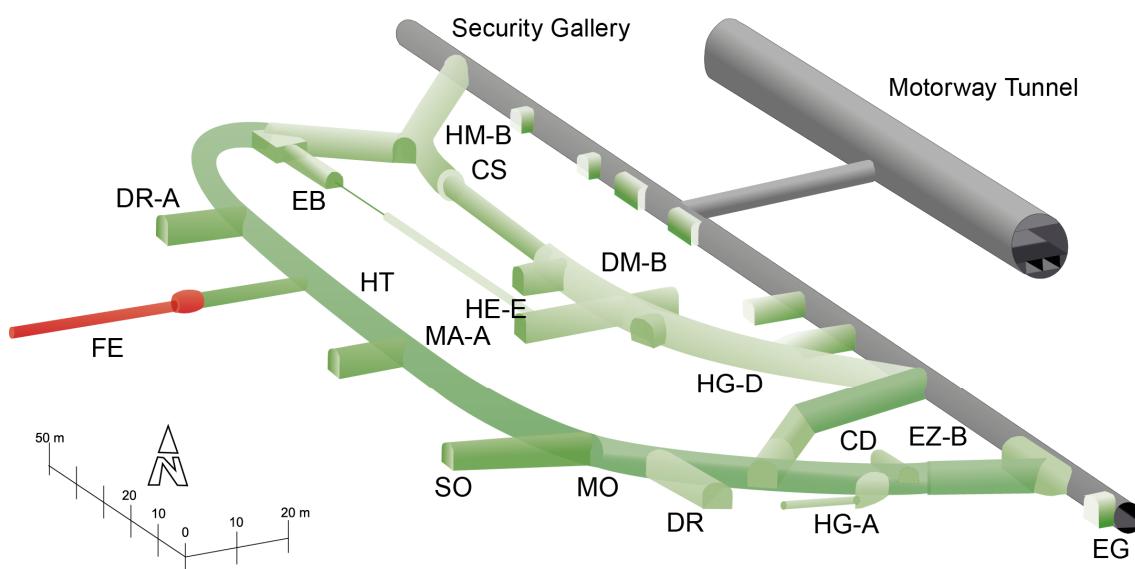


Fig. 5-1: The Mont Terri URL with the location of the most important experiments.
For abbreviations see Appendix A.3 ('List of acronyms').

In the past 20 years, almost 80 experiments have been performed in the URL covering all phases of the repository lifecycle from site investigation techniques to radionuclide transport in the late post-closure phase. The experimental work has provided important input for the Swiss *Project Entsorgungsnachweis* (Nagra 2002b and c), the SGT Stage 1 and Stage 2 documentation (Nagra 2008c, 2010a and 2014a) and the French Dossier 2005 (Andra 2005).

Initial work was focused on investigation methods (drilling, sampling, geophysics) and rock characterisation (mineralogy, porewater geochemistry, transport parameters). More recently, detailed investigations of repository-induced effects (mechanical, heat, hydraulics, geochemistry, gas) have been performed in a range of small- and large-scale experiments. Other experiments served to test models and databases used to predict radionuclide migration in the Opalinus Clay. Finally, larger and more complex demonstration experiments have been implemented to investigate the interaction of the different repository elements. Lessons learned from many of these experiments are discussed in Chapter 7.

5.3.2 The Grimsel Test Site (GTS)

The GTS is Nagra's own site-independent rock laboratory in operation since 1984. The branching tunnel system (see Fig. 5-2) of more than 1 kilometre in length is located at an elevation of 1,730 metres above sea-level, about 450 metres beneath the Juchlistock in the granite and granodiorite of the Aar massif that was formed some 300 million years ago. The special geological conditions encountered at the GTS (alternation between tectonically overprinted and fractured areas and homogeneous intact ones) are ideal for implementing a wide range of experimental concepts and studying a wide variety of topics. A unique characteristic of the GTS among existing rock laboratories worldwide is the existence of a radiation-controlled zone (IAEA Level B/C) in one of the investigation tunnels, which allows experiments to be carried out with radioactive tracers in the geosphere under realistic conditions (natural groundwater flow-field).

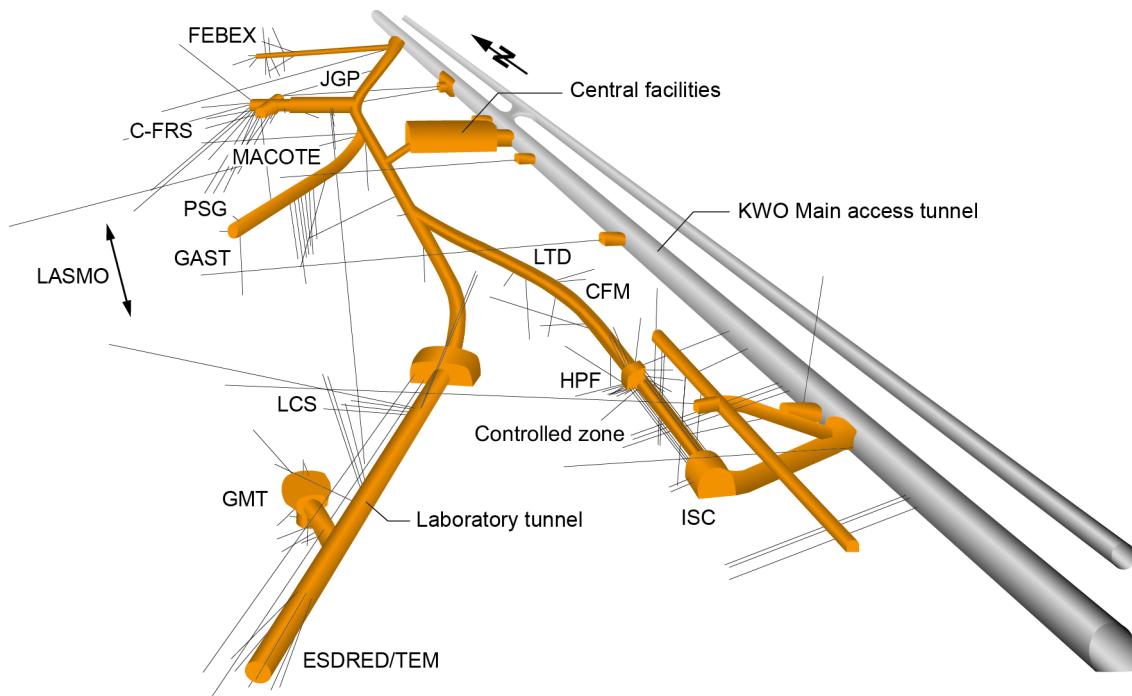


Fig. 5-2: The Grimsel Test Site with the most important experiments and their location.
For abbreviations see Appendix A.3 ('List of acronyms').

The decision to construct the GTS was taken in the late 70s. At that time, the feasibility studies for a geological repository for high-level radioactive waste in Switzerland were focused on the crystalline basement and Nagra was very interested in a research rock laboratory in a formation

with similar geological conditions. The topics examined over the first 5 phases of research (1984 – 2002) can be roughly classified as (see also Vomvoris & Kickmaier 2007): a) development and testing of characterisation technologies for repository sites; b) evaluation of methodologies for repository construction and their influence on the geological barrier; c) development and testing of the procedures for emplacement of the engineered barriers and the models evaluating their temporal evolution, considering the coupled processes of saturation, heating, gas pressurisation, etc.; d) rigorous testing of the models and databases used to evaluate radionuclide migration in a fractured host rock. The experiments involve a large number of organisations from many countries.

The current GTS Phase VI commenced in 2003 with a much longer planning horizon. This was in response to the realisation by Nagra and its partners that the types of questions which could be addressed by small-scale, short-duration studies had been repeatedly examined and that the major challenges remaining required experiments which move closer to full-scale simulation of the repository environment and thus would need to have much longer durations. More than 20 organisations and research institutes from 12 different countries as well as the European Union are participating in the various projects. These can be grouped into the following broad categories:

- Engineered barrier systems (processes and long-term behaviour)
- Engineering and operational aspects of repository implementation
- Waste – EBS – host rock interaction
- Geological barrier processes and characterisation
- Training and geoscience projects beyond radioactive waste disposal

As the focus of the Swiss national programme shifted from crystalline rock to sedimentary rock formations, the focus of Nagra's activities at the GTS has also evolved to reflect the emerging RD&D priorities (see also Blechschmid & Vomvoris 2015). Emphasis has been thus placed on the behaviour of EBS components under natural conditions or repository-induced effects (heat generation, gas) at medium and engineering scales, as well as their interactions. Examples of these are the gas-permeable seal test (the GAST experiment, see section 6.2) and the full-scale engineered barriers (FEBEX) experiment (see section 7.5.3.3).

5.3.3 Laboratory for Waste Management (LES) at the Paul Scherrer Institute (PSI)

The Laboratory for Waste Management (LES) at the Paul Scherrer Institute (PSI) is a unique Swiss competence centre for geochemistry and multiscale radionuclide and mass transport in argillaceous rocks and cement and their applications to deep geological systems and Swiss radioactive waste repositories. LES contributes to maintaining the scientific know-how for the safe disposal of radioactive waste and carries out a research programme in the areas of:

- Interfacial chemistry and transport of radionuclides in clay- and cement-based systems
- Thermodynamics and kinetics of retention in such systems
- Reactive transport studies relevant to repository in-situ conditions, including both modelling and experimental aspects

LES provides Nagra with state-of-the-art synthesis reports on geochemical evolution of the repository systems and geochemical and radionuclide transport datasets that are required to perform robust and reliable safety assessment calculations required at specific milestones in the stepwise repository implementation programme.

The scope of Nagra-relevant studies at LES includes sorption of radionuclides on geological and cementitious materials, diffusion of solutes in bentonite and Opalinus Clay, geochemical modelling, including thermodynamics, and reactive transport modelling including reactions at clay/cement and clay/iron interfaces, as well as corrosion of spent fuel and high-level waste glass. The data and models developed at LES are documented in peer-reviewed scientific literature and PSI/Nagra Technical Reports. A summary is provided on an annual basis (LES 2015).

LES is well equipped to carry out these tasks and maintains an excellent international reputation. Not only do they have very strong expertise in the above-mentioned areas and unique state-of-the-art research facilities such as the hotlab for work with radionuclides, the synchrotron facility (SLS) for micro-X-ray absorption/fluorescence spectroscopy (XAS/XRF) and a neutron source (SINQ; González Sánchez et al. 2008b), but they are also well connected to other research institutes in Switzerland and in Europe, with which they collaborate on a regular basis through EU or other (inter)nationally funded projects.

Major contributions of LES to the Swiss waste disposal programme include the development of sorption databases and mechanistic understanding of radionuclide sorption in clay and cement systems (Bradbury & Baeyens 2006 and Aimoz et al. 2012); laboratory- and field-scale (Mont Terri) experimental studies and modelling of radionuclide transport in compacted clay systems including upscaling (Van Loon 2014 and Churakov et al. 2014); X-ray synchrotron and neutron-based studies of material interfaces (Daehn et al. 2016 and Shafizadeh et al. 2015); development of thermodynamic databases (Thoenen et al. 2014); development of porewater models consistent with mineral dissolution phenomena and multi-scale THC reactive transport modelling of repository conditions (Berner et al. 2013 and Kosakowski & Berner 2013). Some important contributions of LES to the Nagra safety assessments are summarised in section 6.2 and in more detail in Chapter 7.

5.3.4 University of Bern

Uni Bern and Nagra have had a long-standing collaboration since the crystalline programme in the 1980s. Since 1994, the Rock-Water Interaction Group has been involved in all major field investigation programmes as well as in experiments at the Mont Terri and the Grimsel URLs. The Group was also involved in investigation programmes for potential clay or crystalline host rocks of Nagra's sister organisations in Canada, Finland, Sweden, France and Belgium, thus bringing international experience into the Swiss programme.

The major fields of work have been rock characterisation, natural tracer profiles, porewater investigations and modelling, hydrochemistry of deep groundwaters, geochemical aspects of bentonite evolution in the repository near-field and the interaction of clay rocks with high-pH fluids from concrete.

Rock characterisation work included lithostratigraphy, mineralogy and porosimetry investigations (Nagra 2014b, Dossiers II and VI). In addition, Uni Bern contributed to the investigation of paleofluid flow (e.g. Mazurek et al. 2011), the characterisation of water-conducting features in crystalline and sedimentary rocks (e.g. Thury et al. 1994, Mazurek 2000, Nagra 1997, Mazurek et al. 1998 and the NEA synthesis report on self-sealing of fractures: Bock et al. 2010) and the characterisation of residence times and geochemical evolution of groundwater in the host rock-bounding aquifers (Pearson et al. 1991, Waber et al. 2014).

The Rock-Water Interaction Group studied natural tracers in porewater, which provide independent arguments for the barrier function of the host rock and for diffusion coefficients at formation scale (Gimmi & Waber 2004 and Gimmi et al. 2007) and was the leading research group in a synthesis report including worldwide case studies on this topic (Mazurek et al. 2009 and 2011).

A variety of methods have been applied to sample porewater, including advective displacement and squeezing. A large dataset was collected and interpreted within the context of a recent deep geothermal well (Wersin et al. 2013 and 2016). Of special interest were the applicability of (stepwise) high-pressure squeezing (Mazurek et al. 2015) and the characterisation of noble and reactive gases dissolved in porewater (Rufer & Waber 2015). In addition, Uni Bern participates in several geochemical and diffusion experiments at the Mont Terri URL, the latter in joint efforts with LES. This work also included geochemical (transport) modelling (e.g. Gimmi et al. 2014).

Regarding the engineered barrier bentonite, the Group has expertise with respect to geochemical processes and is leading the chemistry working group of the EBS Task Force, an international modelling network. Another field of research is the interaction of clays and concrete. This includes laboratory and in-situ experiments, characterisation of reaction products and reactive transport modelling (e.g. Dolder 2015, Jenni et al. 2014, Wersin et al. 2014).

Erosional and depositional phases in the glacial-to-periglacial Quaternary of Northern Switzerland are being investigated in collaboration with the Quaternary Geology and Paleoclimatology Group of the Uni Bern. Luminescence dating methods have been improved and the sediments of several Quarternary key profiles in Northern Switzerland have been dated (Dehnert et al. 2012, Lowick et al. 2012 and 2015).

Emerging fields of collaboration address the tectonic evolution of the north of Switzerland where the siting regions proposed for further investigation in SGT Stage 3 are located. Novel attempts to geochronologically date the fillings of fracture systems are being pursued to better constrain brittle deformation processes in the area. Most recently, analogue sandbox modelling studies were launched to investigate the likely deformation kinematics of important large-scale fault systems such as the Permo-carboniferous Trough of Northern Switzerland.

5.3.5 Swiss Federal Institute of Technology in Lausanne (EPFL)

A long-term geoscientific collaboration programme between EPFL and Nagra was launched in 2006, aimed at strengthening geoscientific modelling capabilities in the field of coupled THM processes associated with repository-induced effects. Further emphasis has been on the geo-technical characterisation of the Opalinus Clay and the investigation of microbial activity in the repository near-field. Nagra's research partners at EPFL are the Laboratory of Soil Mechanics (LMS) and the Environmental Biology Laboratory (EML). Their involvement comprises multiple research projects at the Mont Terri and the GTS URLs, complemented by participation in projects as part of Euratom, SKB's Modelling Task Force on Engineered Barriers and the Australian Shale Research Centre (SHARC) Consortium (SHARC 2012c). In SGT Stage 2, the LMS has assumed an important role in the development of new QA/QC procedures for geo-mechanical laboratory testing.

The THM-related work concentrated on the geomechanical behaviour of clay-based buffer materials such as granular bentonite and sand/bentonite mixtures in response to thermo-hydro-mechanical loading paths. Two PhDs have been completed, dedicated to the thermo-hydro-mechanical characterisation and modelling of MX-80 granular bentonite (Seiphoori 2014,

Seiphoori et al. 2014, Keller et al. 2014, Ferrari et al. 2014a) and to the hydro-chemo-mechanical characterisation of sand/bentonite mixtures with the focus on water and gas transport processes (Manca 2015, Manca et al. 2016), respectively.

In the context of SGT Stage 2, the LMS has been responsible for a comprehensive geotechnical laboratory programme aimed at characterising the thermo-hydro-mechanical behaviour of the Opalinus Clay (Nagra 2014b, Dossier IV; Ferrari et al. 2012, Favero et al. 2013). In this context, a total of three PhD theses have been initiated, looking at various aspects of THM coupled processes (Favero et al. 2016, Minardi et al. 2016).

At EML, a PhD has recently been completed on exploring the use of hydrogen by micro-organisms (Bagnoud 2015, Bagnoud et al. 2016a and b and Bagnoud et al. *in press*). The main outcome is that microorganisms found in borehole water at the Mont Terri URL are effective in oxidising hydrogen to water. A follow-up study based on these insights will define the backfill parameters to allow bacteria to reduce the gas pressure build-up in a future deep geological repository.

5.3.6 Swiss Federal Institute of Technology in Zurich (ETHZ).

The research group for Geo-environmental Engineering and Clay Mineralogy (Claylab) and the Institute for Geotechnical Engineering (IGT) have been steady partners providing reliable advice and analytical work in numerous RD&D projects such as the "Engineered Barrier Emplacement Experiment" (EB) at the Mont Terri URL (Kennedy 2004, Kennedy & Plötz 2004), the EU ESDRED project on engineering studies and demonstration of repository designs (Plötz & Weber 2007), the HE-E heater experiment at the Mont Terri URL within the framework of the EU project PEBS on long-term performance of engineered barrier systems (Gaus 2011), the GAST experiment at the Grimsel Test Site (Rüedi et al. 2012) and the Full-scale Emplacement experiment (FE) at the Mont Terri URL (Garitte et al. 2015a and b). Recent research focused on the investigation of bentonite treated in different near-field-relevant conditions (temperature, degree of saturation) (Valter & Plötz 2013, Valter 2015). The Institute of Geophysics is involved in several of these projects to study transient behavior of buffer material with geophysical techniques. Further development of monitoring methodologies (Marelli, 2011) and characterization of the saturating materials (Maurer & Spillmann, 2015) are research goals.

A collaboration recently started with IGT on distributed fiber-optic strain sensing supporting the monitoring of the FE experiment at the Mont Terri URL where, besides a Raman spectra distributed temperature sensing (DTS), a hybrid Rayleigh-Brillouin system for distributed strain sensing (DSS) was installed providing detailed insights into the spatio-temporal variations in temperature and strain distributions along the tunnel wall. The collaboration focuses on the long-term performance of these systems in this large-scale experiment which reproduces repository-relevant conditions.

In cooperation with the Geological Institute, novel geochemical tools, such as carbon isotopes in organic matter, are being tested on the Opalinus Clay and its confining units in Northern Switzerland. Novel geochemical tools can potentially be used for correlation of the Opalinus Clay across different boreholes and outcrops and to support depositional models.

In 2016, Nagra started a research cooperation with the Laboratory of Ion Beam Physics (LIP). Isochrone burial dating and depth profiling methods will be critically evaluated and applied to Quaternary sediments from key locations in Northern Switzerland. If successful, the results will be used to reconstruct the regional landscape evolution during the past ~ 2 million years.

The Swiss Seismological Service has recently densified the broadband seismic network in Northern Switzerland (Plenkers 2014) and currently operates 15 stations on behalf of Nagra and swissnuclear. Besides routine analyses, the collaboration includes the development and application of new methods to detect and characterise recent seismicity.

Nagra also participates in the CARNEVAL consortium (Characterization and Removal of Near-surface Effects of Value for Applications in Land Seismics) of the Exploration and Engineering Geophysics group. The CARNEVAL research is focusing on characterising the near-surface zone, understanding its impact on land exploration seismic data, and deriving novel techniques for removing or correcting for the near-surface effect on reflection seismic data. The research focus includes theoretical studies on wave propagation, numerical simulation and modelling and analysis of existing and newly acquired data from several field campaigns. The consortium was extended for another two years in 2016. The group will deepen the methodological developments in a field study focusing on quaternary sediments. Geophysical imaging of ultra-shallow layers above known fault systems is the focus of this applied research.

5.4 The role of international collaboration

Nagra has many bilateral and multilateral agreements with other waste management organisations and research institutes. These provide valuable opportunities for information exchange and offer important insights into technical and management issues in other programmes.

In addition, Switzerland has participated in multilateral RD&D projects in the context of the EU Framework Programmes for many years. These cover a broad range of areas and many ongoing projects are discussed in Chapter 7 in the context of the detailed research programme. An overview of EU Framework projects that were either initiated or completed since the previous RD&D Plan (Nagra 2009a) is given in Tab. 6-1.

In the European context, Nagra is a member of the executive group of the Technology Platform for the Implementation of Geological Disposal (IGD-TP 2016; <http://www.igdtp.eu/>), launched in 2009 by a group of European radioactive waste management organisations and other bodies involved in the long-term European research effort in this field, with the support of the EU. The secretariat of the Platform coordinates RD&D activities following a strategic research agenda and a deployment plan through a number of joint actions and the organisation of exchange forums. In recent years, the IGD-TP has had a significant influence on the thematic areas covered by the projects of the EU Framework Programme.

Nagra also participates in various committees, working groups and projects of the OECD/NEA and is also involved in selected activities of the International Atomic Energy Agency (IAEA). This participation helps Nagra to maintain an overview of developments at an international level and in other programmes and to participate in relevant joint projects.

Through its International Services and Projects Division (Nagra ISP), a wide network of international contacts are maintained and the RD&D needs formulated by the Swiss national programme can be, where appropriate, addressed on a commercial basis where there is a joint interest with other parties.

Next to the international projects in underground rock laboratories (URLs), including those at Mont Terri and Grimsel in Switzerland, Nagra follows the activities in the Meuse-Haute Marne URL (operated by Andra) and participates in studies in the Äspö Hard Rock Laboratory (operated by SKB). Furthermore, close contacts are maintained with the Belgian programme and their underground laboratory (HADES in Mol).

Tab. 6-1: Overview of EU Framework projects (6th – 7th Framework and HORIZON 2020) in which Nagra has participated as a partner since the previous RD&D Plan (Nagra 2009a).

| Project | Period | Project Title |
|----------------|---------------|---|
| ESDRED | 2004 – 2009 | Engineering Studies and Demonstration of Repository Designs |
| MICADO | 2006 – 2009 | Model Uncertainty for the Mechanism of Dissolution of Spent Fuel in a Nuclear Waste Repository |
| TIMODAZ | 2006 – 2010 | Thermal Impact on the Damaged Zone around a Radioactive Waste Disposal in Clay Host Rocks |
| PAMINA | 2006 – 2009 | Performance Assessment Methodologies in Application to Guide the Development of the Safety Case |
| MoDeRn | 2009 – 2013 | <u>Monitoring Developments for Safe Repository Operation and Staged Closure</u> |
| FORGE | 2009 – 2015 | <u>Fate of Repository Gases</u> |
| PEBS | 2010 – 2015 | <u>Long-term Performance of Engineered Barrier Systems</u> |
| LUCOEX | 2011 – 2015 | <u>Large Underground Concept Experiments.</u> |
| DOPAS | 2012 – 2016 | <u>Full-Scale Demonstration of Plugs and Seals</u> |
| CAST | 2013 – 2018 | <u>Carbon-14 Source Term</u> |
| MODERN2020 | 2015 – 2019 | Development and demonstration of monitoring strategies and technologies for geological disposal |

6 Status of RD&D for disposal of HLW and L/ILW

6.1 Introduction

The past ten years have seen important milestones reached in the Swiss repository programme, including:

- Formal acceptance by the Federal Government in 2006 of the Nagra conclusion in *Project Entsorgungsnachweis* that safe disposal of HLW is feasible.
- Initiation of the Sectoral Plan for Deep Geological Repositories in 2008.
- Submission of the Nagra recommendations for Stage 1 of the Sectoral Plan, which proposed the siting regions for repositories for HLW and L/ILW, followed by review by the authorities and formal acceptance of the recommendations by the Federal Government in 2011.
- Decision of the Federal Council (Government) in August 2013 with respect to (1) the acceptance of the Waste Management Programme (Nagra 2008a) and (2) the report describing Nagra's intentions as to how to deal with the recommendations made by the authorities associated with *Project Ensorgungsnachweis* (Nagra 2008b), as well as the conditions for future reporting (Appendix 1).
- Completion of investigations for Stage 2 of the Sectoral Plan and submission of Nagra's Stage 2 proposals in 2015.

A summary of the achievements of the Stages 1 and 2 of the Sectoral Plan is presented in section 3.1.1, in which the focus is principally on geological investigations that were needed in order to satisfy the Sectoral Plan requirements. Throughout this period, significant progress has also been made in RD&D studies in many areas that were outlined in the previous Nagra RD&D Plan (Nagra 2009a), which are described in the next section. All of these and other developments are discussed in the comprehensive presentation of all areas of work in Chapter 7, where the ongoing and proposed future studies are also outlined in greater detail.

In addition, a concise summary of worldwide developments in repository implementation is presented below, with a particular focus on important areas of technology development. These aspects are relevant to the Swiss programme as they provide insights regarding technologies that may influence the direction of Nagra's studies in the period beyond the general licence application, when decisions will be made regarding the detailed design of the engineered barrier system and the equipment needed to operate the repository.

As part of the development of the programme, the whole body of RD&D in one specific domain or in multiple areas is interpreted and integrated into syntheses and assessments. These either support decision-making or feed directly into the safety assessments. Descriptions of the most recent assessments are summarised at the end of this Chapter.

6.2 Achievements in the Swiss HLW and L/ILW programmes

Developments in engineered barrier systems and repository layout

Since *Project Entsorgungsnachweis* (Nagra 2002a), there have been important developments in the evolution of the disposal concepts for the HLW and L/ILW repositories (see also section 4.2). For the HLW repository, engineering studies related to construction and operation have indicated a preference for dead-end waste emplacement rooms, as opposed to the through-tunnels previously considered in the design study of 2002 (Nagra 2002a). The design of the emplacement rooms themselves has also evolved, based on considerations related to the expected need for increased excavation support. The current concept includes a sprayed concrete liner along the SF/HLW emplacement drifts. After every 10th canister or so, the liner is interrupted by an interjacent sealing section (Fig. 6-1), which ensures direct physical contact between the dense bentonite backfill and the Opalinus Clay host rock, thus interrupting potential preferential water flow and solute transport pathways along the liner (see Nagra 2010a). In this section, linear liner elements such as steel ribs and wire mesh between the steel ribs provide rock support.

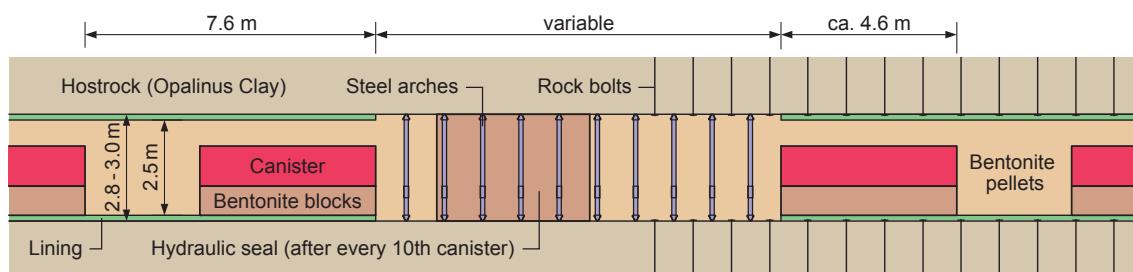


Fig. 6-1: Example layout of a cross-section of a drift showing the interjacent sealing section.

A demonstration of the Nagra concept was achieved with the Full-scale Emplacement (FE) experiment at Mont Terri (Figs. 6-2 and 6-3). The experiment started its heating phase in 2015, following successful installation of the liner, heaters, bentonite and associated instrumentation. The principal objective is to evaluate coupled THM effects on the host rock and EBS at full scale. Further objectives include gaining experience with construction and bentonite emplacement methods. Measurements made during heater and bentonite emplacement clearly show that the target minimum dry density of 1.45 Mg/m³ was exceeded. The monitoring of the experiment will allow testing of THM models of the host rock and bentonite over a period of many years.

Design concept studies have also been carried out for the L/ILW repository. A design measure for the L/ILW repository that would provide additional assurance that gas pressures would remain at acceptably low levels is the use of gas-permeable seals for closure of the L/ILW emplacement caverns. The concept is illustrated in Fig. 6-4 and is based on the principle that the gas entry pressure for the sand/bentonite mixture used for the seal is substantially lower than the gas entry pressure of the far-field host rock. Despite their relatively high gas permeability, such mixtures nonetheless have low water permeability, thus ensuring good hydraulic isolation of the cavern. A full-scale test of a gas-permeable seal (the GAST experiment) has been installed in a cavern at the Grimsel Test Site (Fig. 6-5).

FE Experiment

The Full-scale Emplacement (FE) experiment is a multiple heater experiment (Fig. 6-2). At full scale, it represents a 50 m long section of a HLW repository tunnel. In the test, three spent fuel canisters are represented by three heaters with identical dimensions. The tunnel surface, the heaters and the surrounding rock are completely instrumented.

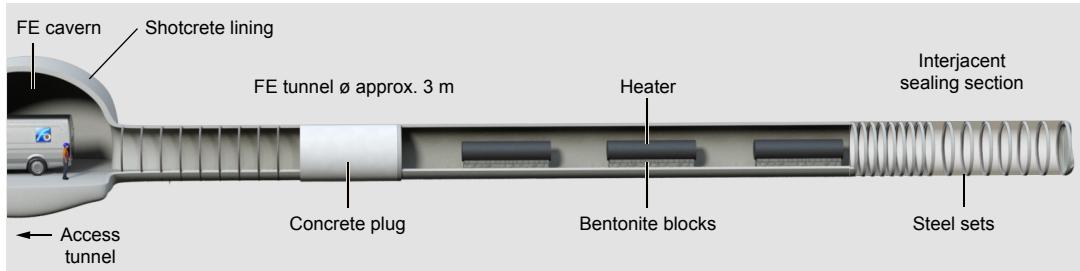


Fig. 6-2: The FE experiment designed and constructed at the Mont Terri URL.

Heating started early 2015, with a planned duration of 10 to 15 years.

2000 sensor readings are recorded every 10 minutes. Among other data, the evolution of the parameter fields for temperature, hydraulic pressure, strain and relative humidity are continually monitored. Novel monitoring technologies such as fiber-optic monitoring of deformation and geophysical monitoring of resaturation have been implemented. A prototype machine has been developed and tested for the backfilling of the tunnel with an optimised granular bentonite material (Fig. 6-3). The backfilling process successfully exceeded the target emplacement dry density of 1.45 Mg/m^3 .



Fig. 6-3: Construction of the FE experiment in the Mont Terri URL (photo: Comet photoshopping).

Operation of the granular bentonite backfilling machine designed to demonstrate the emplacement feasibility according to the requirements (overall emplacement density of 1.45 Mg/m^3).

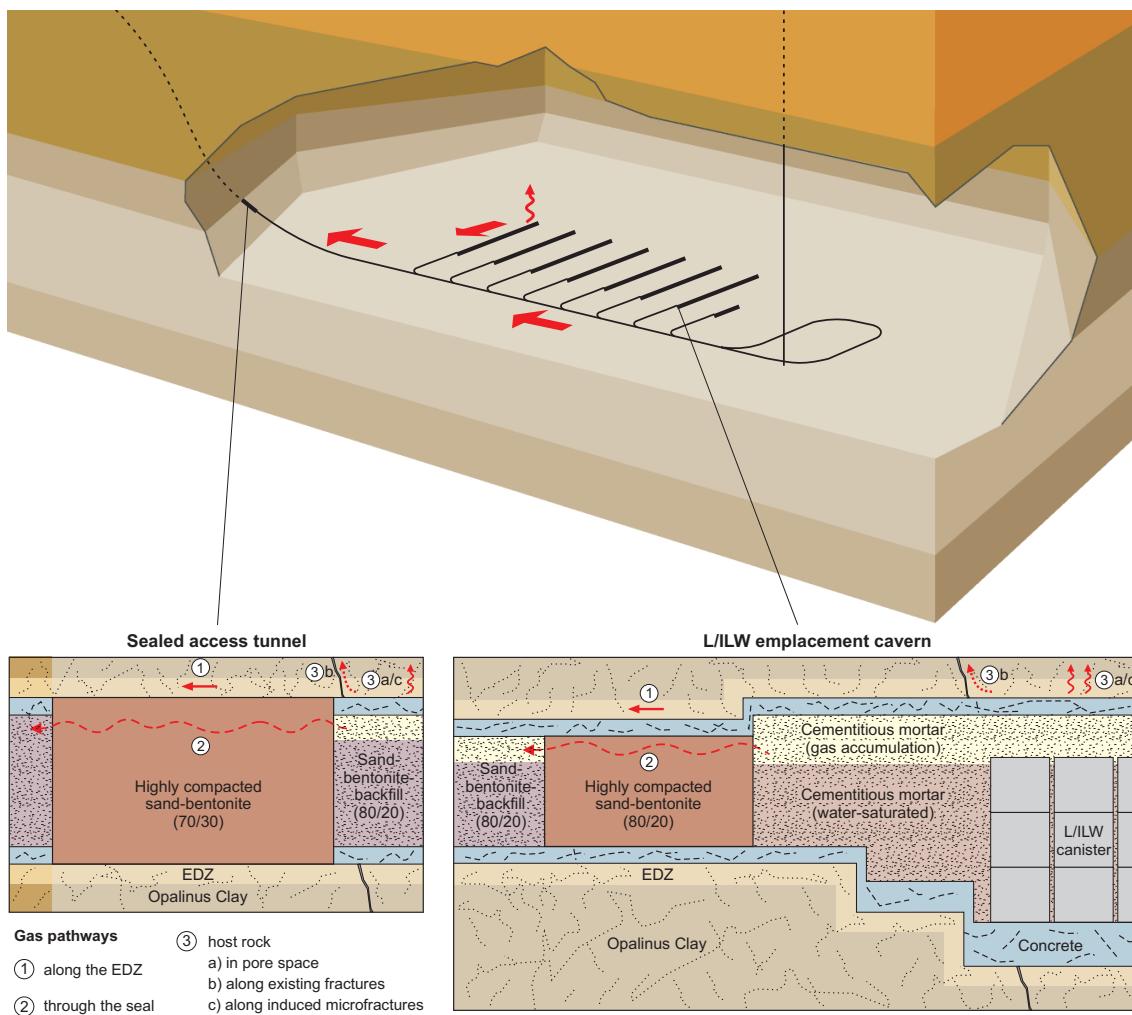


Fig. 6-4: Potential gas transport pathways for degradation and corrosion gases accumulated in the emplacement caverns of a L/ILW repository (Nagra 2008g).

During the past several years, development work on concepts for disposal canisters for SF and HLW has continued. The objective has been to explore possible options, as it is not expected that a final canister design, including materials, would be chosen before about 2040, given that the repository implementation date is foreseen to be about 2050. Studies have included exploration of a wide range of options based on corrosion, fabrication and structural loading considerations (Holdsworth et al. 2014), which showed that the most suitable solution would be a concept that combines a corrosion-resistant external shell that has both a low corrosion rate and a low or negligible hydrogen production rate with an internal structure fabricated from steel or cast iron to provide the necessary structural strength. Other studies include a detailed design study for carbon steel canisters (Patel et al. 2012) and an ongoing collaborative programme of work with NWMO (Canada) on a copper-coated canister concept (see section 7.4.5).

GAST Experiment

The Gas-permeable Seal Test (GAST) aims at i) demonstrating the effective functioning of gas-permeable seals on a realistic scale and with realistic boundary conditions ('proof of concept'); ii) validating and, if necessary, improving current conceptual models for the resaturation and gas invasion processes into sand/bentonite (S/B) seals; iii) determining upscaled two-phase flow parameters for S/B seals. The experiment concept reflects the engineered gas transport system (EGTS), which has been developed to increase the gas transport capacity of the backfilled underground structures without compromising the radionuclide retention capacity of the engineered barrier system (Nagra 2008g).

The test has been constructed at the end of a 3.5 m diameter tunnel, excavated with a tunnel boring machine (TBM). The granitic rock at the GTS provides a stiff boundary with a negligible excavation-damaged zone (EDZ) with a hydraulic conductivity in the same range as, or lower than, that of the seal. The seal element (Fig. 6-5) consists of 23 layers of compacted sand/bentonite with a length of 8 m and target intrinsic permeability of 10^{-18} m^2 . Vertical sand filters were emplaced at both ends for later water and gas injections. Two walls made of compacted bentonite blocks and granular bentonite constituted the watertight seal at the tunnel end and at the confining bulkhead. Sensors are placed at the rock wall and at the tops of selected sand/bentonite layers. Cables and lines from the sensors are routed to the risers and then to the main duct that runs below the seal as shown in Fig. 6-5.

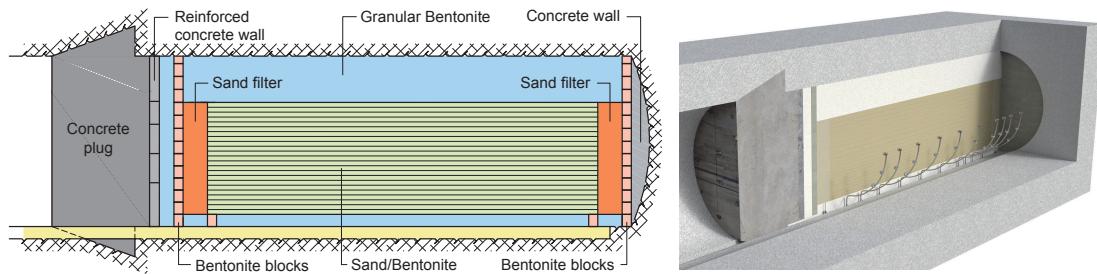


Fig. 6-5: GAST experiment layout (left) and cut-away visualisation (right) showing the sand/bentonite and granular bentonite bodies, the instrument risers and the main duct.

The GAST experiment was constructed in 2011 – 2012 and the currently ongoing saturation phase is expected to last until around the middle of 2017. It will be followed by various gas injection tests and a rigorous dismantling programme.

Studies supporting the safety analyses of Stage 2 of the Sectoral Plan

Preparation of the proposals for the siting regions for Stage 2 of the Sectoral Plan involved selecting at least one site for the surface facilities in each of the geological siting regions as well as narrowing down the number of siting regions to at least two for each repository type based on safety considerations (see section 3.1.1). In addition to applying the broad engineering- and safety-related criteria to each of the potential sites, it was also necessary to perform comparative provisional safety analyses (Nagra 2014c and 2014e).

Much of the underlying research work for these safety analyses was done at PSI-LES (see section 5.3) and involved a comprehensive updating of the parameters and data used in models for radionuclide release and transport. A large number of individual databases containing sorption coefficients in cementitious environments (Wieland 2014), bentonite and the different host rocks and their confining units (Baeyens et al. 2014a) were expanded and revisited based on new experimental evidence. In addition, further diffusion studies were performed and databases for diffusion coefficients in bentonite and in the different host rocks and their confining units

(Van Loon 2014) and solubility constants in cement (Berner 2014b) and clay environments (Berner 2014a) were reviewed and reassessed. Besides providing databases, work was done on modelling HLW repository near-field evolution (e.g. reactive transport modelling at the cement-clay interface (Nagra 2014f, Kosakowski & Berner 2013) or steel-bentonite interface (Bradbury et al. 2014, Gorski et al. 2012, Soltermann et al. 2013), in understanding fundamental processes in sorption and diffusion of radionuclides on argillaceous rocks (Gimmi & Kosakowski 2011, Glaus et al. 2011, Payne et al. 2013) and on studying the evolution of radioactive waste glass (Bradbury et al. 2014, Curti et al. 2009) and release of radionuclides from spent fuel (Curti et al. 2010, Johnson et al. 2012).

In the past 5 years, PSI-LES has obtained a vast amount of sorption data on various argillaceous rocks and MX-80 bentonite in order to thoroughly test the methodology developed (Bradbury & Baeyens 2011, Marques Fernandes et al. 2015; Fig. 6-6) for deriving sorption values based on clay mineral content and porewater composition. In all, a total of 53 isotherm datasets comprising the elements Cs(I), Co(II), Ni(II), Eu(III), Th(IV) and U(VI) on Opalinus Clay, 'Brauner Dogger', Effingen Member, Helvetic Marls and MX-80 bentonite have been measured (Baeyens et al. 2014b). These measured data can be compared with blind predictions. When the results are expressed as the ratio of the predicted values to the measured values, i.e. $R_{d,pred}/R_{d,meas}$ (with R_d the sorption distribution coefficient in L/kg), it can be readily seen that about 80 % of the blind predictions lie within a factor of ± 3 of the measured values, i.e. $3 > R_{d,pred}/R_{d,meas} > 0.3$, and can be considered as being essentially the same. The factor of ± 3 is the uncertainty factor associated with the source measurements on 2:1 type clay minerals and the cation-exchange modelling approach for Cs(I). The results can be visualised by plotting the measured R_d values (x-axis) against the predicted values (y-axis) for all those metals exhibiting surface complexation as the major sorption mechanism. Based on this result, it can be concluded that the methodology applied for deriving sorption values, within the uncertainty bounds given, is strongly supported by this study on argillaceous rocks and bentonite.

Overall, the improvements in understanding have considerably reduced the uncertainties in modelling radionuclide transport in the safety assessments.

Natural tracers in porewater provide independent arguments for the barrier function of the host rock and for diffusion coefficients at formation scale. The Rock-Water Interaction Group at Uni Bern (section 5.3) led a synthesis report including case studies worldwide (Mazurek et al. 2009 and 2011). The studied tracers also include noble gases (Rufer & Waber 2015). The hydrochemistry and isotope hydrogeology of deep groundwaters provide independent arguments related to transport times in deep flow systems and the aquifer-specific hydrochemistry provides evidence of the barrier function of the aquitard in between (Waber et al. 2014).

The thermal stability of bentonite has been examined in detail in a joint study involving Uni Bern and Nagra, as well as Clay Technology and SKB in Sweden (Leupin et al. 2014). The study provided strong evidence of the long-term stability of bentonite, even in the case of near-field temperatures that considerably exceed 100 °C for the first few decades after waste emplacement, as is the case in the present Nagra concept.

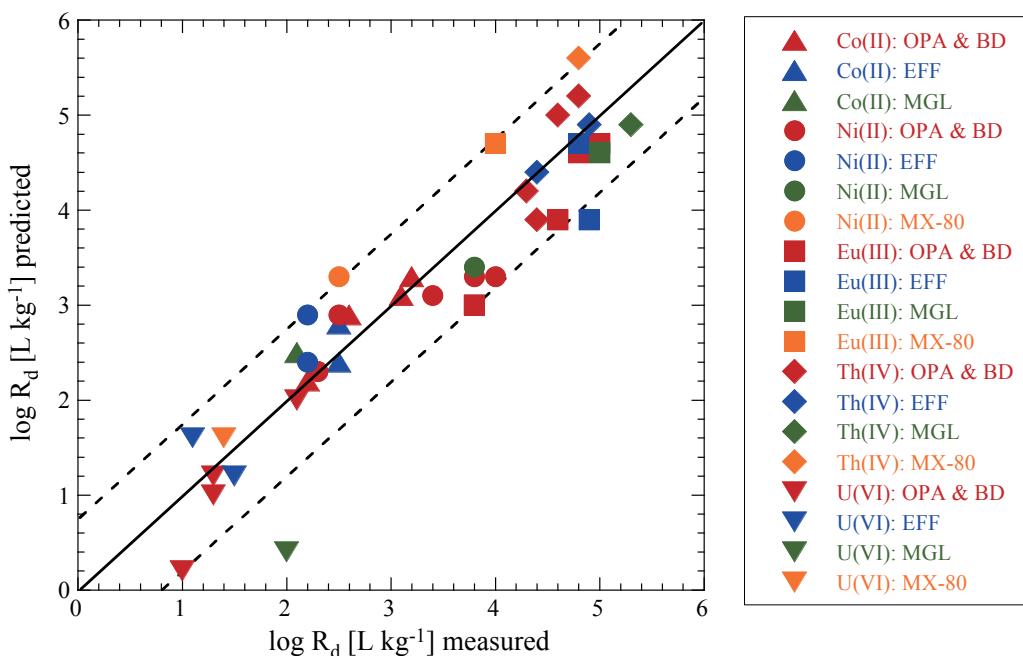


Fig. 6-6: Overview of the comparison of measured and predicted sorption data for Co(II), Ni(II), Eu(III), Th(IV) and U(VI) on different rock types and MX-80 bentonite.

Taken from Baeyens et al. (2014b). The broken lines represent a band width of $\pm 0.8 \log$ units.

Gas generation and transport are important issues in safety assessments of both HLW and L/ILW repositories. New data have been obtained on the corrosion rate of steel in the L/ILW repository (Newman et al. 2016). For these conditions, which are dominated by high-pH cementitious materials, the corrosion (gas generation) rate appears to be considerably lower than the values estimated in previous safety assessment studies. In addition, gas transport through the Opalinus Clay has been studied in more detail in the laboratory, in-situ at Mont Terri and through modelling studies (see section 7.2.3.2). The results have increased confidence in the reliability of the gas transport models used in safety assessment and in understanding the effects of gas on the host rock (see section 6.4.3).

An important recent development is the detailed assessment for both HLW and L/ILW repositories of thermal, mechanical, hydraulic, gas and chemical effects on the host rock, performed to determine if potentially detrimental effects can be avoided or reduced to levels below significance (see section 6.4.2).

6.3 International status of RD&D for disposal of HLW and L/ILW

6.3.1 The Swiss schedule for repository implementation in a worldwide context

The RD&D studies of Nagra's programme can take advantage of the developments in other countries, in particular because these developments in most cases precede those in Switzerland. Schedules for implementation of deep geological repositories for L/ILW and for alpha-toxic or long-lived intermediate-level waste in a number of countries are given in Fig. 6-7. Near-surface disposal facilities for LLW, of which many are in operation worldwide, are not included, although relevant information is also available for these repositories.

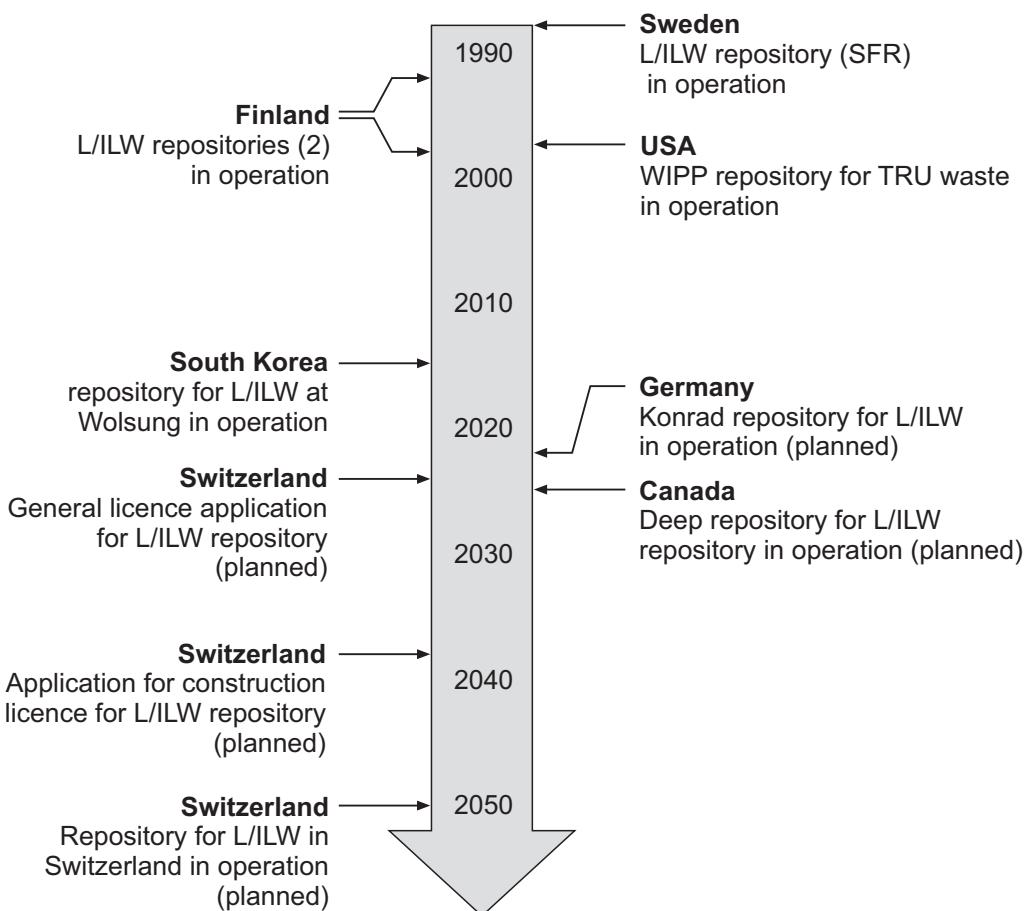


Fig. 6-7: Comparison of some key milestones for development of geological repositories for L/ILW in several countries.

Substantial operational experience exists for L/ILW repositories as some of these facilities have been in operation for over thirty years. The SFR facility in Sweden began operation in 1988 and an application was made by SKB in 2014 to triple the capacity of the repository to permit inclusion of some of the wastes from reactor decommissioning, including reactor pressure vessels. It is apparent from the operational experience with L/ILW repositories that, for the Swiss L/ILW repository, it will be important to take stock of lessons learned from operational incidents and corrective actions. Nonetheless, the fact that most of the operating L/ILW repositories are in fractured crystalline rock suggests that there will be some differences relative to a repository in sedimentary rock, e.g. the much more limited water inflow in sedimentary rock. From the technology development perspective, the concept of controlling gas release from a L/ILW repository with a gas-permeable seal (see section 6.2) appears to be unique to the Swiss programme.

A similar comparison for HLW repository implementation is given in Fig. 6-8. The summaries in both cases are not comprehensive, but are intended to draw attention to the developments in other countries that significantly precede those in Switzerland. The significance of this is that it is reasonable to assume that there are, and will be, many relevant technical developments in these projects that may be expected to enhance the diversity and knowledge base of proven options available to deal with various safety, design and technical development issues in the Swiss programme. Some specific examples that are particularly relevant are discussed in the following section.

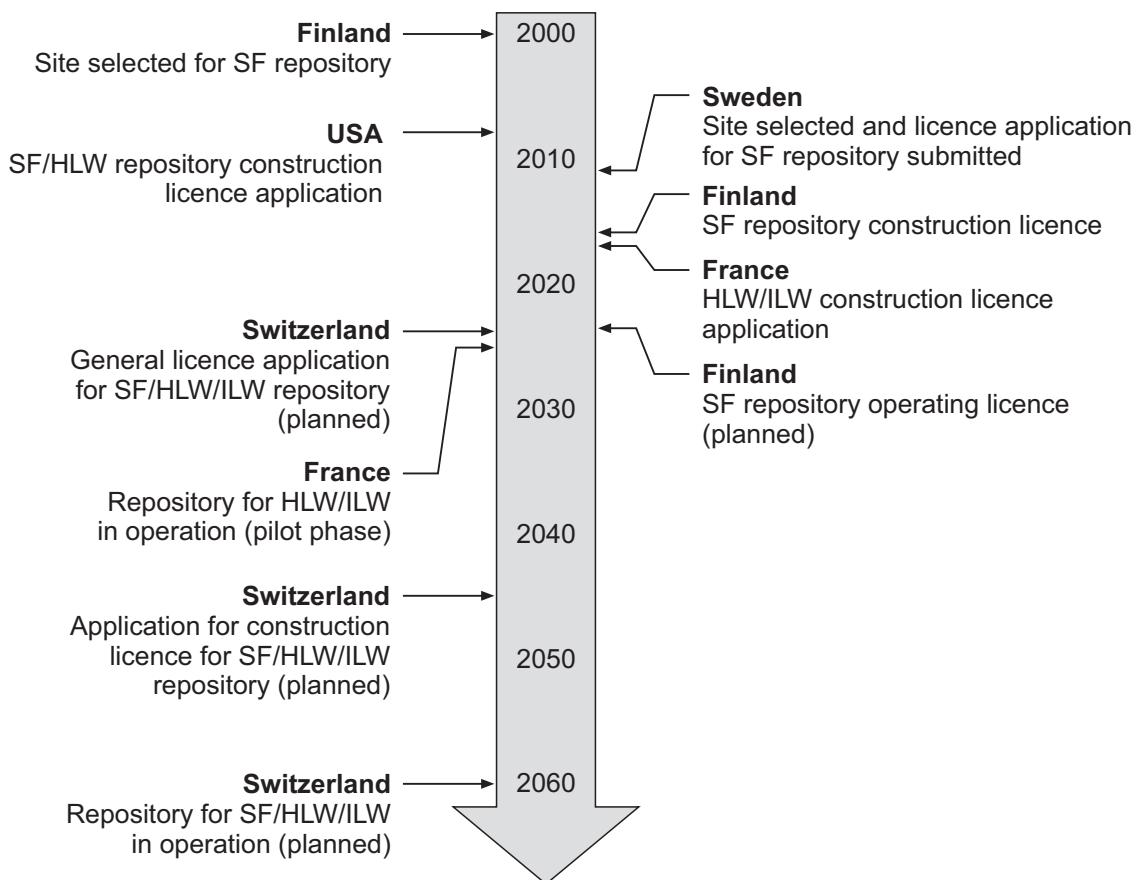


Fig. 6-8: Comparison of some key milestones for development of geological repositories for SF/HLW in several countries.

6.3.2 Status of technology development and demonstration in programmes closer to the construction of a SF/HLW repository

Introduction

Technology development and demonstration work for HLW repositories has advanced significantly in many countries in recent years. In particular, full-scale fabrication of several types of SF disposal canisters has been achieved, as well as fabrication of large buffer and backfill blocks. An important complement to the block fabrication work is the demonstration of full-scale emplacement of backfills and tunnel seals to demanding quality requirements. Studies at several underground research laboratories on tunnel construction and ground support have also progressed significantly. These advances, which have taken place in several national programmes through intensive national efforts, cooperative multi-lateral projects (e.g. the EU LUCOEX project, LUCOEX 2016) and bilateral work programmes (e.g. the KBS-3 copper canister studies of SKB-Posiva and the copper-coated canister studies of NWMO-Nagra), are briefly summarised below, along with comments on expected future developments. The extensive cooperation among disposal programmes leads to valuable synergies and ensures that many different approaches are developed and tested and permits all waste management organisations to profit from the results.

Technology development and demonstration for fabricating buffer and backfill blocks

Pre-compacted blocks of dense bentonite are an essential component in spent fuel disposal concepts in crystalline rock (see Fig. 6-9), such as KBS-3V (borehole emplacement) and KBS-3H (in-tunnel emplacement), as well as in the Nagra horizontal waste emplacement drift concept. Furthermore, such blocks may also be used in the construction of seals in large diameter (up to 5 m) access tunnels in both crystalline and clay rock repositories. The demonstration of such technology at full scale and under industrial conditions is now the focus of attention in several national programmes.

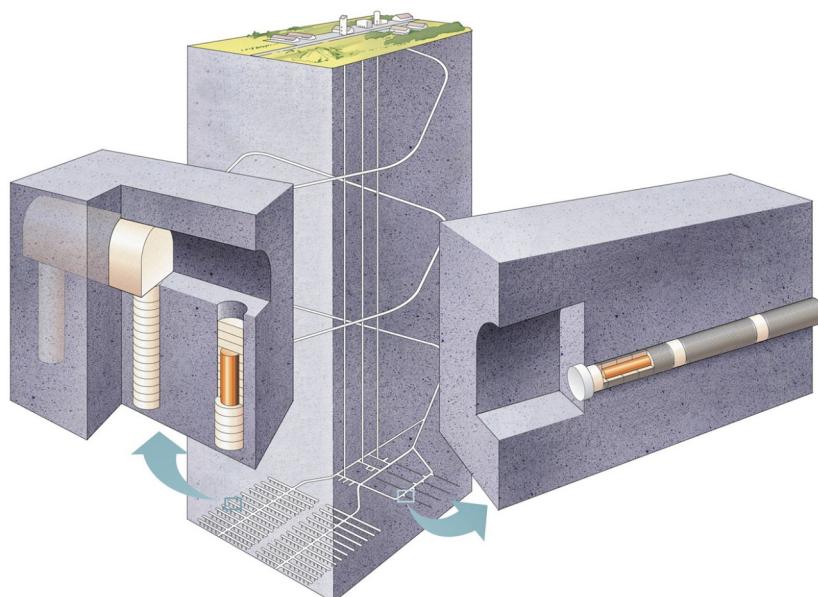


Fig. 6-9: The concepts proposed by Posiva (Posiva 2012b).

Posiva (Peura et al. 2015) has successfully scaled up the isostatic compaction method for MX-80 bentonite blocks from laboratory scale to 2/3 scale over the past few years, with the goal of achieving industrial fabrication of full-scale (1.7 m diameter) blocks by 2017. In addition, they are developing uniaxial compaction technology for preparing backfill blocks with dimensions of $\sim 0.5 \times 0.5 \times 0.3$ m. SKB studies (Eriksson 2014) of uniaxial compaction of full-scale rings and discs of MX-80 show that such blocks can be fabricated, but that equipment improvements along with more experience are required in order to reliably produce high quality blocks at industrial scale.

Technology development and demonstration for granular bentonite backfills and seals

Dense bentonite granulates and granulate/powder mixtures are invaluable for filling of irregular void spaces in repository tunnels, as in the case of Nagra's horizontal waste emplacement concept, for emplacing tunnel seals and for filling gaps between bentonite blocks and the host rock, as in the case of the KBS-3 concept. The technology for producing high density granular bentonite is now fully developed and considerable success has been achieved in emplacing compacted bentonite granulates and mixtures at full scale. Notable examples are the FE experiment at Mont Terri (Köhler et al. 2015, see also section 7.4.4.2) and the Full Scale Seal experiment (FSS) of Andra (Bosgiraud et al. 2014, see discussion below), which in both cases met the overall average density requirement.

Technology development and demonstration of constructing full-scale tunnel seals

Deep geological repositories of all types require a large number of tunnel and shaft seals that act as hydraulic barriers, as well as tunnel plugs that may have a mechanical restraint function without a stringent hydraulic flow requirement. Tunnel and shaft seals, as well as plugs, are located some distance from the heat-producing wastes. Depending on the repository design requirements, these seals may be of composite construction, typically comprising low-pH concrete (to minimise alteration of bentonite) with a crushed granule/powder bentonite mixture that can be emplaced with augers. Andra (Bosgiraud et al. 2014) recently completed full-scale construction of a seal of this type in a mock-up of a tunnel in an above-ground facility. An emplacement dry density of about 1.5 Mg/m³ of the bentonite was achieved and emplacement of low-pH concrete was successful. The experiment allowed the identification of improvements that will be needed for full-scale demonstration of seal emplacement underground. In another sealing test at the Meuse-Haute Marne URL, Andra implemented a procedure to fully seal a gallery over a length of five metres with a bentonite plug, which was hydrated using water injectors to observe the swelling pressure on the gallery walls.

Technology development for construction of SF/HLW disposal canisters

SKB and Posiva have both made great progress with development of the copper canister with cast iron insert for the disposal of spent fuel. Large numbers of prototype canisters have been produced by both organisations. This canister type has been incorporated into the repository designs of SKB and Posiva, for which the site licence (SKB 2011) is currently favourably reviewed and the construction licence (Posiva 2012a) was granted.

Depending on specific requirements for repositories for SF and HLW in different rock types, Nagra canisters for the disposal of SF and HLW are expected to be constructed either from carbon steel alone or from copper with a cast iron or steel internal structure that provides the necessary mechanical strength. Some other options have been considered for canisters, e.g. ceramics or steel canisters coated with corrosion-resistant metals such as nickel or titanium. Examination of the requirements for disposal canisters suggests that ceramic canisters are unlikely to be acceptable from a mechanical strength perspective (Holdsworth et al. 2013). Coatings other than copper may be feasible but little technical development work has been done to assess how such coatings would be applied, principally because of the generally satisfactory outcome of studies of copper fabrication and coating technologies (see section 7.4.5).

NWMO (Canada) have done extensive development work on copper-coated steel canisters (see section 7.4.5). Recent work has included construction of two full-scale prototype disposal canisters for SF.

Andra (2005) has constructed prototype carbon steel canisters for the disposal of SF and HLW.

Technology development for tunnel excavation and support

Clay rocks pose particular challenges in terms of ensuring tunnel support that is suited to the special requirements for HLW repositories. These requirements include the need to ensure stability of waste emplacement drifts in a manner compatible with long-term safety requirements. Special demands include limiting the significance of thermal, rock mechanical, gas-related and chemical repository-induced impacts on the host rock (see Leupin et al. 2016a and b).

Nagra's excavation work performed in anticipation of the FE experiment (see section 7.4.3) at Mont Terri involved constructing a 3 m diameter, 50 m long tunnel parallel to the strike of bedding and to a fault zone using two different tunnel support systems (low-pH shotcrete and steel arches). Despite some challenges, the support methods were successful. Nonetheless, more work is required, some of which can only be done when rock at the repository depth (500 – 800 m) is available for test construction work.

At Andra's URL at Meuse-Haute Marne, some industrial tests were completed focusing on solutions for operation of a disposal facility. Tests included construction drift excavation using a road header and laying of concrete ground supports. In 2013, a road header boring machine, whose toothed head fits on an articulated arm and is able to cover the full cutting face over a diameter of more than 7 m, was used to construct a test gallery. As tunnelling progressed to a length of 83 m, prefabricated concrete segments were placed to support the gallery. The rock is instrumented to measure the response and the effectiveness of the support method.

6.4 Integration of the recent RD&D results in the safety assessments and for optimisation

6.4.1 Introduction

At regular points in the programme, for example as part of the reporting by Nagra for Stage 1 and Stage 2 of the Sectoral Plan, but also in anticipation of the future development of the safety cases, the whole body of RD&D results in one specific or multiple areas is interpreted and integrated into syntheses. The syntheses either support decision-making or feed directly into the safety assessments. Appropriate optimisation measures that would bring additional benefits in terms of safety are documented and reviewed. The appropriateness of such measures is interpreted in an overall context (i.e. also considering operational safety, long-term safety, safety during transport, personal doses, arisings of new wastes, etc.) where this is relevant.

The integration of the RD&D activities related to geological aspects and siting has occurred most recently in the reports supporting the proposals for Stage 2 of the Sectoral Plan (Nagra 2014a).

Two other recent examples illustrating this integration and optimisation are discussed in the following paragraphs. They concern the assessment framework that was developed and applied for bounding the impact of repository-induced effects on the Opalinus Clay on one hand and the assessment of gas generation, consumption and transport and their consequences for the safety of deep geological repositories on the other hand.

6.4.2 Assessments performed to bound the impact of repository-induced effects

Regulatory long-term protection criteria (see definitions in section 4.1) are expected to be met provided the disposal system performs adequately as it evolves over time, with its components fulfilling their various safety functions. During the evolution of the system, a number of events and processes may occur that could potentially be detrimental to these safety functions. Many have potential impacts that are complex, with coupling between thermal, hydraulic, mechanical and chemical effects (e.g. thermal and gas pressure impacts on the hydro-mechanical state of the rock and the engineered barriers). Some events and processes, such as major climatic changes, are external to the disposal system. Others, such as the heat generated by the waste and gas

generated by the corrosion of engineered materials, are internal. The effects of such processes on the host rock are termed "repository-induced effects" and have recently been evaluated in Leupin et al. (2016a and b). Repository-induced and other potentially detrimental effects can, in some instances, be avoided or reduced to insignificance by an appropriate choice of concept and design. However, others will inevitably remain and the performance of the disposal system must be robust enough that the regulatory criteria are nevertheless met. Showing that this is the case is a key role of safety assessment.

Nagra has developed sets of safety function indicators to assess the potential significance of repository-induced effects on the repository safety functions. It was also defined how high (or low) the criteria or values related to these indicators, which are key parameters defining repository evolution, need to be before adverse consequences for the safety functions could potentially arise. The capacity of the current repository concepts to meet these criteria or values has also been tested in qualitative and quantitative assessments. The repository-induced effects included in the assessment are of the following broad types (their state-of-the-art is described in Chapter 7):

- **Thermal effects** (see section 7.5.2): the effects on the host rock and engineered barriers arising principally from the heat generated by the HLW waste; thermal effects can be assessed by measuring the state variables temperature and heat flow.
- **Rock mechanical effects** (e.g. see section 7.5.3.4): the effects arising from the mechanical disturbance to the host rock caused by the excavation of the emplacement rooms and other underground structures; rock mechanical effects can be assessed by evaluating the state variables stress and strain.
- **Hydraulic and gas-related effects** (e.g. see section 7.5.2): the effects of repository resaturation and of gas generation, e.g. due to the corrosion of metals within the repository, on the host rock and engineered barriers; these hydraulic and gas-related effects can be assessed by evaluating the state variables degree of saturation, specific flux of gas/water and porewater pressure.
- **Chemical effects** (e.g. see section 7.5.3.5): chemical interactions between the waste, the engineered materials and the host rock, but with the focus on chemical effects of the waste and engineered materials on the host rock.

It is important to not only consider direct (i.e. thermal, rock mechanical, gas-related and chemical) consequences of repository-induced effects, but also the coupling between them.

The datasets and indicators/criteria proposed (such as gas pressure build-up, rock mechanics and thermal effects) to assess the repository-induced effects are based on generic situations and repository configurations and will become more detailed as repository implementation proceeds. The safety function indicators defined in Leupin et al. (2016a) for a HLW repository are shown in Tab. 6-2.

The methodology adopted comprises the following broad steps:

1. describing the assumed repository concept
2. identifying and describing processes with potentially adverse effects on the safety functions of the barriers
3. making a first qualitative assessment of these effects based on pre-existing data

4. if significant adverse consequences cannot be excluded on qualitative grounds, making a quantitative assessment of these consequences, including, if necessary, radionuclide release and transport calculations
5. based on the insights from Steps 1 – 3, providing input to concept and design development of the repository with the aim of avoiding, minimising or mitigating effects that may have a significant and detrimental impact on repository safety.

Tab. 6-2: Safety function indicator criteria for the assessment of repository-induced effects in a high-level waste repository (after Table 4.1-1 of Leupin et al. 2016a).

| Effects | Relevant process | Potential safety function indicator criteria |
|-------------------|---|--|
| Thermal | Thermal effect on the host rock | Maximum temperature |
| | Thermally induced increase in porewater pressure | Pressure maximum |
| Mechanical | Formation EDZ | EDZ radial extent and hydraulic conductivity |
| | Effect of the EDZ (and other processes in the near-field) on the buffer swelling pressure/density | Maximum and minimum density of the buffer |
| | Vertical propagation of faults related to the formation of the EDZ | Vertical extent of the EDZ |
| | Effect of the EDZ – convergence interaction | Advective water flow (convergence-induced water flow) |
| Gas and hydraulic | Gas pressure build-up | Gas pressure (threshold for pathway dilation and gas fracking) |
| | Gas-induced porewater displacement through the host rock | Porewater displacement |
| Chemical | Degradation of concrete emplacement room liner | Loss of safety-relevant properties of the engineered barriers |
| | Iron-clay interactions | Loss of safety-relevant properties of the engineered barriers |

When assessing the potentially adverse consequences for the safety functions, current understanding of these effects and all associated uncertainties are taken into account. Specific aspects that are assessed include:

- **the reversibility of any impact:** if the impact of a process is reversible, then its adverse consequences are likely to be more limited than if it is irreversible
- **the relevant time period:** some effects occur for only a limited time period (e.g. in the case of thermally induced effects, the period during which high-level waste generates significant heat) and, if radionuclides are fully contained during this period (and if the impacts are reversible), then there may be few if any consequences for repository safety

- **the spatial extent of any impact:** some processes will be spatially limited, e.g. to the repository near-field only, whereas others may propagate further into the repository host rock
- **the relevance to siting:** given that an objective of the Sectoral Plan is to narrow down the number of suitable sites, any relevance of site-specific conditions for the adverse consequences of repository-induced effects is clearly of interest.

Where significant detrimental impacts on the safety functions cannot be excluded on qualitative grounds, a quantitative assessment of impacts is carried out. If the limits can be shown not to be reached for any reasonably plausible path of evolution, then the corresponding adverse consequences can be excluded.

If significant detrimental impacts on the repository safety functions cannot be excluded, e.g. if safety function indicator criteria (or limits) cannot be formulated, or if the criteria could not unequivocally be shown to be met, then additional radionuclide release and transport calculations are carried out to evaluate the nature and extent of any detrimental effect and to assess the implications in terms of safety indicators, principally the regulatory protection criterion.

The site-specific characteristics of the host rock are, where relevant, also taken into account:

- when formulating the safety function indicator criteria, and
- when performing analyses to test whether the criteria are met.

Thus, the assumptions and parameter values used are intended to cover the full range of expected conditions in the potential siting regions. The expected conditions are therefore based, where possible, on site-specific field observations and measurements, complemented by laboratory experiments, supporting calculations and, where necessary, expert judgement. Expert judgement is required because not all the characteristics of the potential siting regions are well known at the present stage of the programme. Thus, especially for poorly described and potentially sensitive characteristics, some more extreme model assumptions and parameter values are considered that are outside the ranges expected at the potential siting regions but are still physically plausible, in addition to realistic assumptions and parameter values. The more extreme calculation cases illustrate the robustness of the repository concept by showing that, even under highly pessimistic or hypothetical assumptions, the nature and extent of any detrimental effects is still insufficient to compromise safety. An example of this type of calculation is that of porewater flow and radionuclide transport along the EDZ of the repository tunnel system, assuming a hypothetically very high EDZ hydraulic conductivity, even though the expected evolution is that the EDZ, once formed, would reseal to some extent.

The results show that these repository-induced effects can be kept below levels that significantly perturb the host rock.

The methodology as described and applied in Leupin (2016a and b) will be refined and revisited during SGT Stage 3 once the site descriptive models of the remaining sites are updated with the information from the field investigations.

6.4.3 The assessment of gas generation, consumption and transport and the consequences for the safety of deep geological repositories

In a deep geological repository for radioactive waste, in the absence of oxygen and presence of water, corrosion of various metals and alloys will lead to hydrogen formation. If present, organic wastes will slowly degrade and generate carbon dioxide, methane and other gaseous species. Depending on local conditions, microbial activity could consume a part of the produced gas. However, if the resulting rate of gas generation exceeds the rate of diffusion of dissolved gas molecules in the pores of the engineered barriers or the host rock, the solubility limit of the gas will eventually be exceeded and the formation of a discrete gas phase will occur. Gas could continue to accumulate until its pressure becomes sufficient for it to be released. The above phenomena were the object of study of a recent Nagra report (Diomidis et al. 2016), which describes and evaluates the evolution of gas-related processes that can influence the long-term behaviour and safety of the L/LW and HLW repositories constructed in Opalinus Clay. The main aim was to present a state-of-the-art synthesis of all processes and phenomena linked to repository-produced gases and to assess their influence on repository performance. The report provides a current snapshot of the available understanding of gas sources, reactions and interactions, generation, consumption and transport. Furthermore, the current scientific understanding was used to define assessment criteria, which were employed to evaluate the influence of repository-generated gas on safety-relevant properties of the engineered and natural barrier system.

The assessment was done by employing a methodology consisting of the following broad steps. Initially, the processes leading to the generation or consumption of gas were identified and described, and a quantitative assessment of their expected rates was done based on the current state-of-the-art (sections 7.5.3.1, 7.3.3.5 and 7.2.3.6). This was followed by addressing each repository type separately. The reference repository configuration and design, as well as its expected evolution after closure, was described (sections 7.5.2.1, 7.5.2.2 and 7.5.2.3). The potential gas sources, which include the radioactive waste allocated to each repository (sections 7.3.1 and 7.3.2), barrier components such as disposal canisters (section 7.4.5), building materials (section 7.4.3) and other gas-generating repository components were quantitatively assessed. The above-mentioned information was employed in modelling the evolution of the gas generation rate and of the cumulative gas volume with time. The outcome of the gas generation modelling was used as input to the modelling of the transport of gas and the resulting repository resaturation, build-up of gas pressure and water flow (section 7.2.3.2). These results were used as performance indicators in assessing the potential consequences for safety-relevant properties of the EBS and the host rock. A common feature in the above methodology steps is that uncertainties and options were combined into specific assessment cases, which were used in a comparative manner to specify the expected ranges of safety-relevant parameters, to highlight the potential effects of mitigating measures and design options aiming to decrease the amount of generated gas, and to identify areas where further research and refinement could have the most benefit. The explored assessment cases were related to the waste inventory and the influence of waste treatment options; uncertainties regarding the rates of heat production and gas-generating and -consuming processes along with interactions between them; alternative materials, packaging, emplacement and construction technologies; options regarding the design of repository components such as plugs and seals and uncertainties related to the two-phase flow and thermal properties of the repository components, the excavation-damaged zone and the host rock.

The main outcome of the assessment is that, for a pessimistic base case, and even for upper bounding cases, gas production in the HLW and L/LW repositories does not compromise the post-closure safety functions of the host rock and the engineered barriers (Fig. 6.10). In all the cases explored, there is a safety margin with regard to the defined safety criteria. Moreover, there are several options available which can further mitigate the consequences of gas production in the repositories.

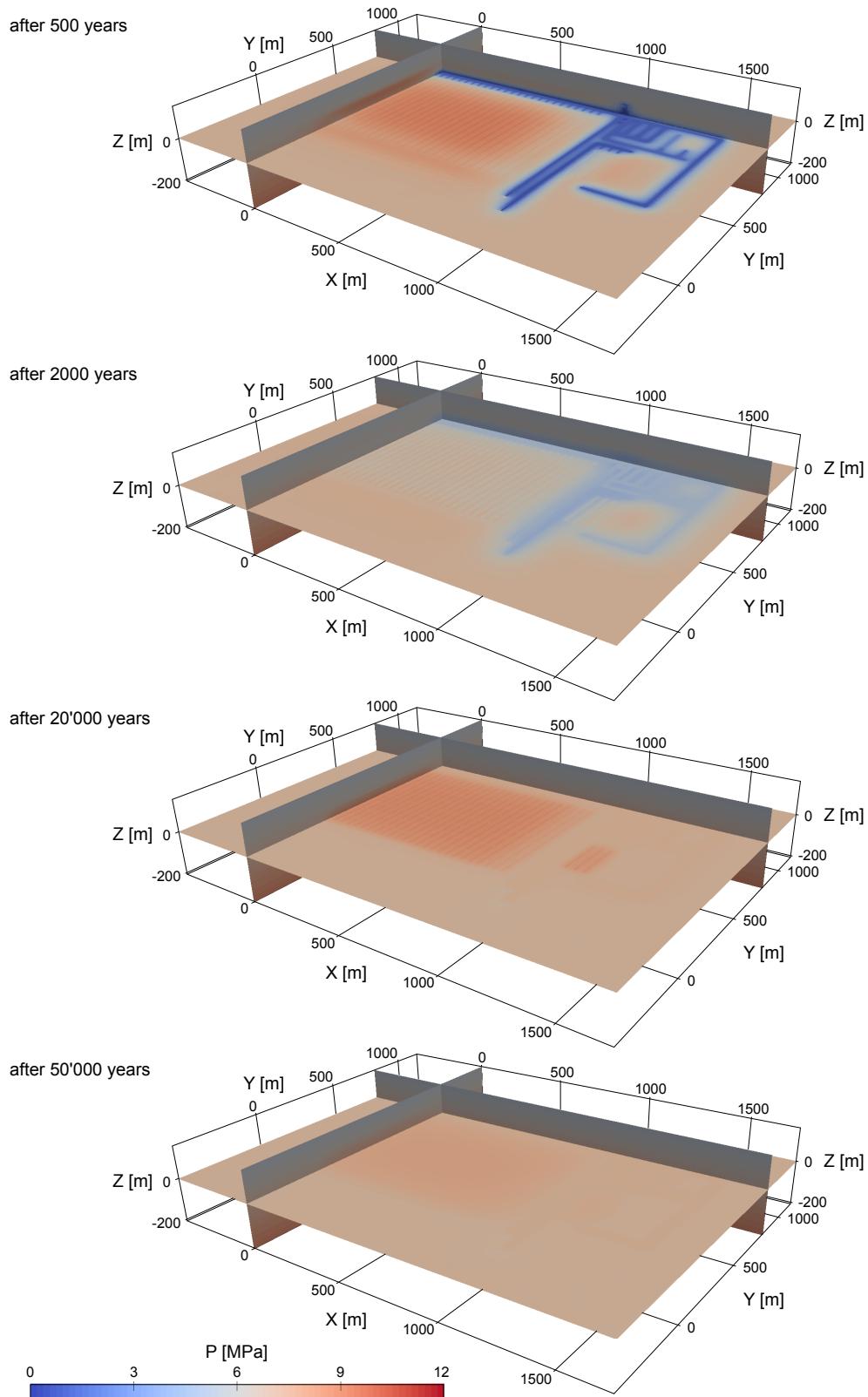


Fig. 6-10: Illustration of the pressures in the HLW repository modelled using a thermo-hydraulic code after 500, 2,000, 20,000 and 50,000 years as a consequence of heat generation, gas production and natural resaturation based on the assumptions in the "base case" (Diomidis et al. 2016).

More specifically for the L/ILW repository, it has been shown that gas production is dominated by H₂ resulting from corrosion and is mainly influenced by the amounts and geometric properties of carbon steel, the associated corrosion mechanisms and rates, as well as the environmental conditions that prevail during the time period for safety assessment. Focused RD&D activities in these areas can decrease the range of uncertainties and increase the accuracy of predictions. It has also been shown that alternative waste packaging technology and treatment of metallic waste by melting can decrease the total amount of repository-generated gas. The build-up of overpressure and resulting porewater displacement can be further controlled by optimising the conditions in the backfilled repository structures so that gas-consuming microorganisms can thrive, and by tailoring the permeability of the engineered gas transport system.

In the case of the HLW repository, corrosion is again the dominant gas-producing process. The major source of gas is the carbon steel disposal canisters, accounting for about 80 % of the total gas volume. As a result, the repository-generated gas can significantly be reduced, if necessary, by the use of canister materials that produce no or small amounts of gas. Further reduction of the gas volume can be achieved by alternative construction and emplacement technologies. The remaining uncertainties influencing the generation of gas are linked to the corrosion process and the environmental conditions prevailing during the period for safety assessment. Apart from gas generation, pressure build-up in the HLW repository can occur due to thermal expansion resulting from the emplacement of heat-generating waste. The thermally induced pressure peak can be similar to, or even higher than, the gas-induced pressure peak, which indicates the importance of interim storage, canister loading and repository layout. On the other hand, the two pressure peaks are temporally separated by thousands of years and thus no interaction between the two processes is expected.

7 Overview of the technical programme of work for the next 5 to 10 years

7.1 Introduction and structure of the work programme

While the current status of RD&D in general is described in Chapter 6, together with an overview of the major achievements in the Swiss programme as well as internationally and how these have been incorporated into recent assessments, this Chapter describes the objectives, scope and the nature of the activities for the next 5 to 10 years in more detail.

It should be noted that studies for both the SF/HLW/ILW and L/ILW repositories are included and are discussed together under the same thematic headings. The scope and volume of work performed specifically for the L/ILW programme to improve process understanding and development of methodology are quite limited, for the following reasons (depending on the specific programme area under consideration):

- There is a high degree of overlap and synergy between areas of work required for the SF/HLW/ILW and L/ILW programmes (e.g. safety assessment methodology, geochemical retention, cementitious materials and high-pH effects, and gas-related processes). In these areas, the scientific basis for the SF/HLW/ILW programme thus provides much of the basis for the safety assessments required for the L/ILW repository.
- The requirements on the performance of most elements are less stringent and the level of understanding for the different processes is therefore less ambitious for the L/ILW repository.
- For L/ILW disposal, there are no thermal issues in the list of RD&D items because of the low thermal output of the wastes.
- The disposal of L/ILW is considered a mature technology, as evidenced by licensing and operation of such repositories in other countries. As a result, the focus of work relates more to the overall assessment of suitable host rocks and some focused technical development issues.

The current RD&D programme described in the remainder of Chapter 7 is largely focused on providing the basis for the synthesis needed for the general licence applications for the repositories for SF/HLW and L/ILW around 2024 (and thus includes supporting the selection of the final sites). However, most activities will continue at some level beyond the submission, as described in Chapter 8.

The relationships between the major research themes addressed in this section are illustrated in Fig. 7-1.

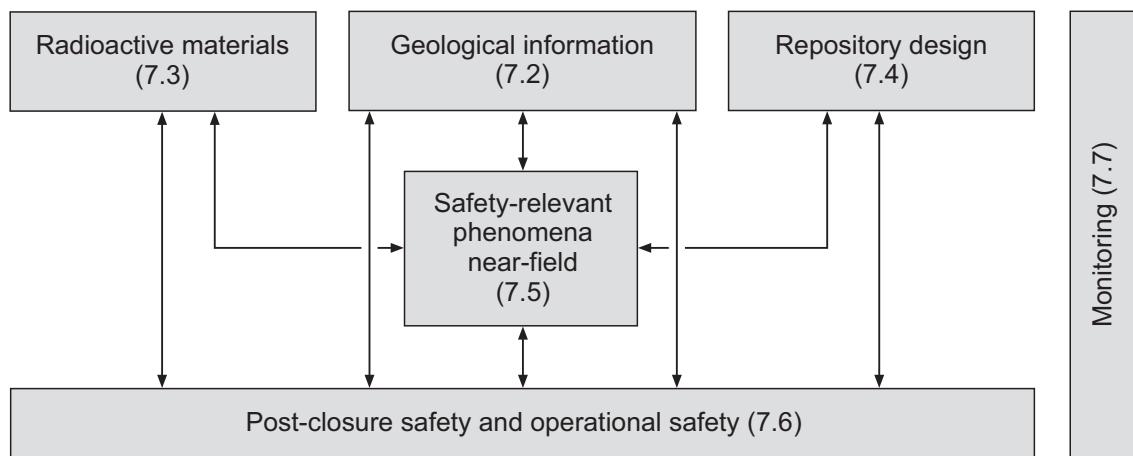


Fig. 7-1: Data and information flow between the major research themes described in the respective sections of Chapter 7.

7.2 Geological information

The geological information needed to provide the basis for making recommendations for site selection and safety case development can be divided into the following broad areas:

- Geometry of geological sequences including host rocks, confining units and regional geological elements (regional faults, overdeepened valleys due to glacial erosion, etc.)
- Properties and characteristic features of host rocks and confining units (host rock and low permeability confining units are sometimes summarised under the term *effective containment zone*, e.g. SFOE 2008)
- State parameters for key safety-relevant parameters (e.g. hydraulic heads, hydrochemical composition of pore- and groundwaters, stress)
- Long-term geological evolution (e.g. neotectonics, erosion)

In the last decades, Nagra, together with its competence centres and contractors, has developed a deep insight into the relevant aspects of the Swiss subsurface (see also section 1.3). Within the framework of the Sectoral Plan, the focus during SGT Stage 1 and Stage 2 was on using existing information through the development of state-of-the-art interpretation and modelling approaches. However, some additional information was obtained by conducting complementary analyses on core material from boreholes drilled earlier and measurements and samples from boreholes of third parties (partially also through participation of Nagra in investigations of third parties such as the Schlattingen boreholes), from observations in railway and road tunnels and, for some of the host rocks, from underground rock laboratories. The geometry of various geological units and elements was based on an additional regional 2D seismic campaign for Northern Switzerland and reprocessing/reinterpretation of existing seismic surveys of Nagra and of third parties, borehole information and some outcrop mapping. The state parameters were derived from data from boreholes of Nagra or third parties or from conceptual considerations. Finally, the assessment of long-term geological evolution was based on reviews and compilations of existing work on past landscape evolution of Northern/Central Switzerland, on Nagra's regional monitoring programme (monitoring of movements through geodetic surveys, monitoring of seismicity) and on more localised studies (e.g. detailed analysis of gravel terraces using high-resolution terrain models).

The state-of-the-art was compiled in Nagra (2014b) and the underlying reports, which describe in great detail the sedimentological and tectonic conditions, the long-term geological evolution, the geomechanical data, the hydrogeological conditions, the barrier properties of the host rocks and the confining units and the conflicts of use for all siting regions, including the proposed sites for SGT Stage 3.

In SGT Stage 3, with two sites proposed, the focus of the RD&D is now shifting towards the development of site descriptive models for each of the sites (establishing local properties, geometries and state parameters) which will serve as the basis for selecting the final sites and developing the safety case. For certain aspects, such as the long-term geological evolution including future hydrogeological conditions, regional assessments remain of high importance. During SGT Stage 3, substantial additional data based on field work from the surface (reflection seismic surveys, shallow and deep boreholes) will become available (see section 7.2.1). Nagra (2014c) concluded that, from a safety assessment point of view, the most important information will relate to the geometry and quality of the host rock and the confining units (thickness of the host rock and location and quality of lithofacial units within the confining units with the potential for strongly increased water flow). It is expected that the exploration programme will complement and/or enhance this information so that the associated uncertainties will be further reduced. For other site-specific geological information to be used directly in the safety analysis and that is important for the dose calculations (hydraulic parameters of the host rock, mineralogy of the host rock, etc.), it is not certain that the work planned for Stage 3 will achieve a significant reduction in the associated uncertainties affecting the dose calculations. However, reducing these uncertainties is not critical as the parameter values currently being used are known sufficiently accurately for the safety assessment. It is nevertheless planned as part of the exploration work for SGT Stage 3 to acquire site-specific information on these parameters, to test the conceptual models and parameters (and the associated uncertainties) used so far and to take into account the site-specific differences.

After granting of the general licence, construction of facilities for underground geological investigations is planned and exploration of the sites from underground (exploratory drifts) is foreseen (Chapter 8).

The structure of the following subsections is illustrated in Fig. 7-2.

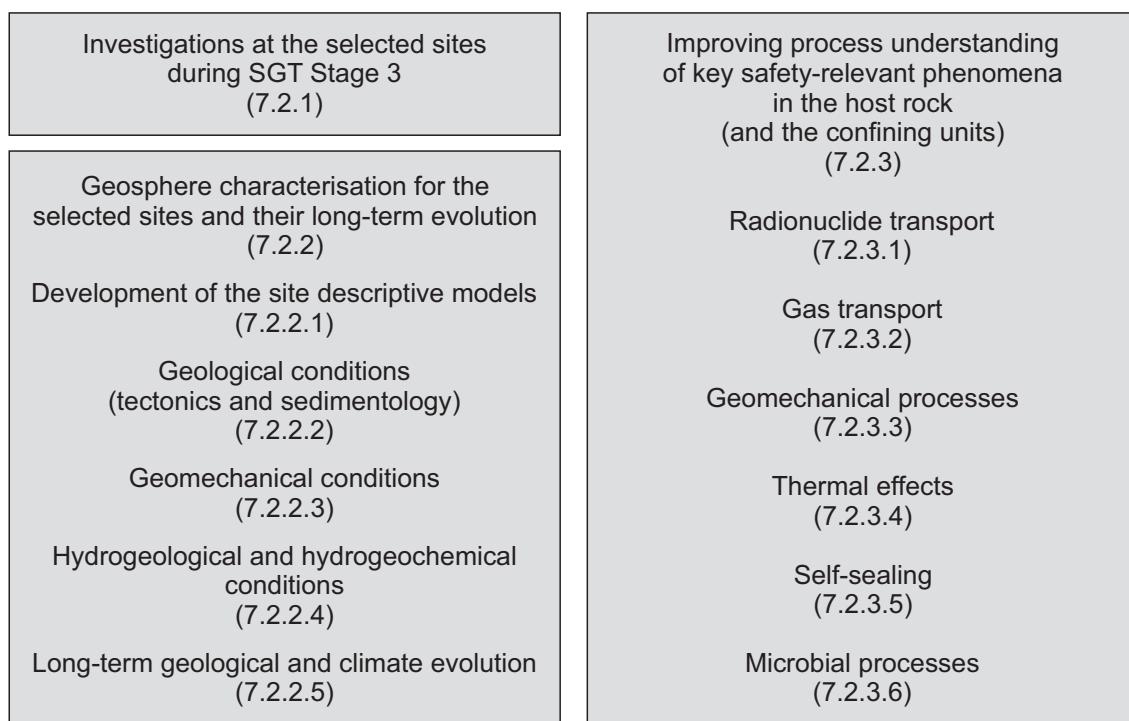


Fig. 7-2: Structuring of the RD&D activities relating to geological information and the understanding of key safety-relevant geological processes.

7.2.1 Investigations at the selected sites during SGT Stage 3

The general licence application must provide the arguments for the site selection, a safety case for the selected site and a plan for the repository at the conceptual design stage.

The aims of the site investigations in SGT Stage 3 relate directly to the legal requirements and are:

- Identify the best suited zones in the siting regions
- Provide the required database for the site selection
- Provide the database supporting the safety case for the general licence application
- Provide the basis for placement of the main repository elements

The exploration programme in SGT Stage 3 (see Figs. 7-3, 7-4 and 7-5) will complement the existing database from previous investigations; these comprise the following: (1) the 2D seismic surveys and Nagra's drilling programme in the 80s focused on the crystalline rocks of Northern Switzerland, but also cored and tested sections in the Opalinus Clay and in the surrounding sedimentary rock units, (2) the 2D seismic campaign carried out as part of the sediment study in the early 1990s, (3) the Benken borehole and the related 3D seismic investigations performed within the framework of the Project Opalinus Clay Safety Report (Nagra 2002c), (4) the 2D seismic campaigns carried out in 2011 and 2012 that densified the geometric information in the siting regions of SGT Stage 1 and Stage 2 and finally (5) a large number of third party data or participation in third party projects (boreholes of various depths for geothermal purposes but also geological surface mapping, tunneling projects, etc.).

In SGT Stage 3, information for discriminating between the siting regions potentially comes from the geology of the confining units, the local tectonic overprint and the thickness and depth situation of the host rock layer. The differences in Quaternary erosion between the siting regions may also help to find the best location for the repositories. In SGT Stage 1 and Stage 2, the regional-scale information has led to the assumption that lithological variations in the Opalinus Clay host rock are small compared to the variations in the confining units and the lithological variations in the host rock were only of subordinate importance for the safety-based comparison between the different siting regions. This assumption will have to be confirmed by the site investigation programme.

The site investigation methods applied in SGT Stage 3 will involve 3D seismic campaigns, exploration boreholes penetrating the host rock layer and, finally, investigations of the Quaternary sediments in the region (boreholes, geophysics, etc.).

The siting regions considered in SGT Stage 3 feature a foreland basin situation with a series of flat-lying, mostly marine Mesozoic and Cenozoic sediments overlying a crystalline basement or continental Permo-Carboniferous trough fillings. Many contacts between the individual geological units represent geophysical contrasts that can be readily detected using seismic methods. In such a setting, 3D seismic measurements can be successfully applied to map seismic marker horizons with high confidence. Faults penetrating the flat-lying layers can be detected by tracing offset horizons. The technique was applied successfully in the Zürich Nordost siting region in the 90s and demonstrated that faults with vertical offsets down to approximately 10 m can be identified and geometrically described in areas with flat-lying sedimentary strata (Birkhäuser et al. 2001).

The 3D seismic surveys for the Jura Ost and Zürich Nordost regions were completed in winter 2015/16. Their focus was on the host rock layer and on generating the best possible image of penetrating faults. The extent of the surveys either included surrounding regional faults or at least allowed their impact on the siting regions to be assessed by including a sufficient perimeter around the areas of interest.

Exploration drilling will be used to complement and calibrate the geometric dataset from the 3D seismic campaigns. Each borehole will deliver a comprehensive local dataset of the properties and state variable distribution in the subsurface. The boreholes will largely be performed using the wire-line core drilling technique and will thus provide samples for geological description and geochemical, hydrogeological, geotechnical and other laboratory work over the significant length of the drilling path. The boreholes will also be used for packer testing to confirm the hydrogeological properties of the host rocks and to investigate in detail the relevant properties of the surrounding units. Additionally, the geotechnical properties of the overlying units will help to plan the construction of the exploration tunnel and shaft for the facilities for underground geological investigations. Extensive borehole geophysical logging will complement the dataset, also in sections with core loss or in sections with destructive drilling.

For the exploration drilling, a substantial number of sites will be identified along the edge of the potential repository zones defined in the course of SGT Stage 2. The placement of the drill sites is aimed at protecting the best suited zones of the siting areas while simultaneously ensuring that representative site-specific data are obtained for each region.

In SGT Stage 3, Nagra's site investigations will take a flexible approach to allow adaptation to the newly acquired data arising in the course of the project. The state of knowledge will be evaluated after each field dataset has been collected and interpreted. If necessary, the programme will be modified accordingly. First, drillsites must be secured by application to the

federal authorities. In these applications, the associated investigation programmes will be defined with the broadest possible catalogue of investigation methods and drill paths. The details of the borehole investigations will only later be defined based on the seismic data and subsequently refined with the results of any previous boreholes whenever necessary.

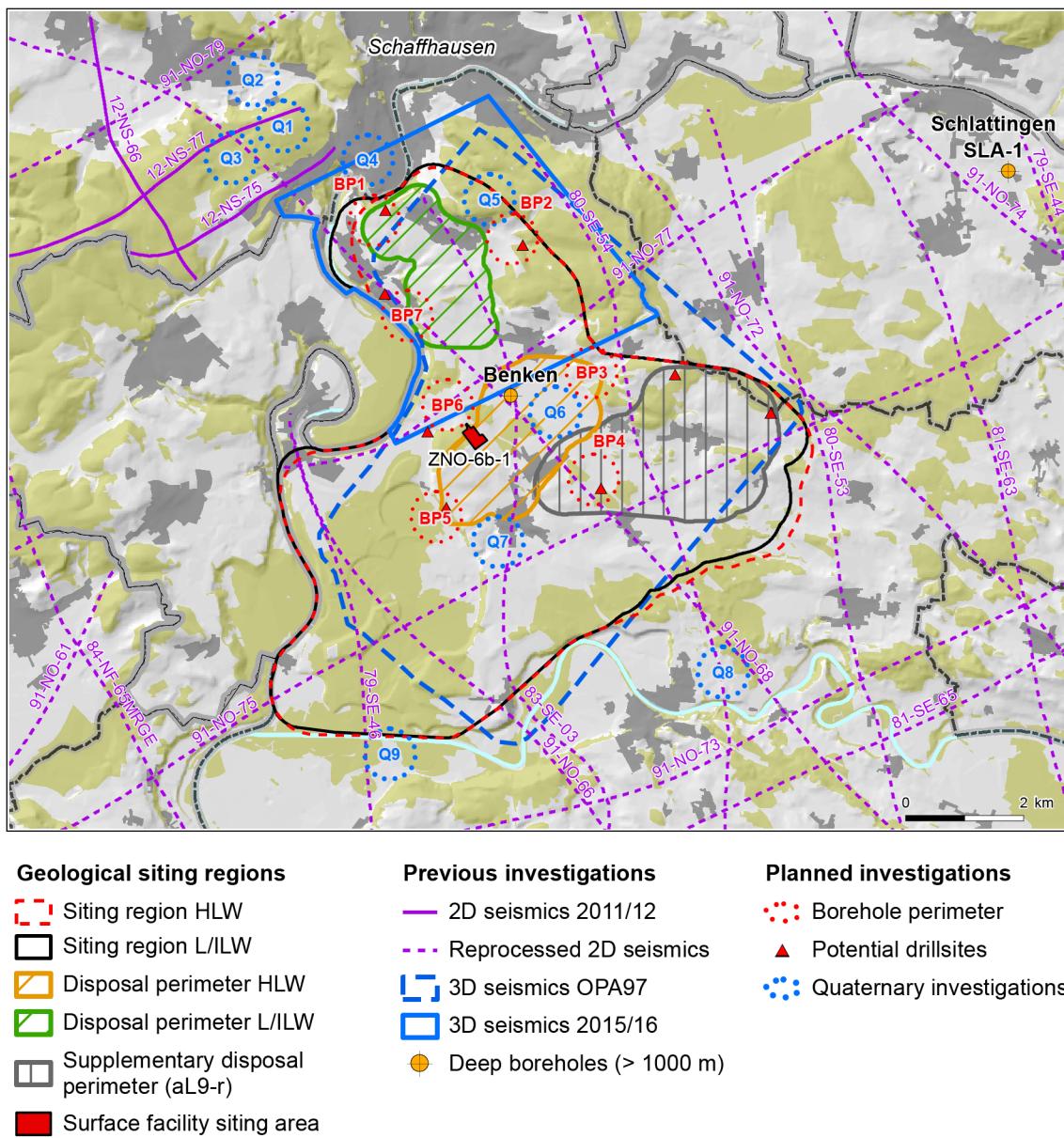


Fig. 7-3: Planned surface exploration programme for the region Zürich Nordost during SGT Stage 3.

Considering the size of the investigation areas (combined potential areas for the two repository types in each siting region) and the low complexity of the local geology, Nagra foresees that a total of 3 – 5 boreholes per siting region will suffice to achieve the exploration targets. These will be located within the proposed borehole perimeters shown in Figs. 7-3 to 7-5, and are subject to a licensing process.

The investigations of the Quaternary deposits in and around the siting regions will increase the database for assessing the relevance for long-term safety of future glaciations. Here, 2D seismic campaigns and other geophysical methods will help to describe the geometry of the bedrock surface and the thickness and general architecture of the Quaternary sediments. Locally, boreholes and possibly also trenches will be used to access sample material for detailed sedimentological description and age dating.

Finally, regional monitoring of the neotectonic activity with the help of seismological and geodetic networks will be continued and – if necessary – updated or amended.

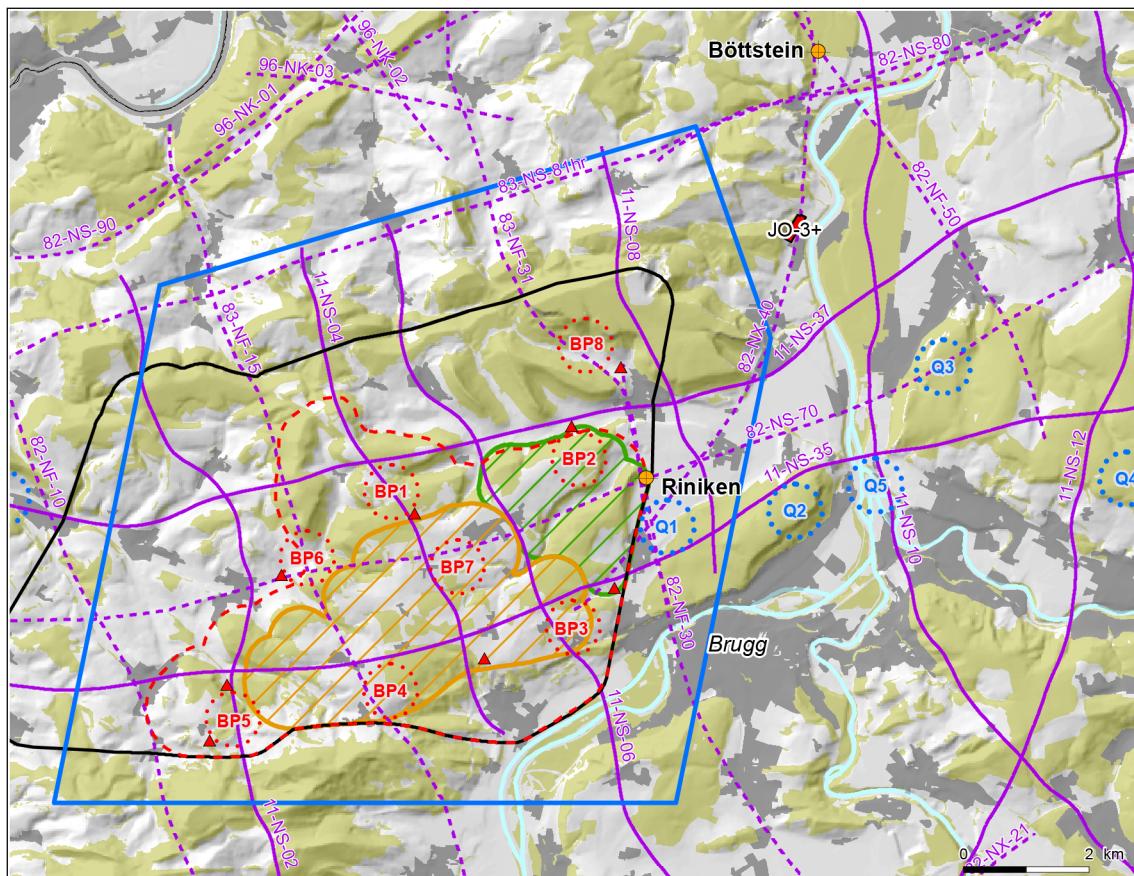
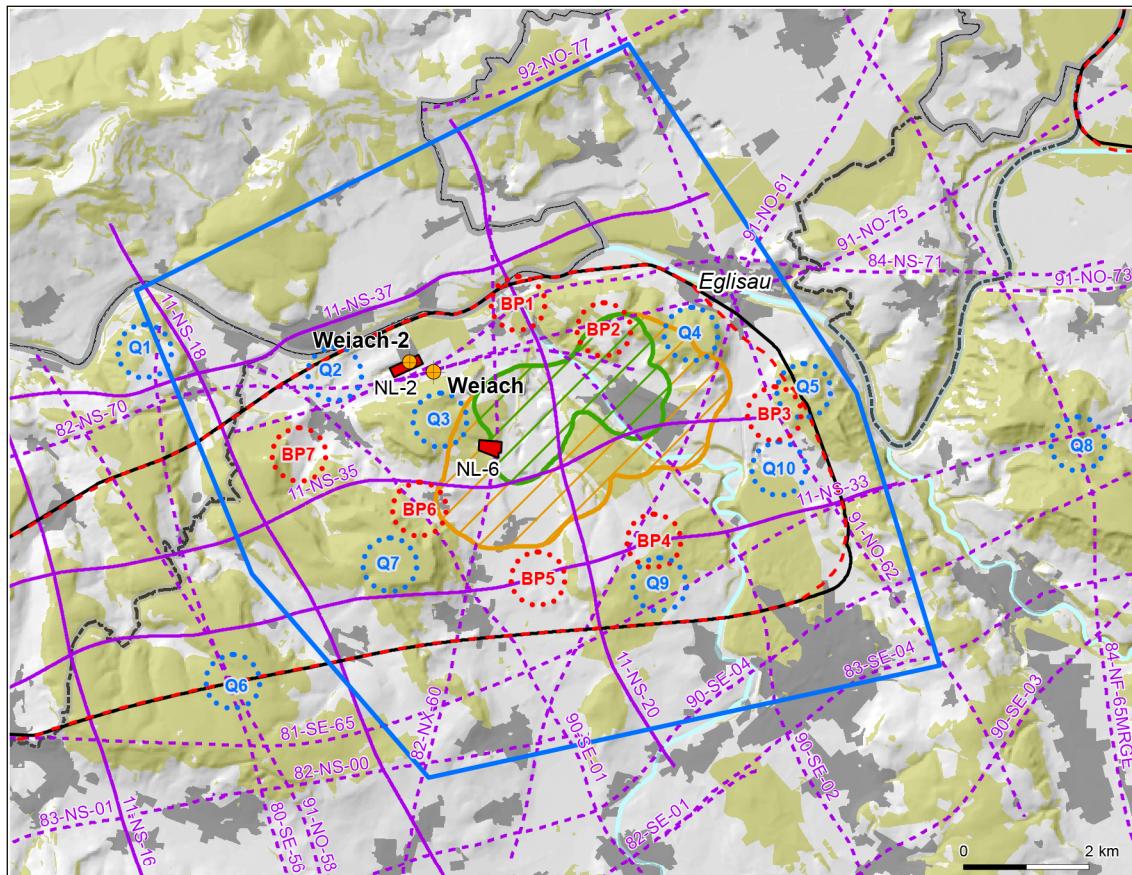


Fig. 7-4: Planned surface exploration programme for the region Jura Ost during SGT Stage 3.

Responding to the regulator's evaluation of Nagra's proposals for SGT Stage 3 (see section 3.1.1), a site investigation programme has also been prepared for the Nördlich Lägern siting region (Fig. 7-5). Here, a 3D seismic survey is foreseen for winter 2016/17. Similar to the regions Zürich Nordost and Jura Ost, 7 locations for deep boreholes will be prepared, of which 3 – 5 are considered to be sufficient for achieving the exploration aims for the general licence application. The site investigation programme for Nördlich Lägern also includes a full investigation campaign of the Quaternary deposits in the area.



| Geological siting regions | |
|----------------------------------|------------------------------|
| | Siting region HLW |
| | Siting region L/ILW |
| | Disposal perimeter HLW |
| | Disposal perimeter L/ILW |
| | Surface facility siting area |

| Previous investigations | |
|--------------------------------|---------------------------|
| | 2D seismics 2011/12 |
| | Reprocessed 2D seismics |
| | Deep boreholes (> 1000 m) |

| Planned investigations | |
|-------------------------------|---------------------------|
| | 3D seismics 2016/17 |
| | Borehole perimeter |
| | Quaternary investigations |

Fig. 7-5: Planned surface exploration programme for the region Nördlich Lägern during SGT Stage 3.

7.2.2 Geosphere characterisation and long-term evolution of the selected sites

Substantial RD&D activities will be undertaken to develop the site descriptive models for the selected sites in Stage 3 of the Sectoral Plan. The term site descriptive model is used to describe a suite of conceptual models of the geological conditions at the proposed repository sites, that can comprise *static models* (lithostratigraphic layer models, fault models), *property distributions* (mineralogy, porosity, hydraulic conductivity, radionuclide retention properties, gas transport properties, stiffness and strength, seismic velocities) and *dynamic models* (defining and predicting the in-situ state conditions, e.g. pore pressure, water saturation, chemical composition of waters, temperature, stress state, strain/deformation).

Site descriptive models can be used for a variety of applications, such as the detailed planning of the site characterisation programmes, as a basis for the abstraction of the site-specific safety assessment and as input for engineering applications. The development of the models is thus largely driven by the requirements defined to conduct the post-closure safety assessment and substantiate the assumptions therein, and by the requirements formulated to develop the more detailed models needed to assess and evaluate constructability and to assess the impact of repository-induced effects.

The final version of the site descriptive model at the time of the general licence application presents the integrated understanding of the site.

The next paragraphs describe the RD&D activities following the model development sequence. It starts with the development of the tectonic and sedimentological models, followed by the geo-mechanical properties, hydraulic properties and state parameters and resulting models and continues with the dynamic hydrogeological and hydrogeochemical aspects.

The long-term geological evolution is discussed in a separate section. It affects the assumptions underpinning the post-closure safety assessment in two aspects: the radionuclide transport pathways and the description of the biosphere.

7.2.2.1 Development of the site descriptive models

Objectives

The objective is to develop and implement a suite of site descriptive models that satisfy the need for a traceable and consistent description of the geological conditions at the proposed repository sites at the scales of interest. The development of the models is largely based on existing methodologies (e.g. Anderson et al. 2013) and the focus of the RD&D activities is on:

- Evaluating the use of the application-oriented geometric up- and down-scaling of the static models (e.g. abstraction of tectonic and sedimentary features), tailored to the requirements of the end-users
- Evaluating the requirements with respect to the description of the properties on the site scale, drawing on integrated interpretation of existing site characterisation data (core logging, laboratory investigations, borehole geophysical logging, attribute analysis of 3D seismic data) and collection of evidence from related applied geoscience domains
- Developing robust calibration/conditioning procedures for dynamic models (pore pressure/groundwater flow, groundwater chemistry, temperature, stress state, strain/deformation) where these are required

An important aspect of the RD&D activities associated with the elaboration of the site descriptive models is the assessment of model uncertainties. Of particular relevance is the propagation of input uncertainties in the model abstraction process (up- and down-scaling of parameters and processes).

Current state-of-the-art and progress since the 2009 RD&D Plan

Drawing on the experience from previous site investigation programmes (Nagra 1997, Nagra 2002b), a number of site descriptive models have been developed in the context of SGT Stage 2. For example, lithostratigraphic and tectonic models were elaborated for the siting regions in Northern Switzerland (Gmünder et al. 2013, Lanyon & Madritsch 2014, Nagra 2014b). These static models formed the basic input for the development of new regional- and site-scale models of groundwater flow and groundwater chemistry (Gmünder et al. 2014, Luo et al. 2013, 2014a, b and c, Waber et al. 2014), temperature distribution (Papafotiou & Senger 2013, 2014a and b) and in-situ stress (Heidbach et al. 2014).

Planned RD&D in the next 5 to 10 years

In the context of SGT Stage 3, a suite of site descriptive models will be elaborated for the proposed siting regions, addressing the geological conditions (section 7.2.2.2), the geomechanical conditions (section 7.2.2.3), the hydrogeological/hydrogeochemical conditions (section 7.2.2.4) and the long-term geological evolution (section 7.2.2.5) on the site scale.

Approaches for geometric up- and downscaling of the sedimentary structures (layer models of lithostratigraphic units) and the tectonic structures (fault models) will be investigated. The level of complexity of the static models will be iterated in close cooperation with the end-users to ensure a traceable and consistent abstraction of the geological conditions on the site scale.

Further international experience will be gained from the French, Belgian, Swedish, Finnish and Canadian programmes. In this context, an exchange within the framework of the International Task Force on Flow and Solute Transport with the Swedish modelling groups is of particular interest, because the concept of site descriptive modelling has been successfully applied in both the site selection process and the construction licence application of the Swedish programme.

Through collaboration in related applied geology fields such as the hydrocarbon industry (e.g. SHARC 2010, 2012a, b and c), carbon dioxide capture and storage and geothermal energy, the state-of-the-art in descriptive site-scale modelling will be monitored continuously.

7.2.2.2 Geological conditions (tectonics and sedimentology)

Objectives

Sedimentological and tectonic characteristics and features of the host rock and its confining units provide fundamental input for the understanding of the hydrogeological and geomechanical behaviour. These aspects thus contribute to ensuring the barrier function of the host rock in the safety case and providing input for engineering feasibility and repository construction and layout. Based on Nagra's activities during SGT Stage 2, it became clear that the proposed siting regions Zürich Nordost and Jura Ost have some significantly different tectonic and sedimentological characteristics that are potentially relevant for site selection.

In the course of SGT Stage 3, Nagra will carry out extensive field investigations including 3D seismics and deep boreholes, the results of which will be used to further refine the knowledge of the tectonic and sedimentological conditions in the potential siting regions. This knowledge will be used to develop tectonic and sedimentological models that will serve as a basis for other dynamic models such as hydrogeological models or stress/strain models (see section 7.2.2.1).

Current state-of-the-art and progress since the 2009 RD&D Plan

Since the publication of Nagra's 2009 RD&D Plan (Nagra 2009a), significant research and exploration activities have been carried out by and/or on behalf of Nagra to further constrain the sedimentological and tectonic description of the siting regions and their respective host rocks. The synthesis report (Nagra 2014a) and the many underlying reference reports provide a solid basis for the planning of future RD&D activities. A brief summary of results related to tectonic and sedimentological characterisation is given below, focusing on the preferred host rock Opalinus Clay and its confining units in the proposed siting regions Zürich Nordost and Jura Ost.

Sedimentological facies analysis and models

Litho-, morpho-, bio-, chemo-, mineralo- and seismostratigraphic approaches were applied during SGT Stage 2 to investigate the sedimentary facies, giving a more detailed view of sedimentological similarities and differences between the siting regions (Nagra 2014a and references therein).

In comparison with other Mesozoic formations, the petrological and geophysical parameters of the Opalinus Clay are, on a larger scale, substantially more homogeneous. However, facies changes do exist within this formation, as was shown for example by detailed investigations in the Mont Terri URL (Müller & Jaeggi 2012). New biostratigraphic studies have shown that the base of the Opalinus Clay in the Mont Terri URL is older than e.g. in the Weiach borehole (Feist-Burkhardt & Pross 2010, Reisdorf et al. 2014). Also, the upper boundary of the Opalinus Clay is diachronous (Feist-Burkhardt 2012).

The facies of the lower and especially of the upper confining units can vary considerably on a regional and local scale. The sedimentological characteristics, sedimentary genesis and temporal-spatial development of the depositional areas of these units were partly reanalysed (Reisdorf et al. 2011, Bläsi et al. 2013, Deplazes et al. 2013, Kiefer et al. 2015). These studies indicated differences between the siting regions, e.g. in the occurrence and extent of 'hard beds' (e.g. calcareous and/or quartz-rich beds). It was shown that these potentially permeable 'hard beds' play an important role in the safety analyses by determining the length of radionuclide transport paths (Nagra 2014a and Nagra 2014b, Dossier II and VI).

Tectonic regime

In the course of SGT Stage 2, a wide variety of studies including regional and integrative interpretation of 2D seismic and gravity data, construction and kinematic restoration of geological cross-sections, mapping of tectonic features in outcrops and development of simplified discrete fracture models were carried out (Nagra 2014b, Dossier II with references therein). The results revealed significant differences regarding the tectonic setting of the two siting regions proposed for SGT Stage 3.

The siting region Zürich Nordost appears to be weakly (if at all) affected by compressional deformation related to Late Miocene Alpine collision tectonics, but lies immediately west of the extensional Hegau-Lake Constance fault zone (Madritsch & Hammer 2012, Ibele 2015, Madritsch 2015). Recent work has revealed that the latter fault zone is characterised by multiple phases of fault reactivation (Egli et al. 2014). By contrast, the siting region Jura Ost is located immediately north of the thin-skinned Jura fold-and-thrust belt that formed due to compressional foreland stresses related to the Alpine collision. As a consequence, the sedimentary stack within this siting region has been mildly detached and transported northwards (Jordan et al. 2015). The deformation style of the Jura fold-and-thrust belt was studied by restoring geological cross-sections as part of a PhD thesis co-funded by Nagra (Malz 2014, Malz et al. 2015). On a regional but also on a siting region scale, significant gradients in shortening values were identified. It could be shown that basement faults associated with the Permo-Carboniferous Trough of Northern Switzerland had a strong influence on the thrust belt's kinematics and present-day structure (Malz et al. 2016).

Planned RD&D in the next 5 to 10 years

The activities in SGT Stage 3 aim to support the three main steps necessary to establish the associated descriptive models for the siting regions (see section 7.2.2.1): feature characterisation, feature distribution/variability and feature abstraction/conditioning. Adding to the activities already foreseen within the exploration programme, the related RD&D activities aim to explore, develop and test less established qualitative and quantitative approaches. Regarding the advanced characterisation of sedimentological and tectonic features, it is of particular interest to develop upscaling and downscaling techniques (seismic to outcrop to core to microscale).

Concerning feature characterisation, potential novel methodological approaches include the testing of XRF analysis tools (to better quantify sedimentary properties, e.g. to trace and correlate different lithologies based on variations in elemental abundances), hyperspectral imaging tools (to better quantify facies variability of samples, e.g. to differentiate shaly versus sandy facies in the Opalinus Clay and as input for geostatistical models) and geochemical tools (e.g. to test novel biomarker tools to support depositional models).

Another aspect is to improve the understanding of the distribution and variability of certain sedimentological and tectonic features. Concerning sedimentological aspects, it is planned to test advanced correlation approaches to trace and correlate subtle sedimentological features and changes on different scales. It is anticipated to develop approaches to analyse and combine different records such as geophysical, compositional, biostratigraphical and sedimentological data to define the variability and distribution of lithofacial units (e.g. 'hard beds') and investigate upscaling/downscaling effects. This will help to better define the lithofacial units of the conceptual models. With respect to the distribution of structural features, activities will focus on the characterisation of small-scale faults below the resolution of 3D seismic data (e.g. faults with vertical offsets below 10 m; see section 7.2.1). The distribution of such "sub-seismic" faults can be estimated based on statistics of resolvable fault density and fault size distributions (Maerten et al. 2002, Lanyon & Madritsch 2014). In addition, the characteristics of tectonic features in relation to certain facies types and indications for regional deformation gradients (determined by means of structural balancing and possible analogue modelling approaches) will be further investigated. These activities may also help to identify areas likely to show a stronger tectonic overprint and "sub-seismic" fracture frequency.

For the interpretation of the structural findings in the siting regions, a good tectonic understanding of nearby larger-scale fault zones is important. Consequently, the understanding of such fault zones (e.g. the Hegau-Lake Constance fault zone) will be further improved during regional synthesis studies to be carried out in collaboration with academic institutions in Switzerland and abroad. Further efforts will be made to better characterise and date fracture-filling veins, to better constrain deformation and fluid-flow events in the past.

Activities related to conceptualisation/abstraction and conditioning of tectonic and sedimentological features aim to support the development of descriptive models for the proposed siting regions considering the nature of the host rock and surrounding rock types (see section 7.2.2.1). Desk studies will focus on identifying appropriate models for conceptualisation (e.g. scaling laws for tectonic features or integration of depositional models) and abstraction (e.g. best practices to simplify complex sedimentological or tectonic features for model integration) and will also consider international experience gained by partner organisations as well as relevant applications in the hydrocarbon industry.

7.2.2.3 Geomechanical conditions

Objectives

The geomechanical conditions describe the rock properties with respect to specific state variables (notably the stress field, pore pressure and temperature distribution), including structural heterogeneities (fractures) at the rock mass scale. They are an essential part of the site descriptive models and relevant not only for site-specific evaluation of the engineering feasibility of a repository (e.g. constructability and operation), but also to assess repository-induced effects and the integrity of the barrier system over geological timescales (post-closure safety). Specifically, stress conditions are also crucial for defining safety function indicator criteria with respect to acceptable thermally and gas-induced fluid overpressures (see Papafotiou & Senger 2016a and b, Marschall & Giger 2016).

Stresses and mechanical properties are scale-dependent due to mineralogical and structural variability of the rock mass. Direct quantitative stress measurements are generally obtained in boreholes or along tunnels, and mechanical properties are constrained in laboratory testing on core samples of centimetre to decimetre scale. Instrumented in-situ (mine-by) experiments in URLs offer the prospect of reconciling laboratory test results and stress measurements with excavation response at the scale of underground structures.

The research activities in this area will focus on developing workflows for upscaling of geomechanical conditions from core sample scale or borehole/cavern scale to the actual repository scale. It is anticipated that static models containing sedimentary facies and tectonic features will be conditioned with geomechanical data using empirical relationships based on properties and property distributions derived from geophysical logging and laboratory testing results. Research activities dedicated to the hydromechanical coupling and deformation behaviour of the Opalinus Clay will be addressed in section 7.2.3.3 (geomechanical processes in the host rock).

While significant effort will be undertaken to characterise the geomechanical conditions at the selected sites aided by the exploration programme planned for SGT Stage 3, it is recognised that underground access will be required to fully characterise the geomechanical conditions in anticipation of repository construction.

Current state-of-the-art and progress since the 2009 RD&D Plan

Stress field

The vertical stress magnitude at depth can generally be estimated with confidence from density logs in boreholes. In contrast, constraining the horizontal stress magnitudes is more challenging. The orientation of the principal horizontal stress magnitude can be derived from drilling-induced borehole instabilities (breakouts, fractures) and fault plane solutions of earthquakes, with the latter also providing information on the relative stress magnitudes (e.g. Zoback 2010). A detailed analysis of such data for Northern Switzerland was recently performed by Heidbach & Reinecker (2013).

For site characterisation, only deep boreholes enable access for active stress measurements in the rock mass (e.g. Zang & Stephansson 2010). Hydraulic fracturing is considered the most reliable method to constrain horizontal stress magnitudes in deep boreholes since strain relief methods (e.g. overcoreing) have not been demonstrated for greater depths (Intera 2011). However, only the minimum horizontal stress magnitude can be determined, and this with the reservation that the overburden is not the least of the three principal stress magnitudes. The maximum horizontal stress magnitude must be calculated based on a number of assumptions. In sedimentary sequences with strongly contrasting rock properties, several studies have found that the minimum horizontal stress magnitudes vary significantly (e.g. Warpinski 1989, Cartwright 1997, Wileveau et al. 2007, Roche et al. 2013, Gunzburger & Magnenet 2014). This highlights the important aspect that extrapolation of stress magnitudes from hydraulic fracturing must account for the spatial heterogeneity of the rock properties, especially across different formations. In addition, tectonic structures can also perturb the local stress field (e.g. Maerten et al. 2002, Yale 2003).

Numerical geomechanical modelling can assist in exploring the sensitivity of the stress field at site or reservoir scale, and hence in estimating the far-field stress tensor (Fischer & Henk 2013). Such studies were conducted with a focus on Opalinus Clay in 2D for the Mont Terri URL (Petrini & Simpson 2008) and in 3D for Northern Switzerland (Heidbach et al. 2014, Hergert et al. 2015).

Mechanical properties

The Opalinus Clay exhibits transitional deformation behaviour between hard soils and weak rocks, which makes geomechanical testing of the material delicate. The latest compilations of geomechanical properties of Opalinus Clay from deformation tests of core samples are reported in Giger & Marschall (2014), Nagra (2016b) and Marschall & Giger (2016). Significant efforts have been undertaken in SGT Stage 2 to develop advanced geomechanical test procedures (Giger et al. 2017). Geomechanical testing of core samples is focusing on constraining elastic (stiffness) and failure strength parameters. In contrast to these "static" properties derived at the core scale, "dynamic" properties can be derived from geophysical exploration. Empirical correlations between (petro-) physical and geomechanical properties have also been compiled in the hydrocarbon industry (e.g. Ingram & Urai 1999, Horsrud 2001, Chang et al. 2006), mainly for the design of wellbore stability. In the hydrocarbon industry, it is current practice to build static geomodels based on a 3D seismic cube and borehole petrophysical data (e.g. Wimmers & Koehler 2014). Andra has also pursued this using the 3D seismic data near the Bure site, deriving a 3D cube of dynamic elastic properties (Mari & Yven 2013). Research activities towards improved assessment of the structural heterogeneity of Opalinus Clay (fractures) are described in section 7.2.2.2.

Planned RD&D in the next 5 to 10 years

A review of the state-of-the-art of geomechanical reservoir modelling in the hydrocarbon industry will be performed. With the new seismic and borehole data generated in SGT Stage 3, the feasibility and need to construct site-specific 3D geological models consisting of static properties (lithostratigraphic layer models, fault models, see section 7.2.2.2) and populated with empirically correlated mechanical properties will be assessed. To this end, static elastic and basic physical properties of Opalinus Clay derived from laboratory testing and characterisation can be linked to geophysical and petrophysical data from site appraisal (3D seismics and deep boreholes).

The borehole near-field will be investigated to assess the potential of thermo-mechanical and chemical impacts for constraining stress magnitudes from hydraulic fracturing. Geomechanical laboratory testing with cores from deep boreholes using refined protocols (see section 7.2.3.3) will also assist in bracketing stress magnitudes from hydraulic fracturing. The far-field stress tensor will be further constrained by geomechanical numerical modelling using the 3D geological model and accounting for stress information (borehole stability, hydraulic fracturing) at multiple boreholes at a particular site. In addition, the extension of the micro-seismic monitoring network in Northern Switzerland (Plenkers 2014) should also generate more earthquake focal mechanisms and hence more information on relative stress magnitudes.

7.2.2.4 Hydrogeological and hydrogeochemical conditions

Objectives

Within the framework of the planned field activities as part of SGT Stage 3, various aspects of hydrogeology and hydrochemistry will be further investigated and refined. The additional data will allow for a higher level of detail in site-specific geosphere characterisation and a reduction of the remaining uncertainties. The activities are intended to improve and develop the tools and methods needed to meet the objectives for the licence application, which are:

- State-of-the-art description and visualisation of the hydrogeological conditions with the focus on the proposed sites. This includes the evaluation of selected scenarios of long-term evolution and provides support for the environmental impact assessment and geotechnical risk assessments. It also aids in evaluating resource conflicts.
- State-of-the-art porewater data, including the spatial variability of porewater compositions (host rock and confining units) and models for radionuclide speciation modelling, forming key input for the safety assessment calculations.
- A sound basis for estimating the anion-accessible porosity (or porosities) of the host rock and confining units as input to radionuclide transport modelling and as a basis for the interpretation of natural tracer profiles.
- Identify and frame relevant impacts of long-term evolution on the host rock and confining units.

Current state-of-the-art and progress since the 2009 RD&D Plan

General hydrogeology and hydrochemistry

Regional and site-specific hydrogeology and hydrochemistry have recently been studied in detail in Nagra (2014b, Dossier V and literature cited therein). Since the last RD&D Plan, major progress has been made regarding the spatial interpretation of the isotope hydrogeology and hydrochemistry of deep groundwaters (Waber et al. 2014) and in the interpretation of the regional deep flow systems using a stationary hydrodynamic model (Gmunder et al. 2014). In addition, this model was used to provide the hydraulic boundary conditions of the local-scale models (Luo et al. 2014a, b, c and d) of the sites considered in SGT Stage 2.

In SGT Stage 3, the planned field activities will provide a refined knowledge of the 3D geology of the siting regions (see sections 7.2.1 and 7.2.2) and additional hydrogeological data will allow for improved interpretation of the hydrogeological system.

Porewater in the host rock and the confining units

For SGT Stage 2, the earlier models (Nagra 2002b, Pearson et al. 2003) were updated and improved (Mäder 2009, Wersin et al. 2016). Following the earlier investigations, the core samples from the geothermal well Schlattingen-1 (Wersin et al. 2013, 2015a) provided a further opportunity to study the Opalinus Clay (plus 'Brauner Dogger') in Northern Switzerland, where it is characterised by lower porosities compared to Mont Terri. A suite of methods was applied to quantify porewater composition, including stepwise high pressure squeezing (Mazurek et al. 2015). It was concluded that, in general, the datasets of Schlattingen and Benken were in agreement. Although overall the porewater compositions can be defined with reasonable accuracy, remaining uncertainties which could be further reduced relate to the determination of the CO₂ partial pressure (and its relation to pH), the determination of the redox-controlling phases, the in-situ cation-exchange populations, the estimation of the sulphate concentration and the value of the anion-accessible porosity (see below). Such uncertainties can partly be reduced through elimination and/or in-depth understanding of artefacts induced in porewater extraction techniques. The state-of-the-art and potential ways forward were consolidated among experts of clay-based programmes in late 2014 (Wersin et al. 2015b) with the focus on the following topics: the role of clay minerals in equilibrium modelling, the controls of pCO₂ and the link to pH, the definition of the redox conditions and trace element contents and the anion-exclusion processes (see next section).

While substantial experience exists for the Opalinus Clay, only a limited dataset is available for the confining units. The work on clay-rich sections of the 'Brauner Dogger' and of the Staffelegg Formation from the Schlattingen-1 borehole showed that the methods developed for Opalinus Clay are applicable (Wersin et al. 2016). In contrast, the work on samples from the Effingen Member (Mazurek et al. 2012) suggests that, in confining units with lower clay mineral contents (e.g. sections of the Passwang Formation), the available toolbox is limited (uncertainties exist e.g. regarding occupancies of the cation exchanger, squeezing and anion porosity to scale aqueous leachates).

While this uncertainty regarding the porewater compositions in the confining units does not require further reduction for the safety assessment calculations, it needs to be acknowledged that porewater tracer profiles provide important arguments about the transport of dissolved constituents in the host rock and confining units at formation scale and over long periods of time. Porewater tracer profiles may be useful for identifying potential lateral transport pathways or pathways along fractures. In this case, multi-tracer approaches are needed to identify or exclude potential disturbances.

A state-of-the-art report on the observation and interpretation of natural tracer profiles in a suite of clay rocks was published within the framework of the NEA CLAYTRAC project (Mazurek et al. 2009, Mazurek et al. 2011). In the Schlattingen-1 borehole, tracer profiles were observed to be similar to those in Benken, underpinning large-scale diffusion-driven transport in the Opalinus Clay (Wersin et al. 2013). In addition, noble gas tracers such as helium point to very long residence times (Rufer & Waber 2015). In the DB borehole at Mont Terri, a high resolution profile across the Opalinus Clay and confining units evidences temporally changing hydrochemical boundary conditions (Waber et al. 2015). A quantitative interpretation of the anion tracer profiles in lithologically variable confining units is generally hampered by the limited knowledge of anion-accessible porosity in the case of lithologies without clays and the scarcity of high-quality groundwater data from the (often low-conductivity) water-conducting zones bounding the confining units.

Anion-accessible porosity

Porosity is a fundamental input parameter for all transport calculations, among other aspects, and provides an approach for estimating diffusion coefficients in clay rocks based on the extended Archie's law (Nagra 2014b, Van Loon 2014, Van Loon & Mibus 2015). Anion-accessible porosity is of particular relevance because it scales transport of the dose-relevant anionic radionuclides and is a base parameter in the interpretation of chloride tracer profiles (see also the previous section). The dependence of the anion diffusion behaviour on the ionic strength of the porewater is being studied in an ongoing PhD thesis (Wigger et al. 2015).

For Opalinus Clay, an accessible fraction of around 0.5 ± 0.05 of the overall porosity is well established for the considered ionic strengths (e.g. Pearson et al. 2003, Wersin et al. 2013 and 2016, Mazurek et al. 2015). For the confining units, only a limited dataset is available and there is currently no model for estimating this value, e.g. based on the varying rock mineralogy and the typically decreasing ionic strength towards the boundaries of the aquitard. This is a limitation for the interpretation of the anion tracer profiles and also for reactive transport simulations, for instance at material interfaces. With respect to the requirement from safety assessment, the impact can be framed with uncertainty bounds.

Long-term evolution of the host rock and confining units

The long-term geological and climatological evolution of the site can potentially lead to impacts on the host rock and surrounding units. This includes changing hydraulic conductivities and other properties during (un)-loading of the Opalinus Clay and the surrounding rocks. Ice loads or permafrost may also affect the deep flow systems or may lead to the reactivation of faults. Regarding the changes in hydraulic conductivities as a function of the overburden, observations are available for Opalinus Clay and a variety of other lithologies from borehole testing and from lab experiments on drillcores (Nagra 2014b). Effects of changing salinities at bounding aquifers (triggered by the climatological and hydrogeological evolution) on the porewater composition in the Opalinus Clay can be predicted based on the interpretation of the present-day observed large-scale tracer profiles.

Planned RD&D in the next 5 to 10 years

The state-of-the-art regarding hydrogeological and hydrochemical characterisation is perceived as mature and will be applied in SGT Stage 3. In this context, related to regional hydrogeology and hydrochemistry, it is planned to evaluate the performance of available modelling codes, to monitor ongoing developments and to contribute to specific code improvements if necessary.

Regarding the hydraulic properties of undisturbed Opalinus Clay, it is expected that the upcoming field campaign in SGT Stage 3 will provide high-quality data based on improved test protocols to confirm the advanced understanding already in place. Special emphasis will be on discontinuities in order to strengthen the dataset concerning fault sealing. Regarding the confining units, the field campaign will provide important data to further constrain the hydraulic barrier properties of these units.

An effort will be made to characterise the porewater in the confining units as this was identified as a remaining uncertainty. The laboratory methods will be further developed and tested and the modelling will be refined, with the aim of reducing, understanding and quantifying experimental artefacts. The work will take place within the framework of the Mont Terri URL programme and as part of ongoing research at Uni Bern and PSI. In addition, an updated porewater model is expected to benefit from refined rock characterisation.

The understanding of the natural tracer profiles will benefit from the improvements of pore-water investigations and the determination of anion-accessible porosity. Regarding the tracer profiles, a special interest will be to define an adapted sampling strategy for the boreholes in SGT Stage 3 such that it makes a maximum contribution to the understanding of transport in the confining units. Emphasis will also be given to collecting high-quality groundwater samples from the water-conducting zone/aquifer bounding the confining units above and below.

Regarding the anion-accessible porosity, further refinement is expected from work in the Mont Terri Project and as part of ongoing research at PSI and Uni Bern.

Scenarios of long-term evolution will be elaborated and the impact on the host rock and confining units will be tested. This contributes to the parameterisation of alternative scenarios in the safety assessment. Among other issues, such scenarios will address the effects of host rock decompaction and repository exhumation in time periods beyond 1 million years after present as required in the ENSI-G03 Guideline (ENSI 2009). In this context, the depth-dependent hydraulic properties and the geochemical conditions (notably the redox state and cation-exchange populations) of Opalinus Clay are being investigated in a shallow borehole in Lausen near Basel.

7.2.2.5 Long-term geological and climate evolution

Objectives

In the context of long-term geological evolution, the three main topics to be distinguished are neotectonics, climate evolution and erosion. Geological processes related to these topics are capable of changing host rock properties and radionuclide transport and release pathways over the period of concern (100 ka for L/ILW and 1 Ma for HLW)²⁷.

Concerning neotectonics, three aspects are relevant, namely the shaking hazard, which defines requirements on the design of the surface facilities and the subsurface infrastructure prior to backfilling, the potential impacts on engineered barriers of seismic or aseismic slip on faults within the repository area (e.g. structural loads on the canister, change of transport properties in the backfill and geological barrier) and tectonically driven or enhanced erosion. The exploration activities to be carried out in SGT Stage 3 (e.g. 3D seismics) will allow exclusion distances

²⁷ ENSI G03 requires dose calculations for repository exhumation beyond a time period of 1 Ma.

from major and from local fault zones within the proposed repository area to be defined. Nevertheless, future neotectonic activity, possibly involving the formation of new faults around or within the repository, cannot be fully excluded.

Climate evolution strongly influences future landscape, biosphere and hydrosphere evolution and is therefore relevant for safety assessment (e.g. Näslund et al. 2013, Becker et al. 2014). The range of possible climate evolutions has to be described and captured using different scenarios. These scenarios are generally based on reconstructions of the past climate evolution (using paleoclimate archives) and on climate simulations.

For a geological repository in Northern Switzerland, future erosion is one of the key aspects for site selection and the safety case. Erosion may lead to a decreasing overburden and, as a consequence, to increasing host rock permeability (decompaction) or even the partial or total exhumation of the repository. Therefore, convincing landscape evolution scenarios for the siting regions need to be developed considering a wide variety of processes such as base level changes, the evolution of local topography and the formation of glacial overdeepenings. A thorough reconstruction of past landscape evolution and a general understanding of the relevant erosion processes are key aspects for the development and justification of these scenarios. For Northern Switzerland, glacial overdeepening is of particular concern.

For both site selection and the general licence application, all of the above-mentioned aspects will be addressed by long-term evolution scenarios. The activities described aim at improving the confidence in these scenarios by gathering additional constraints for the reconstruction of the geological, climatic and geomorphic past and by investigation of the key factors and processes guiding the future evolution.

Current state-of-the-art and progress since the 2009 RD&D Plan

Since Nagra (2009a), a wide variety of research activities aimed at a better understanding of Northern Switzerland's long-term geological evolution have been carried out by, or on behalf of, Nagra. A recent synthesis of these activities and results can be found in Nagra (2014b, Dossier III and references therein). A brief summary of the general key topics of neotectonics, climate evolution and erosion is given below.

Neotectonics

Regional geomorphic investigations across Northern Switzerland supported by Nagra did not provide clear evidence for neotectonic activity in the area during the Quaternary (Fraefel 2008, Kock 2008). However, more recent detailed local analyses of known fault traces using high-resolution LiDAR terrain models suggest that these results have to be treated with caution because signs of such activity might be very subtle due to the degrading effect of Quaternary surface processes; thus mild neotectonic activity cannot be fully excluded (Nagra 2014b, Dossier III).

Instrumental geodetic measurements indicate that recent crustal movements in the area of Northern Switzerland are slow. According to GPS measurements, horizontal displacements are $< 0.5 \text{ mm/y}$. During SGT Stage 2, the network of GPS stations was densified with 11 additional permanent stations to further consolidate these measurement results (Studer & Zanini 2013). Vertical movements, constrained along a series of regional profiles of precision levelling measurements, yield uplift rates of $< 0.25 \text{ mm/y}$ (Fuhrmann & Zippelt 2013, Schlatter 2013). Selected profiles indicate a slight differential uplift across the Jura Mountains.

The historical and instrumental record of seismicity in Switzerland suggests that the area of Northern Switzerland is characterised by comparatively low seismic activity with a relatively high percentage of earthquakes occurring at depths $> 5 - 10$ km (Nagra 2014b, Dossier III). Inversion of focal mechanism and other stress indicators yields a recent tectonic regime of strike-slip to extensional (at greater depths), with the maximum horizontal stress axis being oriented roughly NNW-SSE. In 2012 – 2013, the existing microseismic network in Northern Switzerland and southern Germany was densified with 10 additional stations, including 3 bore-hole seismometers (Plenkers 2014). The recordings of these new broadband stations will considerably increase detection limit and localisation accuracy of seismic events. Concerning seismic hazard assessment, sophisticated probabilistic methods have been developed for safety assessment (shaking hazard) and design of critical surface infrastructures (e.g. nuclear power plants) with the support of Nagra (Abrahamson et al. 2004, swissnuclear 2013).

Climate evolution

In the last few years, increased efforts have been undertaken to review and synthesise the paleoclimate data for Northern and Central Europe for the period prior to Late Glacial and Holocene times back to Marine Isotope Stage (MIS) 5 (e.g. Helmens 2014, Heiri et al. 2014). These reviews summarise the paleoclimatic studies of lake and peat sediments, speleothems, glacier records and loess-paleosol sequences. Recently published studies of speleothems provide new insights into the northern Alpine paleoclimate back to MIS 7 (Moseley 2014, Häuselmann 2015). During the last glacial period, an ice lobe probably reached the internal Alpine foreland at least once (MIS 4) before the last glacial maximum (MIS 2) (e.g. Ivy-Ochs et al. 2008, Gaar 2013). The climate in Europe during MIS 2 and 4 was further investigated by Hofer et al. (2012a and b) by modelling the impact of different glacial boundary conditions (e.g. height of the Laurentide ice sheet, radiative forcing, sea surface temperature) on the atmospheric circulation pattern and precipitation in Central Europe.

On the initiative of some of Nagra's sister organisations, the likely timing of future glaciations in the period of concern (10^5 to 10^6 years) has been investigated for different variants of anthropogenic CO₂ scenarios by climate modelling (Texier et al. 2003, Bioclim 2003, Pimenoff et al. 2012, Brandefelt et al. 2013, Ganopolski et al. 2016, see e.g. Fischer et al. 2015 or Nagra 2014b, Dossier III for a summary). The models indicate that the next severe glaciation is unlikely to occur before 50 ka AP and that the anthropogenic emission of greenhouse gases may delay the next severe glaciation for several 100 ka. Currently, within the IAEA project MODARIA (Modelling and Data for Radiological Impact Assessments), a common understanding of how to better bracket uncertainty in long-term climate modelling and how to downscale the models to an appropriate scale as input for biosphere and landscape evolution modelling is being developed.

Erosion

As outlined in Nagra (2014b, Dossier III), past and future erosion in Northern Switzerland can be assessed by looking at the following aspects: (1) evolution of the local base level, (2) lowering of the local topography and (3) the carving of overdeepenings during future glaciations.

The evolution of the local base level over the last 2 – 2.5 million years can roughly be reconstructed by analysing gravel terrace complexes (e.g. Preusser et al. 2011, Graf 1993, 2009a and b). While the uppermost terrace complex is dated based on mammal remains (Bolliger et al. 1996), only few age constraints are available for the lower terraces (see Kuhlemann & Rahn 2013 for a summary). Dating of Quaternary sediments older than the age range of radiocarbon

dating is therefore critical to better constrain the past landscape evolution and neotectonics. In this regard, an ongoing project initiated by ENSI and the Nuclear Safety Commission (NSC) applies cosmogenic nuclide burial dating methods to the Deckenschotter deposits from Northern Switzerland (Akçar et al. 2014, Claude et al. 2014). With the support of Nagra, a variety of luminescence dating methods and protocols have been applied to "old" (> 100 ka) infills of overdeepened glacial troughs in Northern Switzerland (Dehnert et al. 2012, Lowick et al. 2012 and 2015). The results confirm that, in earlier glacial-interglacial cycles, the ice extent and the amount of glacial overdeepening were considerably larger than during the Last Glacial Maximum (LGM). While the large extent and geomorphic effect of the penultimate glaciation (MIS 6) become more and more evident, the timing and impact of the older glaciations, particularly of the so-called most extensive glaciation (MEG), is still under debate.

Future ice ages might cause an important external perturbation to repository evolution in that they have the potential to alter the landscape by glacial erosion and sedimentation, lead to the formation of permafrost, and impose significant transient hydraulic, mechanical, thermal and chemical changes that can influence groundwater flow and radionuclide mobility (Fischer et al. 2015). In Northern Switzerland, deep glacial erosion, i.e. the formation of deeply incised troughs and overdeepened valleys, is of primary concern. Two international expert workshops on glacial erosion modelling and on glacial overdeepening organised by Nagra (Fischer & Haeberli 2010 and 2012) pointed to the potential value of diagnostic modelling for understanding processes and quantifying uncertainties and for testing sensitivities and process parameterisations, and highlighted the importance of glacier hydrology for ice dynamics and erosional processes. A subsequently initiated ice-flow modelling study of the Rhine glacier during the last ice age (Fig. 7-6) aimed at identifying regions of fast flowing ice conducive to glacial erosion indicates that, despite cold climatic conditions with low mass balance gradients at the LGM, the potential for glacial erosion exists even beneath the low-lying lobes that extended far into the Alpine foreland (Cohen 2015). In another study, improved process understanding of the mechanisms of subglacial meltwater erosion is gained by adapting state-of-the-art models of fluvial erosion and transport to the subglacial environment and implementing the resulting governing equations in models of subglacial hydrology (Flowers & Beaud 2014, Beaud & Flowers 2015, Beaud et al. 2014 and 2016). Through a continuation of the Greenland Analogue Project with Nagra's sister organisations (SKB, Posiva and NWMO), basal water pressure conditions, hydraulic gradients and subglacial water flow are being investigated at the ice sheet scale. Finally, a geometric and morphological characterisation of existing overdeepenings provides an empirical quantitative knowledge base of glacial landforms (Jordan 2010, Pietsch & Jordan 2014, Haeberli et al. 2015 and 2016, Patton et al. 2015 and 2016).

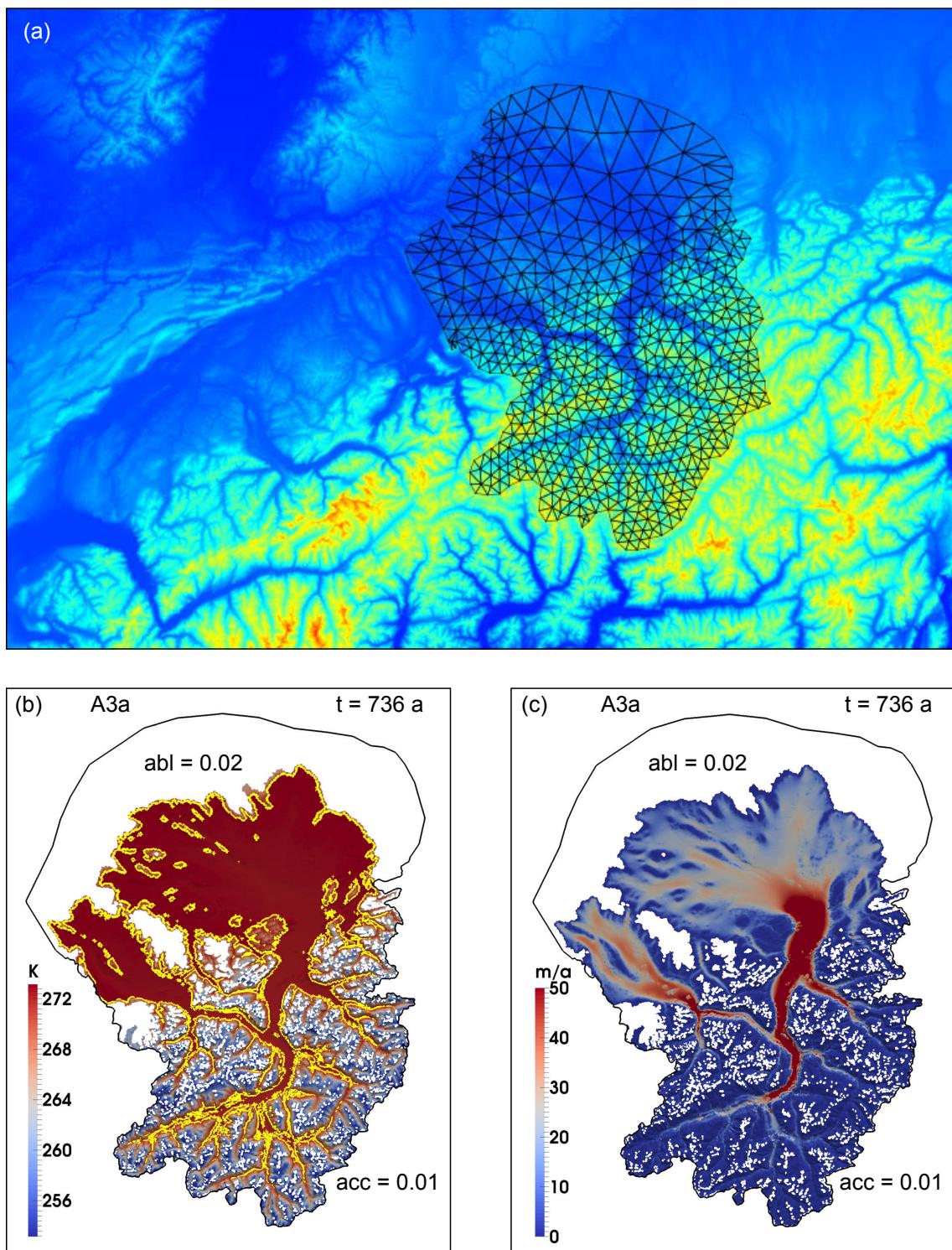


Fig. 7-6: Ice-flow modelling of the Rhine glacier at the LGM (Cohen 2015): (a) Model domain superimposed onto a DEM of Switzerland and southern Germany; (b) Simulated basal temperature; a basal temperature at the melting point (red inside yellow outline) is a necessary condition for basal sliding; (c) Simulated basal sliding velocity, a direct proxy indicator for glacial erosion.

Planned RD&D in the next 5 to 10 years

Neotectonics

A first series of activities is aimed at improving the characterisation of past neotectonic movements (for example desk studies to test morphometric analyses such as stream gradient analysis and support of paleoseismological investigations) and extending the instrumental record of recent crustal movements (for example by testing novel tools such as nanoseismology). As such, these activities will complement those carried out during the siting region characterisation in SGT Stage 3.

A second series of activities is dedicated to the exploration of possible future neotectonic scenarios. Of particular interest are the likelihood and potential effects of future reactivation of regional basement faults (for example associated with the Permo-Carboniferous Trough of Northern Switzerland or the Hegau-Bodensee Graben) and ongoing deformation of the Jura fold-and-thrust belt. It is anticipated to initiate numerical geodynamic modelling studies to address these issues.

Given that future neotectonic activity within the repository area, possibly involving the formation of new faults, cannot be fully excluded over the period of concern, a third branch of activities will explore the potential effects of neotectonic movements and seismicity on the various elements of a repository and the geological and engineered barriers. It is planned to carry out desk studies integrating the experience of partner organisations (e.g. Fälth & Hökmark 2010).

Climate evolution

A first set of activities will concern the past and future climate evolution on a global scale, particularly the effects of future orbital forcings and different anthropogenic CO₂ scenarios on the future global climate evolution, including the timing of glaciations. In this field, Nagra will coordinate its activities with its sister organisations.

A second series of activities will aim at increasing the understanding of the local climate in the central Alps and their northern foreland over a full glacial-interglacial cycle to better understand how the global climate system influences the local conditions and to obtain better constraints on local temperature and precipitation as input for biosphere and hydrosphere, ice flow and erosion modelling. Nagra will therefore support and, if necessary, initiate projects aiming at (1) improving the local paleoclimate database (e.g. cave, lake and peat sediments) and (2) developing climate models with appropriate spatial and temporal resolution. Subsequently, the climatic peculiarities of the glacial-interglacial cycles that presumably led to ice extents > LGM and to considerable overdeepening (e.g. MIS 6) will be analysed and compared to the last glacial-interglacial cycle. This should help to identify climatic conditions that favour severe glaciations and erosion in the Alpine foreland.

Erosion

Although the overall fluvial incision during the past 2 million years can be roughly quantified, particularly thanks to biostratigraphical age dating of the Higher Deckenschotter deposits, a higher resolution incision history of this period is hampered by the lack of further robust age datings. Also, a better understanding of the timing of the formation of the glacially overdeepened bedrock troughs can only be gained if the infills of the troughs can successfully be dated. In SGT Stage 3, sediment cores from the overdeepened valleys located in the vicinity of the repository sites (Thur and Aare valleys) will be retrieved for age dating. Consequently, a

first series of activities regarding future erosion will attempt to test methods for dating the Quaternary sediments collected during field activities in SGT Stage 3, e.g. luminescence dating, terrestrial cosmogenic nuclide dating, uranium-thorium dating of cements, magnetostratigraphy or dating of mammal remains.

A considerable part of the overburden of the Jura Ost siting region is located above the base level anticipated in scenarios for the next million years (see Nagra 2014b, Dossier III). Desk and modelling studies will be carried out to improve the understanding of the past evolution of the local topography in this area as a basis for developing future erosion scenarios. High resolution terrain models will be considered in this connection.

A series of studies are being considered to improve the overall process understanding of deep glacial erosion. The behaviour and extent of ice flow systems such as the Rhine glacier, Aare glacier and Rhone glacier will be investigated by means of ice flow modelling under different climatic conditions. In the external Alpine foreland, subglacial fluvial action strongly influences the efficiency of glacial erosion. To better constrain the factors that control the depth of glacial overdeepening, it is planned to carry out coupled numerical simulations of ice flow, glacial hydrology and glaciofluvial erosion and sediment transport. Moreover, Nagra will seek to integrate hydraulic engineering expertise to investigate sediment transport in pressurised flows on adverse slopes. Most of the overdeepenings are located in the Molasse substratum and terminate close to the outcrop of the base Tertiary. It is planned to assess the lithological control on overdeepening formation by studying the influence of limestone bedrock and karst systems on subglacial hydrology and thus the efficiency of erosion and sediment evacuation.

7.2.3 Improving process understanding of key safety-relevant phenomena in the host rock (and the confining units)

The following sections describe the improvement in process understanding of key phenomena occurring in the host rock and the confining units. These are subsurface processes which also occur in the absence of a repository. They are therefore described as part of the geological understanding.

First, the radionuclide transport processes in the undisturbed host rock and confining units are considered. The barrier properties of the rock form the basis for the safety assessment calculations. Requirements for defining RD&D activities in this domain are derived directly from the radiological safety calculations and the corresponding sensitivity analyses. The status of the work is perceived as mature. Reducing further uncertainties is not critical for many aspects as the parameter values currently being used for post-closure safety assessment are known sufficiently accurately.

Next, the key phenomena taking place in the host rock that strongly determine the impact of the repository-induced effects are described. The repository-induced effects themselves are described in detail in section 7.5. Repository-induced phenomena such as mass and heat transport and geomechanical (and chemical) processes will take place under conditions that deviate significantly from the initial natural conditions encountered at selected sites prior to the construction of the repository. An adequate level of process understanding is therefore required to be able to describe the repository-induced effects and assess their impacts. The improved process understanding thus contributes to:

- The confidence that the repository-induced effects are correctly described at the conceptual and parametric level
- Ensuring that the performance criteria (safety function indicators) formulated for bounding the repository-induced effects are adequately and comprehensively characterised and are thus legitimate and complete
- Ensuring that the corresponding safety function indicator criteria can be defined sensibly and can be met with high confidence

Based on the current state-of-the-art, the impact of repository-induced effects on the isolation properties of the host rock for the SF/HLW and L/ILW repositories has been systematically evaluated (see section 6.4.2 and Leupin et al. 2016a and b).

The phenomena are described here independently of each other for clarity, although it is acknowledged that a strong coupling exists between them. The joint impact of all the phenomena and the link to the performance criteria are incorporated and described as part of the evaluation of the near-field in section 7.5.

7.2.3.1 Radionuclide transport

Objectives

Post-closure safety assessment requires a sound knowledge of radionuclide migration in geological media to describe the transport and retention of relevant radionuclides in the host rock and the confining units. Concepts for radionuclide transport in sedimentary rocks have been developed and will be refined and potentially adapted to site-specific conditions. Suitable modelling approaches and robust datasets of transport and retention properties with adequate uncertainty bands are needed to reliably describe radionuclide migration in the geosphere.

To assess the uncertainty of the retention properties of the host rock under in-situ conditions, a profound understanding of the transport and reaction processes is required. This has largely been achieved in the last 15 years and the knowledge base can be considered mature, especially for the Opalinus Clay. In addition to site-specific datasets that will be collected in SGT Stage 3, the understanding will be brought up to date and remaining uncertainties will be further reduced. Most of the research is linked to the migration processes in the near-field of the HLW repository, with the focus on the bentonite buffer. Both diffusion and sorption models describing clay systems are generally applicable both to processes in the near-field and in the host rock (see also section 7.5.4).

Current state-of-the-art and progress since the 2009 RD&D Plan

In the Opalinus Clay and in the confining units, advection/dispersion and/or diffusion with radionuclide-specific sorption on the rock matrix govern the transport of radionuclides. Opalinus Clay has a very low hydraulic conductivity and a high self-sealing potential, qualifying it as an efficient hydraulic barrier. Nonetheless, a net hydraulic gradient may exist across the Opalinus Clay, inducing a very slow flow. Based on the Benken borehole dataset, it has been demonstrated that transport is dominated by diffusion, as illustrated also by natural tracer profiles (section 7.2.2.4). The confining units with lower clay mineral content, in contrast, potentially contain discrete transmissive features (joints, faults) where advective/dispersive flow may govern transport. As the host rock is the most important geological barrier to radionuclide transport, the following section focuses on studies of diffusion in Opalinus Clay.

Diffusive transport of radionuclides

In the last 15 years, the diffusion properties of Opalinus Clay have been studied in detail at PSI and elsewhere (Van Loon & Soler 2004, Van Loon et al. 2004a, Van Loon et al. 2005a, Van Loon et al. 2007, González Sánchez et al. 2008a, Gimmi & Kosakowski 2011). Advanced modelling approaches help to understand diffusion at different scales (Gimmi 2008, Churakov et al. 2014). The diffusion data can be upscaled from small laboratory samples (Van Loon & Soler 2004) via URL experiments (Tevissen et al. 2004, Van Loon et al. 2004b) to the formation scale (Gimmi & Waber 2004, Gimmi et al. 2007, Van Loon et al. 2012). An important milestone was the finalisation of the diffusion and retention (DR) experiment at the Mont Terri URL. A cocktail of radionuclides was circulated in a borehole, resulting in a field database that complements the databases from experiments at laboratory scale. Important progress was made in the understanding of the effect of the rock anisotropy, the anion-accessible porosity, the differences in penetration depth of tracers and the effect of a borehole disturbed zone on the diffusion of nuclides (Gimmi et al. 2014). In SGT Stage 2, an empirical approach was derived at PSI using a comprehensive set of diffusion data from different argillaceous rocks and compacted clay (Van Loon 2014, Van Loon & Mibus 2015). This approach considers the effects of anion exclusion, surface diffusion, temperature and anisotropy on the diffusion coefficient.

Sorption of radionuclides onto clay surfaces

The methodology for deriving sorption databases for argillaceous rocks (partly also applicable to crystalline rocks) has been advanced during the last two decades at PSI (Bradbury & Baeyens 1997a and 2003, Bradbury et al. 2008 and 2010). The latest approach, used in SGT Stage 2, is based on sorption isotherms derived from measurements on pure clay minerals and considers the mineralogy of the rock, the pH of the solution, the speciation of the radionuclides and the transfer from lab to field (Baeyens et al. 2014a). The method is adapted to so-called 2:1 clay minerals (e.g. illite, montmorillonite) which are proxy minerals for clay minerals dominating sorption in Opalinus Clay. The approach is supported by a large number of sorption measurements (e.g. Baeyens et al. 2014b), an advanced sorption model (2 Site Protolysis Non Electrostatic Surface Complexation and Cation Exchange (2SPNE SC/CE) developed for montmorillonite (Baeyens & Bradbury 1997a and Bradbury & Baeyens 1997b) and illite (Bradbury & Baeyens 2009a and b), spectroscopic measurements on the surface speciation of sorbed radionuclides (Marques Fernandes et al. 2010, Daehn et al. 2011) and atomistic modelling (Churakov & Daehn 2012). Some aspects of the work are highlighted in sections 5.3.3 and 6.2.

The datasets of other waste management organisations with clay-based programmes use host rock-specific datasets derived from different sources. Andra's diffusion datasets are based on an extensive measurement programme addressing similar effects as in the Swiss programme mentioned above. The sorption values in Andra (2005) are taken directly from batch sorption

experiments on core samples of Callovo-Oxfordian Clay, from systematic and mechanistic studies on pure clay minerals (mainly illite) or from chemical analogy for elements for which no sorption data exist.

Concepts for radionuclide transport in safety analysis

Within the framework of Sectoral Plan Stage 2, concepts for radionuclide transport were developed for the provisional safety analyses (Nagra 2014b, Nagra 2014c). The concepts consider diffusive transport in Opalinus Clay and a variety of scenarios of diffusive and advective-dispersive transport in the confining units. In addition to the available field data, the clay mineral content of the lithofacial units served to estimate the bounds of the hydraulic properties of fractures and faults (Fig. 7-7).

The siting activities planned for SGT Stage 3 will provide site-specific validation of these concepts and refinements of the geo-datasets. Key contributions of the investigations in SGT Stage 3 with respect to the concepts of radionuclide transport include:

- Refined knowledge of the thickness and lateral continuity of the lithofacial units in the siting areas, including the expected inventory of discrete elements.
- Site-specific datasets of key properties of the lithofacial units such as porosity, mineralogy, diffusion properties, hydraulic conductivity and transmissivity.
- Additional datasets and observations to constrain the concepts (e.g. water-conducting features, tracer profiles).
- Site-specific state conditions (e.g. hydraulic heads).

Regarding the Opalinus Clay, the investigations are expected to provide site-specific validation of the existing concepts, such as dominant diffusive transport and the absence of relevant advective flow along fractures or faults. In addition, the new datasets will provide the basis for better constraining the variation of properties such as porosity or mineralogy within the siting areas. This will allow better framing of the uncertainty in the dose calculations.

The confining units can substantially contribute to the overall barrier function of the geosphere. In comparison to Opalinus Clay, they are characterised by a more heterogeneous lithology and typically lower clay mineral contents. It is expected that advective transport in water-conducting features (fracture systems, faults) may be important for some lithofacial units. In order to better frame the properties of subvertical faults or fracture systems, the field exploration programme foresees inclined boreholes.

As shown in Fig. 7-7, in SGT Stage 2, a reference situation is defined where the release point is set in the first intersected layer where horizontal transport in a fractured layer is most plausible. Uncertainties in the existence of water-conducting horizontal layers are expressed in alternative assessment cases. The length of the transport pathways is derived from the thickness of the sedimentary units considered. Again, uncertainties are taken into account in alternative assessment cases.

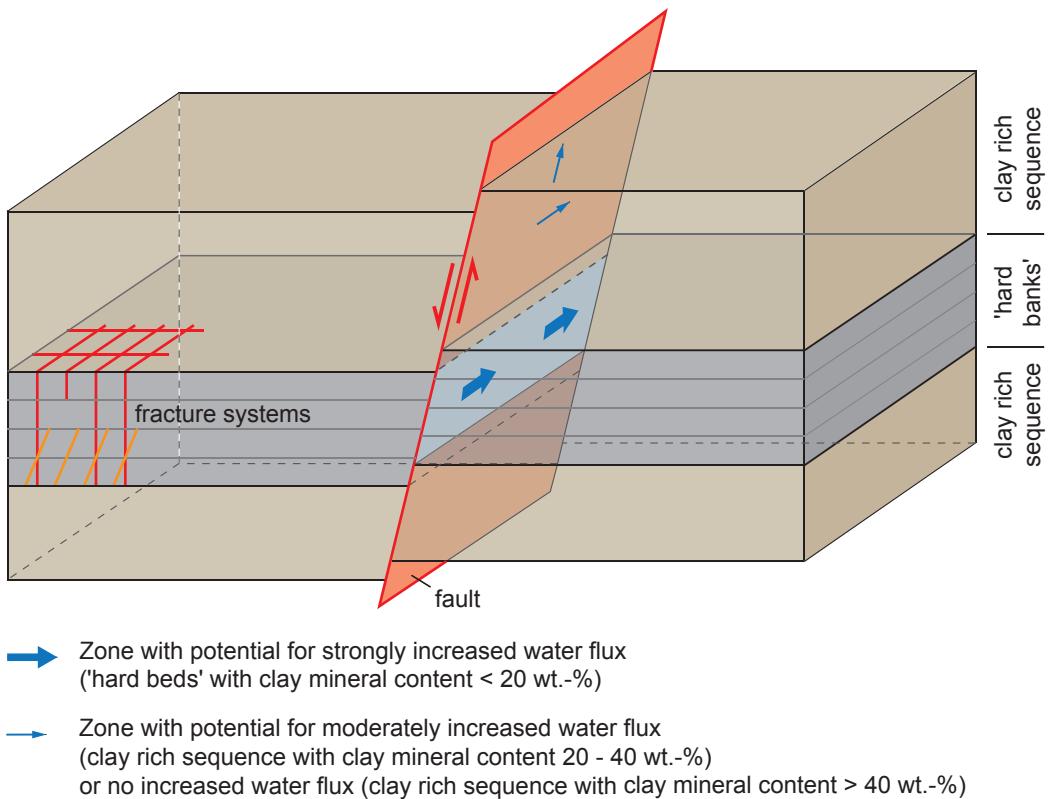


Fig. 7-7: Schematic representation of potentially water-conducting features in a system of clay rocks with intercalations of 'hard beds' (from Nagra 2014b).

Planned RD&D in the next 5 to 10 years

The following refinements to reduce remaining uncertainties are foreseen.

Diffusive and advective/dispersive transport in the host rock and confining units

A topic in the geochemistry of radionuclides in clay systems that is internationally acknowledged is the transferability of sorption data measured and modelled in dispersed systems (low solid/liquid ratio) to the compact system of the host rock. For some elements (e.g. Na, Cs, Sr), experiments and modelling support this transferability (Van Loon et al. 2005b and 2009). For strongly sorbing tracers, first diffusion experiments have been carried out within the EU project CATCLAY (e.g. Glaus et al. 2015). Building on this, a systematic comparison of sorption values from dispersed (classical batch) systems with data from diffusion experiments in compact systems will be made. Additionally, in further diffusion experiments using strongly sorbing tracers, e.g. transition metals, it will be studied whether these elements migrate by surface diffusion. Special focus will be placed on the aqueous chemistry in the narrow pore space where overlapping near-field electric double layers may change the physico-chemical properties of water. The experimental work will be accompanied by modelling studies.

The conceptual models of radionuclide transport in safety analysis are considered to be substantiated and robust. In the next years, it is foreseen to increasingly adopt integral hydraulic situations from hydrogeological modelling in scenario development and analysis. This also includes the long-term evolution of distinct hydraulic situations and their corresponding likelihood. This will further improve consistency between the understanding of geological and hydro-

geological evolution on the long term and the abstractions used in safety analysis. Further, the site-specific understanding of the hydrogeological conditions, especially the hydraulic properties of the confining units, will be improved (see section 7.2.2.4). This, in turn, will allow a further reduction of uncertainties in the conceptualisation of radionuclide transport in safety analysis.

Sorption of radionuclides onto clay surfaces

The existing sorption database will be further developed in the next years.

The development of the so-called "bottom-up approach" based on mechanistic understanding of sorption processes on pure clay minerals (Bradbury & Baeyens 2011, Marques Fernandes et al. 2015) will be continued. Sorption modelling on single minerals will be used to understand and to predict radionuclide sorption in more complex porewater/mineral systems. To this end, thermodynamic sorption databases consisting of model parameters (site types, site capacities, surface complexation constants, selectivity coefficients) for montmorillonite and illite will be developed. Until now, the competition of radionuclides for sorption sites was only considered in a simplified way in safety analysis. In the next years, existing experimental results in multi-element systems at various concentrations will be modelled and complemented by spectrometric measurements to identify the speciation of the sorbate. The application of the "bottom-up approach" aims to take into consideration the concentration dependence of sorption, competing sorption processes and also to better reflect the porewater chemistry in the rock units when deriving sorption databases for safety assessment. Consequently, the new approach will facilitate adaptation of sorption data to site-specific and realistic porewater conditions.

The sorption behaviour of some redox-sensitive radionuclides is still subject to uncertainty. In sorption experiments under controlled redox conditions, spectroscopic measurements and modelling, the sorption of U(IV), Np(IV), Tc(IV) and Se(-II) will be characterised and quantified.

Aqueous Fe will be present in porewater due to corrosion of steel. Sorption competition of radionuclides with major and trace elements (including Fe(II)/Fe(III)) is still subject to uncertainty and will be further investigated experimentally to provide a basis for the improved description of sorption competition phenomena.

In addition to studies on release and stability of ^{14}C compounds in the near-field (see sections 7.3.3.4 and 7.5.4), the behaviour of low molecular weight organic compounds in the host rock will be further studied to assess their impact on ^{14}C transport in the geosphere and implications for dose calculations. This is being investigated in an ongoing PhD project deriving quantitative relationships between the sorption properties and structural elements of organic model compounds.

7.2.3.2 Gas transport

Objectives

Various gases may be produced in both the HLW and L/ILW repositories, principally as a result of the corrosion of metals and (microbial) degradation of organic matter (section 7.3.3.5). Gases will be dissolved in the porewater and eventually, when the solubility limit is exceeded, a separate phase may form. The principal impacts of gas are expected to be increased pore pressures and thus changes in effective stress in the surrounding host rock, associated with

potential effects on integrity of the host rock (reactivation of natural faults, creation of gas fractures). In addition, the creation of a sustained gas pressure in the near-field may affect water flow in the host rock, ramp/access tunnel and shaft and thus have some effect on the transport of dissolved and volatile radionuclides. It thus needs to be ensured that gas does not significantly and adversely affect the barrier function of the host rock and the safety function indicator criteria defined related to overpressures are fulfilled.

In this section, emphasis is given to the phenomenological understanding of gas transport processes in the Opalinus Clay and the associated mechanical impact on the rock matrix. The simulation of the associated gas transport and deformation mechanisms is done with THM process models, which are based on unsaturated, non-isothermal constitutive laws. The fundamental understanding of how gas can be released through the intact Opalinus Clay matrix and along discrete fractures (including the mechanism of fracture activation) serves as a basis for the conceptualisation of gas transport in the near-field. The enhanced understanding of the evolution of the safety-relevant properties and processes in the near-field by model-based gas transport analyses is assessed in sections 7.5.2.1 (HLW) and 7.5.2.2 (L/ILW). Gas generation including the possibilities for its reduction are discussed in section 7.3.3.5. The phenomena and processes associated with the biogenic consumption of corrosion gases (hydrogen) are treated in section 7.2.3.6.

Current state-of-the-art and progress since the 2009 RD&D Plan

Gas transport through low-permeability rock formations is controlled by the hydraulic and mechanical properties of the rock mass (intrinsic permeability, porosity, rock strength), by the pore pressure, water saturation and the in-situ stress state of the host rock and by the gas source term (including potential gas-consuming processes, i.e. sinks) in the backfilled underground structures. Nagra has contributed significantly to the understanding since the gas issue was identified as being potentially safety-relevant in the late nineties (Nagra 1997, Nagra 2004, Marschall et al. 2005, Croisé et al. 2006, Nagra 2008g, Marschall et al. 2013). A conceptualisation of the transport mechanisms of gas in Opalinus Clay has been proposed by Nagra (Marschall et al. 2005) and confirmed on several occasions (Nagra 2008g, Senger et al. 2013). Phenomenological considerations suggest the following basic transport mechanisms (Fig. 7-8):

- Advection-diffusive transport of gas dissolved in the porewater
- Visco-capillary two-phase flow (flow of immiscible fluids in a poro-elastic porous medium)
- Dilatancy-controlled gas flow (flow of immiscible fluids associated with subcritical crack growth)
- Gas transport along macroscopic tensile fractures (hydro- and gas-fracturing, associated with supercritical crack growth)

The phenomenological description of flow and transport processes is related to the microstructural conceptualisation of the porous medium. In ultra-low permeability rock such as the Opalinus Clay, a network of connected pores in the range of micro- to nanometres defines the space where flow of immiscible fluids can occur (Keller et al. 2013a and b). Assuming that the skeleton of the solid rock matrix is subjected to elastic deformations only – in other words, the void volume of the pore network remains essentially constant – the flow of liquids and gases in the porous network can be described by well-known hydrodynamic approaches, such as (multi-phase) flow in equivalent porous media and flow in channel/fracture networks, respectively (Neuweiler et al. 2004, Marschall & Lunati 2006, Wettstein et al. 2012).

Since Nagra (2009a), significant confirmation of the phenomenological understanding of gas transport in disturbed and undisturbed Opalinus Clay and similar host rock types has been obtained through Nagra's participation in the EURATOM NF-PRO (near-field processes) and especially the FORGE (fate of repository gases) projects (Marschall et al. 2013, Harrington 2013), as well as the SHARC collaboration project (SHARC 2010, 2012 a, b and c). In the FORGE project, the focus was on the interpretation of gas-related laboratory and in-situ experiments, formerly conducted at the Mont Terri URL (HG-A and HG-D experiment, respectively). The existing database of two-phase flow parameters (capillary pressure curves, relative permeability, gas entry pressure) of the Opalinus Clay was extended by inverse modelling of in-situ gas threshold pressure tests. Furthermore, the regime of pathway dilation was investigated by model-based analyses of gas permeability tests in triaxial cells. In the SHARC project, water retention measurements, gas permeability tests and microstructural pore connectivity measurements on Opalinus Clay samples from the Schlattingen-1 borehole were conducted, providing information on the gas transport capacity of the Opalinus Clay at greater depth (850 – 950 m). Within the framework of SGT Stage 2, the extension of the experimental database (Senger et al. 2013) formed the key input for the site-specific sensitivity studies of gas overpressures in the repositories for SF/HLW and L/ILW, respectively (Papafotiou & Senger 2014c, d and e). The model analyses indicated that the development of gas overpressures in the backfilled repository structures are manageable for all assessed geological settings based on the currently available information.

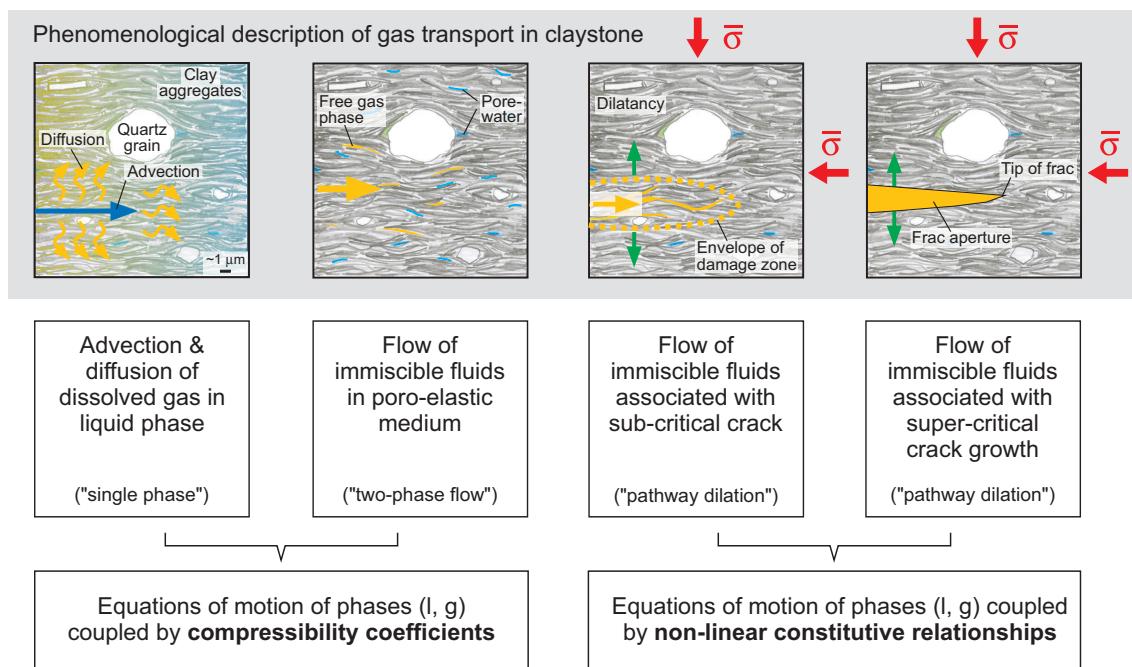


Fig. 7-8: Classification and analysis of gas transport processes in ultra-low permeability rock such as the Opalinus Clay (from Senger et al. 2013).

Planned RD&D in the next 5 to 10 years

In SGT Stage 3, site-specific model analyses of gas release are envisaged, demonstrating that the build-up of gas overpressures in the backfilled repository structures will not impair post-closure safety. This includes a detailed assessment of the role of the host rock as a potential escape route for the repository gases which will be based on:

- Robust empirical evidence to support the conceptual understanding of the relevant phenomena and processes in the host rock.
- A reliable experimental database, representing the relevant gas transport mechanisms and the corresponding gas-related properties of the host rock (expected values and uncertainties). This includes gas transport in the pore network of the intact/dilated rock matrix and gas transport along (re-)activated fractures.
- Adequate modelling tools for site-specific model analyses of gas transfer through the host rock (matrix flow and fracture flow, respectively).
- Evidence from in-situ (validation) experiments, demonstrating the transferability of gas transport mechanisms and the corresponding properties from the lab scale (centimetre scale) to the tunnel scale (decimetre to metre scale).

The focus of the activities in the next years will be to refine and complete the elements above, and more specifically on:

- Completion of the SHARC-II joint industry framework (2014 – 2016) on gas shales (as certain of their properties show great similarity to Opalinus Clay). The project will contribute to the extension of the existing experimental database on the relevant gas transport mechanisms and the corresponding gas-related properties of the Opalinus Clay.
- Development and benchmarking of upscaling techniques for modelling gas transport in heterogeneous media (porous media, fractured media) within the framework of existing international collaborations (EBS Task Force) and with Nagra's research partners (ETHZ, ZHAW, EPFL). Modelling gas percolation processes through different facies of the Opalinus Clay with distinct spatial variability will provide guidance for upscaling two-phase flow parameters from the core scale to repository scale. In addition, recent developments of percolation models (Wettstein et al. 2012) will be completed, providing methods for upscaling gas transfer through fracture networks and along the EDZ around sealed tunnel sections.
- Optimisation of the in-situ gas test programme as part of the upcoming site investigations. In this context, detailed characterisation of hydromechanical site conditions at the experimental site is a necessary prerequisite for demonstrating the transferability of the gas-related results from Mont Terri to the conditions at the candidate sites in Northern Switzerland.
- Ongoing survey of the state-of-the-art through literature studies on specific topics (gas sorption, saturation-dependent diffusion coefficients, natural gas seeps and case studies of the failure of natural gas storage systems, large scale onshore CO₂ studies providing further information regarding potential induced seismicity).

7.2.3.3 Geomechanical processes

Objectives

Geomechanical processes control rock mass behaviour and hydraulic properties of the host rock. They are therefore relevant for different functional requirements such as tunnel support design and maintaining the barrier function after emplacement. Extensive experience was gained from mine-by tests and excavation work at Mont Terri and from underground work in similar claystones (e.g. the Callovo-Oxfordian at the Meuse-Haute Marne URL, France), as well as from laboratory tests on Opalinus Clay cores from deep wells. Transfer of these empirical data from laboratory tests to the scale of underground structures and from Mont Terri to the potential repository site by taking into account the different geological conditions needs to be established as far as this can be justified by the amount of data available.

This requires robust laboratory testing on cores taken at a depth range covering the future repository level, as well as the further development of a rigorous constitutive framework. The effect of the variation in tectonic disturbance between Mont Terri and the candidate repository sites in Northern Switzerland also needs to be accounted for in transferring experience gained at the Mont Terri URL.

It needs to be acknowledged that underground access is required to fully validate and refine the framework.

Mechanical processes related to gas pressure build-up (pathway dilation, fracture reactivation) are assessed in section 7.2.3.2. Mechanical processes related to thermal effects caused by the heat-emitting SF/HLW (thermal compaction, fracture reactivation) are discussed in section 7.2.3.4.

Current state-of-the-art and progress since the 2009 RD&D Plan

Opalinus Clay exhibits a strong hydromechanical coupling stemming from a combination of low hydraulic diffusivity, relatively large pore volume and low compressibility of the solid. The coupling is observed in laboratory testing at the core scale (Giger & Marschall 2014) and also in instrumented mine-by tests at Mont Terri (e.g. Lanyon et al. 2014a).

The hydromechanical coupling is expressed in the following three key categories characterising the geomechanical behaviour of Opalinus Clay:

- *Volumetric behaviour:* Change in mean stress leads to a reduction (consolidation) or increase (swelling, see self-sealing in section 7.2.3.5) of pore space under drained conditions. Mechanical properties such as stiffness and strength are directly related to the consolidation state of Opalinus Clay (Giger & Marschall 2014). It is noteworthy that porewater drainage or uptake is time-dependent and controlled by the low permeability of Opalinus Clay.
- *Shear behaviour:* Shear is related to a change in the deviatoric stress. Theoretical analyses of anisotropic (transverse isotropic) materials such as Opalinus Clay suggest that changes in the deviatoric stress during excavation can lead to volumetric strains which, in turn, can lead to elevated pore fluid pressures (Graham & Houlsby 1983), and hence to stress conditions favouring yielding. Failure in Opalinus Clay is characterised by strain localisation (development of rather discrete shear planes) and noted as strain-softening (reduction of deviatoric stress with increasing strain after reaching a peak value).

- *Retention behaviour:* Unsaturated conditions (matrix suction) and chemical imbalance of the pore fluid (osmotic suction) can affect the properties of laboratory samples (e.g. Ferrari et al. 2014b, Wild et al. 2015). It was also demonstrated at the Mont Terri URL that cyclic deformation of tunnel surfaces due to seasonal variations in humidity and temperature may lead to progressive degradation of the tunnel wall (e.g. EZ-B niche, Möri et al. 2012). Control of relative humidity (ventilation) is therefore noted as a key aspect to be considered in underground structures.

Quantifying the underlying physical processes controlling the geomechanical behaviour of Opalinus Clay requires robust testing in the laboratory. This is particularly challenging for materials with strong hydromechanical coupling, as it calls for very careful sampling and handling of core material and appropriate test protocols involving proper saturation and consolidation with balanced pore fluids prior to deformation testing. There has been general recognition of these aspects within the EU TIMODAZ project (thermal impact on the damaged zone around a radioactive waste repository in clay host rock) (e.g. Li 2011). Other clay-based programmes (Andra in France, ONDRAF/NIRAS in Belgium) have also ranked appropriate and careful geomechanical testing as a key priority. Nagra is currently making significant progress in this area within the SHARC joint industry framework (SHARC 2010, 2012a, b and c) and with a number of research projects (Ferrari & Laloui 2013, Ferrari et al. 2014a). Several other studies have highlighted the importance of appropriate testing for similar materials to Opalinus Clay (e.g. Menaceur et al. 2015).

There is evidence that mineralogical and structural variability within the Opalinus Clay can strongly impact the geomechanical behaviour. This has been observed in laboratory testing (e.g. Bossart & Thury 2008, Ferrari et al. 2010) and in deep boreholes (e.g. Matter et al. 1987 and 1988, Nagra 2001, Ebert 2014). At the Mont Terri URL, convergence data indicate strong differences between the "shaly" and "sandy facies" of the Opalinus Clay (Lanyon et al. 2014b), as well as across fault zones within the same "facies" (Thöny 2014). Detailed microstructural investigations are currently also devoted to this aspect within the SHARC research initiative (e.g. SHARC 2010, 2012a, b and c).

The current constitutive law developed for Opalinus Clay is an elasto-plastic material law which combines critical state soil mechanics with the Hvorslev limit state (Nagra 2014b). It accounts for stress-dependent properties as a function of the consolidation state, but aspects related to capturing post-failure behaviour, dealing with anisotropy and time-dependent behaviour need to be further assessed and possibly integrated.

The recognition and quantification of the retention properties of Opalinus Clay (e.g. Ferrari et al. 2014b) represents a major advance in the geomechanical understanding of Opalinus Clay since the 2009 RD&D Plan. The retention properties highlight the effect of unsaturated conditions on the mechanical behaviour of Opalinus Clay and this is of particular relevance for designing certain elements of the underground construction (tunnel support, ventilation) as well as the definition of appropriate geomechanical testing protocols.

Planned RD&D in the next 5 to 10 years

The geomechanical database will be complemented by new laboratory tests. In a first step, testing protocols will be developed which take into account insights gained from detailed sample characterisation (e.g. Ferrari et al. 2014b) and will involve careful monitoring of sample saturation and volumetric equilibrium during the consolidation phase. Testing may involve novel equipment (e.g. Monfared et al. 2011) and alternative stress paths to better mimic the excavation behaviour (e.g. triaxial unloading rather than loading). Progress in geomechanical

testing will be discussed in close interactions with sister organisations focusing on clay-based host rocks (Andra and ONDRAF/NIRAS in particular) and industry partners and in other platforms (i.e. SHARC framework and Mont Terri URL).

Particular attention will be given to linking the results of deformation tests to mineralogy and attempts to establish a facies-specific database. Robust geomechanical tests should also be able to quantify pore pressure coupling parameters and thereby provide additional confidence in the effective stress concept used to assess the mechanical behaviour of Opalinus Clay. Digital rock methodology (3D imaging combined with numerical modelling) is a complementary approach to mechanical testing to gain insights into the elastic properties (Keller 2016).

With more robust testing protocols and a larger database, it is anticipated that constitutive models can be refined by better integrating mineralogical variability, material anisotropy and the post-failure domain (e.g. structural disturbance), hereby including time-dependent processes.

7.2.3.4 Thermal effects

Objectives

SF/HLW is heat-emitting immediately after emplacement and for many decades thereafter. In this early phase, due to differential thermal expansion of water and minerals, Opalinus Clay reacts to a temperature increase with a rise in the porewater pressures and associated mechanical effects. The thermo-hydro-mechanical (THM) response of the Opalinus Clay and the upper confining units needs to be sufficiently understood to assess the consequences with respect to its safety functions as a transport barrier for dissolved radionuclides and to assess the impact on the overburden (surface heave) and potential neighbouring faults. Pore pressures need to remain below a specified threshold to ensure that the natural barrier is not subject to potential damage or induced seismicity. This threshold defines the safety function indicator criterion for bounding the repository-induced effects due to hydraulic overpressures. Mechanical (plastic) deformation and the associated impacts on the hydraulic rock properties that could occur if the threshold is exceeded are discussed in section 7.2.3.3.

The objective of the work is to characterise the impact of heat on the integrity of the host rock and the upper confining units under conditions as close as possible to those anticipated in the repository with particular focus on:

- Extension of the experimental THM database, providing new insights into the long-term deformation behaviour of Opalinus Clay and the upper confining units in response to thermal perturbations (thermal consolidation, thermally induced loss of strength and enhanced creep).
- Development of advanced THM process models, integrating new experimental evidence from long-term laboratory and in-situ experiments.
- Evaluation of THM models within the framework of benchmark exercises at the tunnel scale (model validation).
- Reliable assessment of expected overpressure developments and the risk of fault (re-) activation at the repository scale for the selected sites.

These models contribute significantly to the definition of the requirements with respect to the optimisation of the thermal loading of the canisters as well as the minimum required spacing between the waste and between the emplacement drifts and thus to the optimisation of the overall layout and the footprint of the HLW/SF repository.

Although increased temperatures can potentially also influence chemical processes, these are not the focus as the temperature increase is limited to below the paleotemperature of the Opalinus Clay and is of short duration (order of a few decades).

Current state-of-the-art and progress since the 2009 RD&D Plan

The thermal impact on the Opalinus Clay (and adjacent layers) is characterised by strongly coupled behaviour. Gens et al. (2007) state that the strongest coupling is from thermal to hydraulic and mechanical behaviour. Pore pressure increase is controlled primarily by temperature increase and the largest contributor to deformation and displacement is thermal expansion. Significant but more moderate effects are identified from the coupling of hydraulic to mechanical behaviour. The dissipation of pore pressures induces additional displacement and strains, but, because of the large clay stiffness, these are smaller than the thermally induced deformations. Other couplings are likely to have a smaller impact.

Since Nagra (2009a), significant progress has been made in characterising the thermal impact, both at the URL scale and with respect to modelling approaches used to assess the impact under repository-relevant conditions.

At the laboratory scale, THM tests on Opalinus Clay samples from Mont Terri and the Schlattingen-1 borehole were conducted as part of the SHARC project (SHARC 2012c). The experiments include suction measurements, oedometer tests and triaxial tests on core specimens in the temperature range 20 – 80 °C. An advanced constitutive model has been developed as part of an ongoing PhD thesis (Favero *in prep.*), which describes the non-isothermal deformation behaviour of unsaturated Opalinus Clay.

The thermal conductivity of Opalinus Clay and other argillaceous rocks was fitted on the basis of several Mont Terri URL experiments (Garitte et al. 2014).

The in-situ characterisation of the thermal impact is of particular importance due to its strongly coupled nature and a series of heater tests, with increasing complexity, have been designed and constructed. After conducting and interpreting the first heater tests in direct contact with the Opalinus Clay (Wileveau & Rothfuchs, 2007), the HE-E experiment at the Mont Terri URL was started in 2011. This is a 1: 2 scale heater test (heater surface temperature of 140 °C) (Gaus et al. 2014a and b), which allowed the prediction and then measurement of the thermally induced overpressures, as well as their dissipation. Measured results were in good agreement with state-of-the-art THM models (Gaus et al. 2014b). With a constant heater temperature, a maximum hydraulic overpressure of 1 MPa was measured, which started reducing quite rapidly. These observations and the corresponding modelling framework will be confirmed and refined in the years to come based on the monitoring data from the FE experiment, the 1:1 scale heater test at the Mont Terri URL initiated in early 2015 (Müller et al. 2017; section 6.2).

Large 1:1 scale experiments, based on a single canister or a tunnel section with several canisters, have also been designed and constructed in other programmes and full-scale demonstrations are being analysed at the Meuse-Haute Marne URL (France) as part of the LUCOEX project (Euratom 7th Framework), in which Nagra also participated, and at the HADES URL (Belgium) where the large-scale PRACLAY test was initiated in early 2015 (Li et al. 2013).

At the larger repository scale, one must rely on THM models that have been informed by the outcome of laboratory and URL experiments. 3D repository-scale elastic THM modelling of the Opalinus Clay and overburden has been performed (Te Kamp & Konietzky 2009), assessing the thermally induced hydraulic overpressures and the earth's surface heave. Other approaches

using the TOUGH code (Senger et al. 2014a) and 3D calculations addressed the thermal impact in a similar fashion, but also incorporated other mechanisms (such as unsaturated conditions and gas generation) that contribute to the development of hydraulic overpressures. The assumptions underlying both approaches have been compared. So far these approaches assume a fully elastic and homogeneous behaviour of the geological units.

On the site scale, non-isothermal hydraulic models (Papafotiou & Senger 2013, 2014a and b) have provided valuable information for bracketing the effective thermal conductivity of the intact Opalinus Clay, by inverse modelling of temperature profiles from temperature logs in deep boreholes.

Planned RD&D in the next 5 to 10 years

Long-term laboratory tests aimed at bracketing the stiffness behaviour, strength degradation, creep and thermal conductivity of Opalinus Clay at elevated temperature will continue in collaboration with LMS/EPFL²⁸. The dependence of the non-isothermal deformation behaviour on Opalinus Clay properties (e.g. mineralogical composition and pre-consolidation pressure) will be investigated as a prerequisite for site-specific assessments.

The HE-E and FE experiments (see section 6.2) at the Mont Terri URL will be continued for several years. The increasingly extensive dataset will allow significant model validation and refinement. As part of the Mont Terri programme and international modelling networks, expert modelling teams incorporating new approaches in their models will contribute to the interpretation. Based on the outcome, a smaller scale experiment aimed at characterising the thermal impact of multiple emplacement drifts (rather than one as represented by the FE experiment) may be considered at the Mont Terri URL if required.

Through international collaboration, the results of ongoing large-scale experiments in foreign URLs will be integrated, leading to more comprehensive understanding of the mechanical and hydraulic response of the thermal pulse in different types of clay rocks.

The large repository-scale models will be refined and the boundary conditions and parameters (initial temperatures, mechanical properties of the rock) will be adjusted to those encountered at the selected sites based on the results of the drilling programme in SGT Stage 3. On the site scale, detailed statistical analyses of the geothermal gradients in the host rock and the confining units with temperature profiles from shallow boreholes will provide complementary input for the site-specific THM models.

Large-scale geomechanical model development for real sites in related domains (e.g. applications for hydrocarbon and geothermal purposes) will be monitored to assess if these can enhance understanding.

²⁸ Note, a PhD thesis on THM modelling of the SF/HLW near-field has been initiated recently by swissnuclear in collaboration with LMS/EPFL. The project is followed closely by Nagra.

7.2.3.5 Self-sealing

Objectives

Self-sealing is a favourable feature of the Opalinus Clay, ensuring the restoration (recovery) of the barrier function of the rock when fractured. The capacity of the rock to self-seal is of special significance in the context of repository-induced effects (damage of the host rock in response to the excavation processes, gas- and thermally induced overpressures) and long-term geological evolution (fault (re-)activation in response to neotectonic processes, erosion and glaciation).

The concept of self-sealing assumes that the transmissivity of fractures is restricted when sufficient mechanical confinement of the rock is ensured (typically $T_f < 1 \times 10^{-10} \text{ m}^2/\text{s}$ when mean effective stress $> 3 \text{ MPa}$, corresponding to an overburden of $> 200 \text{ m}$).

The objective of the work is to further increase confidence in the self-sealing process and further constrain the range of conditions and properties under which this occurs. A particular focus will be on:

- The collection of further phenomenological and experimental evidence, confirming the effectiveness of the self-sealing capacity of clay-rich rock for a wide range of THM conditions
- Refinement of mechanistic (conceptual) models of self-sealing and implementation in application-oriented numerical simulation tools
- Further confidence-building by advanced in-situ validation experiments (Mont Terri URL)

Current state-of-the-art and progress since the 2009 RD&D Plan

The state-of-the-art with respect to self-sealing is mature. Based on early phenomenological evidence on the restricted transmissivity of fractures in Opalinus Clay when the overburden exceeded approximately 200 m (Gautschi 2001, Nagra 2002b), several major research programmes have been launched to investigate in detail the self-sealing mechanisms in clay-rich formations. Early conceptual frameworks were established in Nagra (2004). The impact of EDZ self-sealing on radionuclide transport along the backfilled underground structures of a geological repository for SF/HLW in the context of safety assessment was illustrated by Smith et al. (2004). Substantial experimental efforts have been invested on the laboratory and the field scale as part of the Euratom Programme, including the EB experiment (Mayor et al. 2007), the SELFRAC project (Bernier et al. 2007) and the NF-PRO initiative (Aranyossy et al. 2008). A state-of-the-art review report on self-sealing of fractures in argillaceous formations in the context of geological disposal of radioactive waste was compiled by Bock et al. (2010).

From a phenomenological perspective, the following self-sealing mechanisms were identified as important:

- Compaction of the solid framework (consolidation)
- Mechanical closure of fractures (increased normal stress, contractant shear, "creep")
- Physico-chemical interaction between porewater and clay platelets (swelling)
- Sedimentation (colloidal phases) and precipitation (solute) on fracture walls

Various direct shear test studies on Opalinus Clay have been performed by the British Geological Survey (e.g. Cuss et al. 2011), with the focus on gas permeability, demonstrating that shearing is an efficient self-sealing process on the laboratory scale. At the Mont Terri URL, new experimental evidence has been gained at the field scale on the efficiency of self-sealing mechanisms which prevent axial flow around the inflated megapacker system in the HG-A microtunnel (Lanyon et al. 2014a).

As part of the FORGE Project (EU 7th Framework Programme), extensive experimental evidence has been collected and numerical modelling efforts have been conducted to address the efficiency of the EDZ in clay-rich host rock formations as a preferential flow path (Harrington 2013). In this context, several studies addressed the self-sealing capacity of Opalinus Clay (Alcoverro et al. 2013, Marschall et al. 2013).

Simple hydromechanical fracture closure laws have been implemented in numerical EDZ models to simulate the impact of fracture self-sealing on the hydraulic conductivity of the EDZ around a backfilled tunnel (Lanyon & Senger 2011, Alcolea et al. 2014; see also Fig. 7-9). The modelling approach by Alcolea et al. (2014) was benchmarked with in-situ data from the HG-A (gas path through host rock and seals) experiment at Mont Terri (Alcolea et al. *in prep.*).

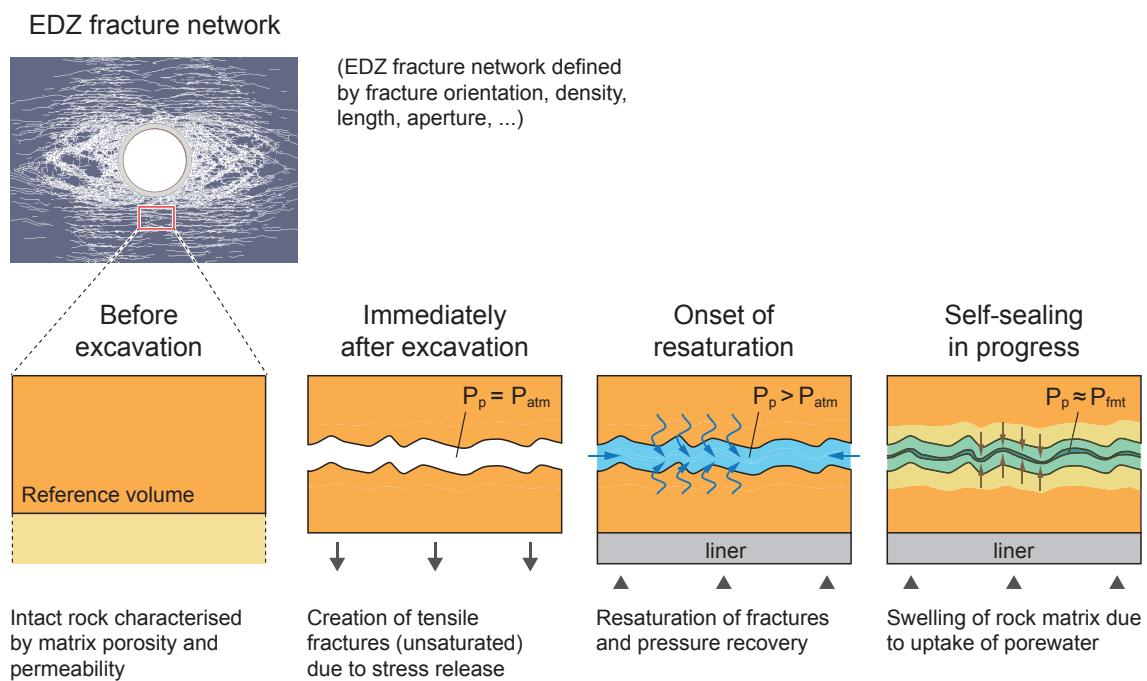


Fig. 7-9: Schematic representation of the conceptual framework for EDZ fracture closure in Opalinus Clay, covering the key phenomena and features from the early post-excavation phase until static formation pressure recovery (after Alcolea et al. 2014).

Planned RD&D in the next 5 to 10 years

To further reduce remaining uncertainties, advanced hydromechanical laboratory tests (shear box, triaxial cell) aimed at separating the impact of different mechanisms on the self-sealing process (closure laws for normal and shear stress, chemico-osmotic closure processes, impact of temperature) will be continued in collaboration with expert geomechanical laboratories. A particular focus will be on the impact of the mineralogy of the rock (facies variability) on the self-sealing process.

Conducting experiments further characterising fracturing and self-sealing will be evaluated. The main focus of these experiments will be on self-sealing of (reactivated) tectonic rather than excavation-induced structures. Following reactivation or generation of a fracture surface (e.g. by mechanically (hydrofracking) or thermally induced fluid overpressure), its closure and associated hydraulic and strength properties will be studied.

Through international collaboration, the results of ongoing large-scale experiments in foreign URLs will be integrated (large-scale gas injection test GPZ-1, Meuse/Haute Marne URL), leading to a more comprehensive understanding of the hydromechanical and hydrochemical processes which control the self-sealing capacity of clay-rich rocks. Furthermore, the state-of-the-art regarding fault permeability investigations in related industries (geothermal, hydrocarbon) will be surveyed.

Development of advanced modelling tools will assess the reactivation/closure of tectonic fracture systems in response to repository-induced effects and long-term geological evolution. For this, the detailed mechanistic understanding of closure/reactivation mechanisms at the scale of geomechanical laboratory tests must be linked to the geomechanical conditions at the repository scale (see also section 7.2.2.3), including the impact of the near-tunnel stress fields, the observed temperature distribution and the spatial variability of hydromechanical properties.

7.2.3.6 Microbial processes

Objectives

Undisturbed Opalinus Clay has been shown to have very limited pore space (Keller et al. 2013b), thus limiting any microbial activity. The formation of an EDZ alters (possibly temporarily) the properties of the host rock adjacent to the emplacement rooms, sealing zones and other underground structures. This is likely to result in an increased porosity, leading to a higher hydraulic conductivity and gas permeability (Nagra 2014h) and thus potentially providing more space for microbial activity (Stroes-Gascoyne et al. 2007 and Stroes-Gascoyne 2011). Wherever the porous structure of Opalinus Clay has been disturbed and favourable conditions are present, microbial activity cannot be excluded. In general, it can be concluded that microbial activity might be expected where physical and chemical conditions such as the required water activity, physical space and available substrates allow for it. In densely emplaced bentonite, like undisturbed Opalinus Clay, microbial activity is highly limited or non-existent.

Microbiological activity in the near-field of a repository in a clay host rock may result in:

- Microbially influenced corrosion (MIC) in the case where the bentonite is not performing as required; this could reduce the longevity of the waste containers (King et al. 2010). MIC would occur through the formation of corrosion-inducing aggressive environments under biofilms or through the production of corrosive metabolites. For the latter, sulphate-reducing bacteria (SRB) that produce sulphide are of specific concern (see discussion in sections 7.5.3.1, 7.5.3.3 and 7.5.3.5).

- Microbial activity could reduce the gas pressure build-up resulting from anoxic corrosion of the waste containers by oxidising H₂ gas anaerobically, or possibly by the formation of CH₄ from H₂ and CO₂ (Madigan et al. 2015). These possible microbial gas sinks are discussed in detail in Leupin et al. (2016a and b) and in the following paragraphs.
- Microbial gas production (mainly CO₂ and CH₄) may contribute to the build-up of a gas phase in a repository. These processes are considered in the assessment of the gas-related issues in a L/ILW repository (Diomidis et al. 2016) and have been shown to have no negative effect on the performance of the repository.

There are several ways for microorganisms to become part of a repository environment. By far the most likely way is (quasi-unavoidable) external contamination, i.e. introduction of micro-organisms because of anthropogenic activities related to repository construction. In addition, physico-chemical changes may occur during construction and operation that could stimulate any microorganisms that are present in a dormant state in the host rock.

Understanding processes in the near-field related to microbial activity will allow determination of where microbial processes are likely to occur and frame the impact they might have.

Furthermore, as explained in section 7.2.3.2, it needs to be ensured that gas does not significantly and adversely affect the barrier function of the host rock and that the safety function indicator criteria defined to bound the repository-induced effects are fulfilled. In assessments so far, it has conservatively been assumed that all generated gas remains stable from a chemical viewpoint and contributes to the gas pressure build-up in the repository. Hydrogen consumption might contribute to reducing the gas overpressures and the conditions which favour this will be investigated in greater detail up to the general licence application.

Current state-of-the-art and progress since the 2009 RD&D Plan

A clear sign of microbial activity in a borehole filled with Opalinus Clay porewater was observed for the first time in the Porewater Chemistry (PC) experiment in the Mont Terri URL (Mauclaire et al. 2008). The low pH and the high sulphide concentration in the porewater were strong indicators that microbially mediated reduction of dissolved sulphate to sulphide had taken place. Sulphate-reducing bacteria (SRB) had been proven to exist in a dormant state in the Opalinus Clay before, but their activity in the Opalinus Clay had yet to be shown (Stroes-Gascoyne et al. 2013, Stroes-Gascoyne et al. 2008). The MA (microbial activity) experiment was the first to demonstrate that in-situ microorganisms thrive in clay rock when there is sufficient water, enough space and the necessary nutrients (electron donor, electron acceptor, carbon source, energy source). In the latter experiment, the presence of a large variety of microorganisms (including various SRB) and their potential to consume introduced H₂(g) while reducing sulphate to sulphide in the porewater (Bagnoud et al. 2016b) could be demonstrated.

Evidence from other experiments in the Mont Terri URL such as the HT (hydrogen transfer) experiment (Vinsot et al. 2014) confirms these findings: hydrogen partial pressure was shown to drop faster than could be explained by diffusion into the host rock.

The discovery of bacteria able to reduce sulphate and oxidise hydrogen is not new and goes back to 1981 when Odom & Peck (1981) published their paper on hydrogen cycling as a general mechanism for energy coupling in the sulphate-reducing bacterium *Desulfovibrio* sp. All sulphate-reducing bacteria (SRB) known are able to use H₂ as an electron donor because its presence is necessary for energy generation. In the absence of exogenous H₂, SRB generate small amounts of H₂ to complete the electron transfer and generate energy. Hence, it is well known that the coupling of sulphate reduction and H₂ oxidation can occur in the environment.

In the case where sulphate becomes a limiting electron acceptor and is no longer available for the oxidation of hydrogen, CO₂ from the bicarbonate in the Opalinus Clay porewater can reduce hydrogen to microbially mediate this redox process, leading to the formation of methane.

This process is known from the literature (Madigan et al. 2015) but has not yet been evidenced in (disturbed) Opalinus Clay. Part of the new MA-A (microbial studies) experiment will investigate if this process might also be contributing to the gas pressure build-up.

Planned RD&D in the next 5 to 10 years

In a next step, a project is foreseen that will focus on the conditions needed in the engineered barriers for L/ILW to allow microorganisms to thrive, to oxidise hydrogen and thus reduce the gas pressure build-up in the repository (Fig. 7-10). The planned MA-A experiment is designed to provide a scientific basis for answering these questions by circulating natural Opalinus Clay porewater through a series of modules filled with barrier material with different properties, while also adding H₂(g) or CH₄(g).

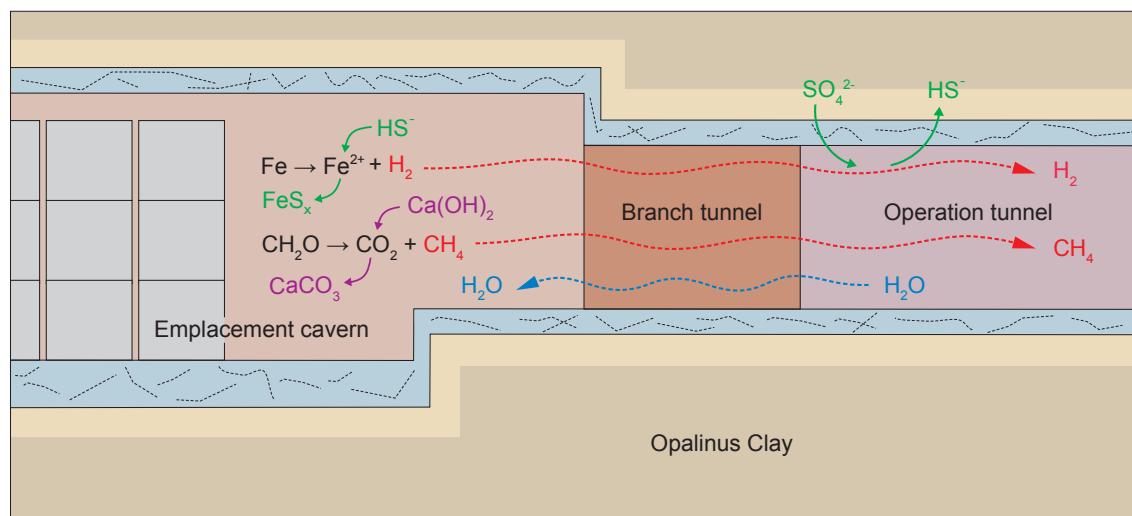


Fig. 7-10: Conceptual scheme of different gas-related reactions in a L/ILW repository.

The figure shows that the likelihood of gas-related reactions depends on the local physical and geochemical conditions of the different repository compartments.

This experiment aims at determining if microorganisms can act as a sink for gas and thus be able to reduce the gas pressure build-up in a geological repository if they find the optimum living conditions (space, water, nutrients). First scoping calculations showed that if the backfill of a repository contains enough sulphate, the gas pressure build-up can be substantially lowered.

A major step regarding the enhanced understanding of microbial activity in repository-relevant environments is expected from the EU project MIND (microbiology in nuclear waste disposal) (MIND 2016), where Nagra is participating in the end-user group.

7.3 Radioactive waste and materials

The basis for the planning and design of a deep geological repository as well as for any related safety analysis is adequate knowledge of the radiological and material properties of all waste streams destined for disposal.

Towards this end, the ISRAM database ("Information System for Radioactive Materials") has been established and is maintained and operated by all producers/managers of radioactive waste as well as Nagra. ISRAM contains radiological (e.g. nuclide inventory, dose rates), material (e.g. chemical composition) and other supporting information (e.g. date of conditioning, current storage location) for all existing radioactive waste packages from the operation of the NPPs and from medicine, industry and research in Switzerland.

In addition to ISRAM, and in order to account for wastes that are expected to be generated in the future, Nagra has established a database with the objective of comprehensively inventorying all Swiss radioactive wastes that will be disposed of in the repositories (i.e. both existing and future wastes such as radioactive materials arising from the decommissioning of the NPPs). This database MIRAM ("Model Inventory for Radioactive Materials") forms the basis for safety and design studies for the repositories. In MIRAM, the ISRAM data are complemented with results from production forecasts as well as RD&D aimed at further characterising all Swiss radioactive wastes (past and future) and providing a solid basis for analyses. RD&D efforts include the further development and refinement of characterisation methods such as calculation methods (nuclear codes and software), measurements and experiments. MIRAM (Nagra 2014d) is periodically updated to include the latest ISRAM accounting for existing wastes, developments and results from the RD&D efforts and to reflect changes in regulations (e.g. the Radiological Protection Ordinance) or other boundary conditions affecting the future production of wastes (e.g. NPP operating lifetime).

The scope of RD&D for radioactive waste and materials also extends beyond the purposes of inventorying. With the application for the HLW and L/ILW repository construction licences foreseen in the next decades, it is important to ensure today that waste being produced meets acceptance requirements for disposal in the planned repositories. This is ensured by the implementation of preliminary Waste Acceptance Criteria (WAC) and the collection of data from waste producers to ensure compliance with such criteria. The WAC also provide boundary conditions for developing the repository design and operational procedures. Such criteria are related to:

- Defined contents of radionuclides in the waste packages
- Defined maximum thermal output of waste packages
- Design of waste canisters and arrays of waste canisters to ensure nuclear subcriticality
- Radiation effects, including dose rates and radiation damage to materials
- Gas generation
- Chemical durability

The development of appropriate conditioning methods for future waste streams might therefore be required and Nagra must ensure RD&D towards this end.

Moreover, ongoing RD&D will continue in order to refine the understanding of safety-relevant characteristics of wastes such as radionuclide release mechanisms, criticality safety and generation of gases. Additional RD&D is also planned to further understand the impact of dry storage,

transportation and handling on spent fuel assemblies. Finally, research effort will be devoted to optimising the loading of spent fuel assemblies into the final disposal canisters to be disposed of in the repository. An overview of the structure of the subsections that deal with these topics is given in Fig. 7-11.

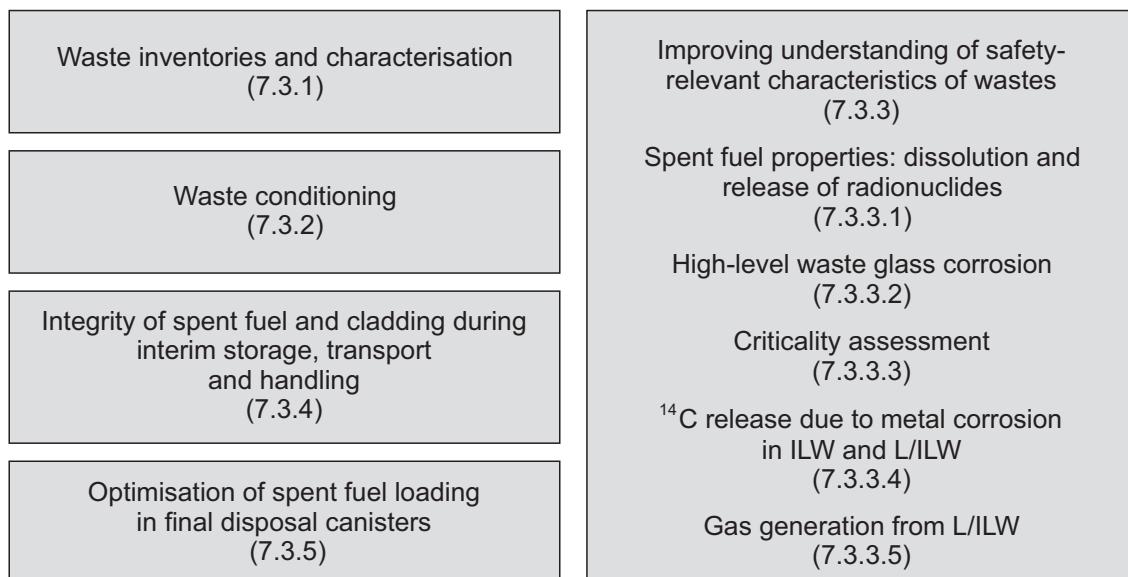


Fig. 7-11: Structuring of the RD&D activities related to radioactive waste and materials.

7.3.1 Waste inventories and characterisation

Objectives

The objective of inventorying and characterisation is to fine-tune methods and tools used in order to improve the technical data included in the Swiss radioactive waste database. More specifically, RD&D efforts are aimed at further consolidating data for all wastes that have been produced or are expected to be produced in Switzerland. Such data include the radionuclide inventory of wastes, radiological and related characteristics (e.g. dose rates and heat output), as well as the detailed material characteristics of wastes (e.g. chemical inventory of waste components).

Current state-of-the-art and progress since the 2009 RD&D Plan

Since the 2009 RD&D Plan, the MIRAM 08 (Nagra 2008f) database has been extended to integrate the latest inventorying/characterisation efforts. The resulting database, MIRAM 14 (Nagra 2014d), constitutes a comprehensive database which contains all relevant technical data for repository safety analyses.

RD&D efforts in the context of MIRAM 14 and beyond (e.g. in relation to operational safety and logistics) have been devoted to refining the characterisation of low-, intermediate- and high-level wastes and spent nuclear fuel. The characterisation methods include measurement, calculation and correlation, as well as documentation from the waste producers. Such efforts include the following:

- *Low- and intermediate-level waste (L/ILW)*: For reactor and NPP decommissioning wastes, 3D models of the Swiss NPPs have been developed and Monte Carlo neutron transport simulations have been performed to calculate the energy-dependent neutron fluxes and resulting activation of the in-core and ex-core reactor components (Nagra 2011b – 2011e, Pantelias 2013). In this context, collaborations have been established with the Swiss NPPs and the Oak Ridge National Laboratory (USA) for the implementation of state-of-the-art neutron transport/activation methods and codes. Furthermore, the calculations are validated with in-situ full-cycle measurements conducted at the NPPs (Pantelias & Volmert 2015). For operational wastes, the MIRAM 14 database integrates all data for waste packages that have been produced since MIRAM 08. In addition to RD&D work, standard chemical analyses have been used to verify the correlations between easy to measure nuclides (e.g. key gamma-emitting nuclides) and difficult to measure nuclides (e.g. beta emitters) for various waste streams (e.g. resins, sludge).
- *Spent fuel (SF) and long-lived intermediate- and high-level wastes (HLW/ILW) from reprocessing*: Spent fuel assembly inventory calculations have been further refined (Caruso & Panadero 2014, Caruso 2016). Further validation of the 2D depletion calculations with international experimental programmes has been conducted, including high burnup fuel. In the context of the reprocessing wastes, international collaboration with waste management organisations has enabled the benchmarking/validation of the inventory of high-level reprocessing wastes (Caruso et al. 2015).

Planned RD&D in the next 5 to 10 years

The planned RD&D aims to ensure that reliable, up-to-date technical data for all Swiss radioactive wastes forms the basis of future MIRAM updates. More specifically, the following actions are planned:

Reactor and NPP decommissioning wastes

Efforts in this context aim to i) further develop and extend the 3D Monte Carlo models of the Swiss NPPs, ii) validate the optimised NPP models based on the results of in-situ campaigns and further radiochemical analyses, and iii) couple neutron transport and activation codes, also considering the upcoming shutdown and dismantling of NPPs.

International and national collaborations will continue towards this end (e.g. Oak Ridge National Laboratory (ORNL), Swiss NPPs, ETHZ/EPFL, German NPPs and expert companies). More specifically, the NPP models will be further optimised based on the results of in-situ neutron activation measurement campaigns (NPPs Gösgen and Mühleberg campaigns have been completed as of 2016 and campaigns in NPPs Beznau and Leibstadt are ongoing/planned until 2017 and 2018).

The overall validation process for all Swiss NPP 3D Monte Carlo models based on the in-situ campaigns is expected to be completed in 2019, allowing the transfer of the updated decommissioning waste data into the new MIRAM version in time for the general licence application.

Chemical and radiochemical analyses of NPP component samples are additionally planned and further collaboration with NPP Mühleberg during dismantling will provide an important opportunity for the radiochemical analysis of samples.

Finally, the objective of the NPP activation calculation efforts extends beyond inventorying and aims to additionally support the Swiss NPPs in the planning of decommissioning and the dismantling of the NPPs in a cost-effective way.

Research wastes

Nagra supports PSI in the validation of accelerator activation calculations through the development of an experimental setup (i.e. Bonner sphere for measuring high energy neutrons).

Spent fuel

Although generally well understood for SF, further refinement of inventories and heat production data will be obtained by the ongoing development and validation of 2D/3D LWR fuel models. Ongoing activities in this context include collaboration with EPFL/PSI for high-fidelity depletion calculations.

Reprocessing wastes

International collaborations for the further verification of the radionuclide inventories in reprocessing wastes have been initiated and will be extended. More specifically, a working group consisting of ANDRA, GRS, ONDRAF/NIRAS and Nagra has been established for this purpose.

7.3.2 Waste conditioning

Objectives

The objective is to ensure the development of adequate methods that might be required for the future conditioning of waste streams, in coordination with PSI and the NPPs. Furthermore, the scope of efforts in the context of conditioning aims to further address the recommendations of ENSI with respect to reducing the metallic and organic content of waste (Nagra 2016a, Appendix A and ENSI 2015a).

Current state-of-the-art and progress since the 2009 RD&D Plan

Research and development for waste matrices and conditioning of L/ILW is based on preliminary Waste Acceptance Criteria and on the regulations and advice of the regulatory authority (HSK 2007, ENSI 2015c, ENSI 2013). Compliance with the requirements is assessed within the procedure for obtaining a Disposability Certificate, including quality control programmes to verify important product parameters. The Disposability Certificate is part of the documentation that must be submitted to ENSI to obtain a licence for the production of waste packages of the specified type. The approval of a waste package type means permission for the operator for autonomous conditioning of future waste.

Since the generation of gases from metallic and organic L/ILW waste and their impact is an important aspect of assessing long-term safety, alternative waste conditioning methods for the reduction of the gas production potential in L/ILW have been evaluated (Rüdebusch 2008,

Ferrière & Kluth 2013; see section 7.3.3.5). Melting is an industrially approved conditioning method for metal wastes. There are two main effects. First, there is decontamination potential for metals, since many nuclides are transferred to secondary waste. Hence, metals could be partly released from radiological control and be recycled or disposed of conventionally. Second, melting leads to a decrease in the surface to volume ratio. Both effects are beneficial with respect to reduction of gas generation. An evaluation of mineralisation methods for organic radioactive waste led to pyrolysis as the conditioning method of choice. Compared to metal melting, there is less experience in industrial pyrolytic treatment of ion-exchange resins. Therefore, experimental pilot tests for the treatment of Swiss ion-exchange resin simulants with respect to their mineralisation potential have been performed (*Stein in prep.*). The scope and limitations were demonstrated on a pilot scale. Based on current understanding of the post-closure safety consequences of the presence of the organics in the waste, no elimination of organics from the waste is required. These consequences are discussed in the respective sections and are linked to gas generation (see section 6.4.3), geochemical conditions (pH) in the cementitious near-field (section 7.5.3.2) and complexation and preferential transport of radionuclides in the near-field (section 7.5.4).

Planned RD&D in the next 5 to 10 years

Best available techniques for the conditioning of radioactive waste will be continuously screened and evaluated also internationally. In this context, Nagra intends to participate as end-user in the HORIZON2020 project THERAMIN (Thermal Treatment for Radioactive Waste Minimisation and Hazard Reduction) if it becomes accepted. Furthermore, Nagra will coordinate the potential development of conditioning methods adequate for the treatment of new waste streams.

7.3.3 Improving understanding of safety-relevant characteristics of wastes

RD&D on the characteristics of the various types of wastes is required to provide data for operational and long-term safety assessments. The properties of greatest importance in safety assessment are the rate of release of radionuclides and the rate of gas production under disposal conditions, as well as confirmation that wastes will not exceed criticality requirements in either waste handling operations or under long-term disposal conditions. In relation to radionuclide release, experience from prior safety analyses (Nagra 2002c and 2014c) shows that improving the understanding of the radionuclide release from spent fuel, as well as reducing uncertainties in the release rate of ^{14}C from L/ILW, are of the greatest importance. In contrast, while uncertainties associated with long-term HLW glass corrosion remain, the significance of these uncertainties in long-term safety assessment is low. In the case of release of radionuclides other than ^{14}C from L/ILW, there is little benefit in further improving understanding as the consequences are acceptably low, even with the basic assumption in release models that all nuclides are released from the waste within 100 years after being placed in the repository.

7.3.3.1 Spent fuel properties: dissolution and release of radionuclides

Objectives

The objective of studies on the release of radionuclides from UO₂ and MOX spent fuel assemblies is to develop a better understanding of this topic as a basis for improving the radionuclide release model used in safety assessment. Areas of specific interest include:

- The release of radionuclides from Zircaloy cladding and structural materials of the fuel assemblies as a result of corrosion processes
- Changes in solid-state properties arising from radioactive decay and, in particular, changes that may affect subsequent radionuclide release
- The mechanisms controlling the release of radionuclides from spent fuel in the repository environment, including the release of some radionuclides from the fuel/sheath gap (the instant release fraction) and as a result of slow dissolution of the fuel matrix

RD&D on the integrity of spent fuel during interim storage, which is also relevant to radionuclide release, is discussed in section 7.3.4.

Current state-of-the-art and progress since the 2009 RD&D Plan

The processes resulting in aqueous radionuclide release from spent fuel assemblies include:

1. Release of activation products from Zircaloy and other metal parts of the fuel assemblies, which involves rapid release of a small fraction of the ¹⁴C inventory along with some other activation products associated with the oxide film on Zircaloy, followed by slow release of the remaining activation products as a result of corrosion.
2. Release of the so-called IRF (instant release fraction) from the fuel assemblies, which represents principally the fraction of the total inventory of certain radionuclides (e.g. ¹³⁵Cs, ¹²⁹I and ³⁶Cl) in the fuel that is released from the gap (the interconnected void space in the fuel rod). Release from the gap is analogous to fission gas release (FGR) in that the released radionuclides are present in the gap at the end of fuel irradiation in the reactor. In safety assessment, they are assumed to dissolve instantaneously when a canister is eventually breached and water intrudes into it.
3. Release by slow fuel matrix dissolution, whereby the largest fraction of the radionuclide inventory (the remaining fission products and activation products as well as the actinides) is released congruently at the rate the matrix of the fuel dissolves. This process is controlled by the geochemical conditions in the groundwater that exist when the canister is breached. Many of these radionuclides precipitate upon their release as a result of low solubility.

It is expected that spent fuel will be placed in disposal canisters that would prevent access of water to the fuel for thousands of years. Under such conditions, only solid-state mechanisms could lead to changes in properties. The principal solid-state processes relevant to long-term spent fuel behaviour are related to actinide decay, which may influence the diffusion of fission products in the UO₂ lattice and also result in the ingrowth of He from radioactive decay. The cladding may eventually fracture as a result of the pressure from fission gas and the gradual build-up of He gas produced by alpha-decay within the fuel rods. As a result of the accumulation of He within gas bubbles in the fuel, some fracturing of grains may eventually occur, although this is only expected in the case of higher alpha activity MOX fuel (Wiss et al. 2014). The effect of alpha radiation-enhanced solid-state diffusion of fission products has been

addressed in several modelling and experimental studies. In principle, such a process could cause the inventories of fission products at grain boundaries to increase over time. Ferry et al. (2008) indicate that the radiation-enhanced diffusion coefficient is less than $10^{-26} \text{ m}^2/\text{s}$, which would lead to an average atomic displacement of only ($0.5 \mu\text{m}$), i.e. about 10 % of the grain diameter in the fuel, after 1 million years (SKB 2010a); the process is thus of low relevance.

Zircaloy cladding and fuel structural materials (stainless steel) are highly corrosion-resistant in repository porewater (Diomidis 2014), with corrosion rates of $< 10 \text{ nm/a}$. The long-term rate of corrosion of these materials is sufficiently well defined for the purposes of safety assessment calculations performed for the spent fuel repository. A small fraction of activation products in cladding and structural materials may be present in the oxide film that has formed in the reactor and be more rapidly released (Yamaguchi et al. 1999). This process is not well understood and is being studied in the EU Project CAST, in which Nagra and PSI are participating. This project is largely focused on corrosion-based release of ^{14}C from irradiated materials under alkaline conditions in support of studies for assessment of L/ILW repositories (see section 7.3.3.4).

Fission gas release from spent fuel is known to correlate with the IRF of some radionuclides (Johnson et al. 2012). Thus, the fission gas release for full core loads of the Swiss reactors has been calculated in order to obtain reliable average fission gas release data (Areva 2010 and 2012, Oldberg 2009). Combined with measurements of radionuclide release from spent fuels studied by Nagra in collaboration with PSI, SKB and Studsvik for fuel with burnups from 45 to 65 GWd/tHM reported in Johnson et al. (2012), these data have provided the basis for a radionuclide release model for spent fuel reported in Johnson (2014). PSI and Nagra have continued to collaborate through involvement in the EU FIRST-Nuclides project, which was completed in 2014. Studies performed at PSI have shown that ^{79}Se , a long-lived radionuclide, substitutes for oxygen in the UO_2 lattice (Curti et al. 2014), consistent with the observation that it does not appear to contribute to the IRF (Johnson et al. 2012).

Although low redox potentials are expected in a repository at the time of canister breaching ($> 1,000$ years after closure), the presence of alpha radiation inside spent fuel canisters can affect the redox conditions of solutions in contact with the spent fuel surfaces. In particular, it is important to understand whether alpha radiolysis is likely to generate sufficient oxidant concentrations, e.g. hydrogen peroxide, such that the dissolution rate of the spent fuel might be accelerated. Here, an important factor influencing corrosion kinetics is the presence of hydrogen, principally from canister corrosion, near the fuel surface. Spent fuel dissolution experiments performed over the past several years have shown that the presence of hydrogen and the absence of oxygen result in a complete suppression of oxidative dissolution (Röllin et al. 2001, Fors et al. 2009, Carbol et al. 2009). Studies of the dissolution of UO_2 have clarified the mechanism responsible for this observation, which involves reaction of hydrogen gas with the fuel surface. Electrochemical studies of SIMFUEL (simulated spent fuel) have demonstrated that oxidation of H_2 to H^+ occurs on fission product alloy particles (metallic particles containing Ru, Tc, Rh, Mo and Pd), which are also present in spent fuel. Because UO_2 is a semiconductor, this reaction is galvanically coupled to the cathodic reduction of U(VI) species on the fuel surface (Shoesmith 2008 and 2013), resulting in very low potentials and prevention of oxidative dissolution.

Fuel matrix dissolution rates for repository safety assessment studies have been estimated in several national programmes based on such findings. Shoesmith (2013) proposed a best estimate dissolution rate of UO_2 for hydrogen-dominated conditions of $\sim 2 \times 10^{-6} \text{ mol m}^{-2} \text{ a}^{-1}$. Consistent with this, recent reviews by SKB (2010a and b), Posiva (2012a) and Johnson (2014) have proposed a best estimate fractional dissolution rate of 10^{-7} a^{-1} .

Planned RD&D in the next 5 to 10 years

The results from the EU CAST project on release of ^{14}C from irradiated metals in the repository will be evaluated. Where relevant, the information will be used to support models for release of activation products from irradiated Zircaloy and other fuel assembly structural materials.

Safety analysis calculations using the IRF estimates of Johnson & Schneider (2005) and Johnson (2014) give results that show that radiation dose estimates for geological disposal of spent fuel are directly proportional to the IRF of ^{129}I . Thus, it is beneficial to further improve understanding in this area. Final results from the EU FIRST-Nuclides project (Kienzler et al. 2014) have led to the initiation of a proposal for a follow-up EU project (DISCO) on the dissolution of spent fuel under canister corrosion conditions (in the presence of hydrogen and iron). This project will also look at the impact of doping on spent fuel dissolution.

7.3.3.2 High-level waste glass corrosion

Objectives

The objective is to improve mechanistic understanding of the behaviour of HLW glass in the repository environment, such that improved models can be developed for post-closure safety assessment that describe the time-dependent release of radionuclides after canister breaching.

Current state-of-the-art and progress since the 2009 RD&D Plan

Vitrified HLW has been produced industrially since the 1970s by COGEMA (and more recently Areva) in France and by BNFL in the UK as a result of reprocessing of spent fuel. A large body of data on the dissolution kinetics of HLW glass is available from dedicated EU projects carried out over the past decades (SOURCE-TERM, GLASTAB, NF-PRO), from experiments performed at PSI (Curti 2003) and other laboratories (e.g. McGrail et al. 2001). Complementary evidence from suitable natural analogues is also used in support of estimating long-term dissolution behaviour. A comprehensive summary of these studies has been reported by Bradbury et al. (2014).

It is observed in experiments in water that, after an initially high dissolution rate for a period of weeks to months, a residual rate is then reached that is about 10,000 times lower. The driving force maintaining this residual rate is presumed to be the small difference in free energy ("affinity") between the dissolving glass and the silica phase precipitating on the glass surface (Grambow 1985, Grambow 1987, Curti et al. 1993, Vernaz & Dussossoy 1992). This model continues to be supported by some researchers (e.g. McGrail et al. 2001), whereas others (Gin et al. 2001) claim that the reduction in glass corrosion rate observed at longer times is due to the protective properties of the amorphous gel layer formed on top of the fresh glass. The properties of the gel layer can be influenced by incorporation of elements that may either increase (e.g. Zn) or decrease (e.g. Ca or Mg) diffusivity through the gel, thus leading to a higher or lower residual rate (Thien 2010, Thien et al. 2010, Thien et al. 2012).

There is ample laboratory and field evidence that the corrosion of borosilicate glasses may be enhanced by the presence in the leaching solution of clay (e.g. Curti & Smith 1991, Curti et al. 1993, Lemmens 2001, Godon et al. 2008) or Fe corrosion products such as magnetite. In-situ experiments that include clay performed within the framework of the CORALUS (corrosion of α -active glass in underground storage conditions) project (Valcke 2007) show that the residual rate remains high even after 7 years, an effect that has been explained by sorption of silica on

clay minerals. However, other experiments show that, as the ratio of MX-80 bentonite (containing 2 % soluble silica) to glass is increased, the dissolution rate decreases (Bradbury et al. 2014). It is thought that the dissolving amorphous silica from the clay is sufficient to both quickly saturate the sorption sites on the clay and to raise dissolved Si concentrations, so that the silica released through glass corrosion can build a protective gel layer. The net effect is a reduced glass corrosion rate relative to the case of glass dissolving in a solution with a small amount of added clay. Studies are continuing to investigate these effects.

Studies of glass dissolution in the presence of Fe oxides (Bart et al. 1987, Grambow 1987, Werme et al. 1990, Zwicky et al. 1989) indicate that the addition of Fe oxides leads to an increased glass corrosion rate and that the total amount of corroded glass depends on the quantity and specific surface area of the added Fe corrosion product, which is again consistent with the hypothesis that Si sorption drives the glass corrosion kinetics. Nevertheless, as pointed out in Bradbury et al. (2014), this effect is probably transitory since the slopes of the reported datasets versus time (and therefore the glass corrosion rates) decrease after a short period of time.

Experimental evidence collected over the past decades consistently indicates that radiation damage and water radiolysis have little influence on glass corrosion kinetics. This conclusion is based on comparative experiments of radioactive glasses and the corresponding inactive simulations (Werme et al. 1990, Feng et al. 1993 and Matzke 1997).

The dissolution behaviour of natural volcanic and archaeological glasses has been investigated in several studies in an attempt to gain insights into the long-term dissolution kinetics of radioactive waste glasses. Although there are differences in composition and alteration conditions between waste glass and natural volcanic or archaeological glasses, there is still a benefit in studying the dissolution of these analogues.

The estimation of long-term glass dissolution rates for safety assessment based on the above and other data is discussed in Bradbury et al. (2014). The recommended rates are identical to those selected for the Opalinus Clay Project (Nagra 2002c), since more recent experimental evidence does not justify a modification of these rates.

The time for complete dissolution of the HLW glass in the repository can be estimated within reasonable bounds, although there remains uncertainty about the long-term dissolution rate. Safety assessment studies (Nagra 2002c) show that the HLW glass makes a relatively small contribution to radionuclide release from a repository, largely because of the very slow transport of radionuclides through Opalinus Clay; thus there is no large incentive to further reduce the uncertainty in the dissolution rate.

Planned RD&D in the next 5 to 10 years

The present series of long-term glass dissolution experiments that have been in progress at PSI since 1978 will be terminated. Ongoing studies being performed in France and Belgium will be followed through literature studies, with a view to producing a synthesis of results and estimates of the glass dissolution rate for the safety assessment for the general licence application.

7.3.3.3 Criticality safety assessment

Objectives

The objective of RD&D in the context of criticality safety is to assess the potential for criticality in a repository for spent fuel and HLW and to ensure that analysis and design measures comply with the requirement for subcriticality in a repository.

Current state-of-the-art and progress since the 2009 RD&D Plan

The proposed approach for dealing with criticality assessment for spent fuel disposal is to utilise burnup credit (i.e. taking "credit" for the fact that the reactivity of spent fuel has decreased according to the resulting burnup of fissile nuclides and build-up of neutron-absorbing nuclides) to assess loadings of spent fuel canisters. Burnup credit is already widely used for analysis of criticality safety in the licensing of interim storage of spent fuel assemblies in storage bays and for dry storage/transport canisters (OECD/NEA 2012b).

An agreement between PSI and Nagra was established in 2013 to develop a methodology for criticality evaluations based on burnup credit, ensuring that this method could be applied to all spent fuel assemblies discharged from Swiss reactors.

The work resulted in a review of burnup credit (BUC) approaches in other countries (Herrero 2015a). The review covered a broad range of issues, including:

- National programmes, practices and strategies for BUC applications for disposal of spent PWR/BWR UO₂ and MOX fuels
- Relevant phenomena for disposal applications and identification of priorities with regard to BUC
- International guidelines and standards for BUC implementation
- Licensing and regulatory issues/concerns
- Existing BUC calculation methodologies and associated RD&D needs

The RD&D needs include codes/data for depletion, decay and criticality calculations, the verification and validation basis, uncertainty quantification, criticality safety criteria, canister loading criteria and implementation requirements. This has to be backed up by international research programmes, expert groups and coordinated activities related to BUC and experimental/computational benchmarks relevant to long-term disposal.

In 2015, the available codes for isotopic decay calculations for short, intermediate and long-term (repository) timeframes were assessed. This work included a comparative review of methods and solution schemes for depletion/decay calculation sequences, of employed nuclear data libraries for decay calculations and of assessment of associated uncertainties (Herrero et al. 2015b). In addition, participation in selected international benchmarks including the OECD/NEA WPNCS Expert Group BUC Phase V-II Long-Term Decay Benchmark and the OECD/NEA WPRS UOX Depletion/Decay benchmark (Herrero et al. 2016) has been initiated.

Planned RD&D in the next 5 to 10 years

The methodology and tested codes will be applied to the reference configurations relevant to disposal, i.e. to nominal disposal canister designs and fuel assembly (FA) loadings. Criticality safety analyses will be determined for unirradiated fuel, followed by realistic case configurations for typical Swiss discharge burnups.

Following this, canister loading curves will be developed, which will provide, for all the spent fuel assemblies, the curves of minimum burnup vs. initial enrichment that will ensure compliance with the defined upper subcriticality limit, accounting for biases and uncertainties related to the key elements of the methodology.

Finally, calculations will be performed for degraded configurations, such as may occur on the long term in the repository after extensive corrosion and structural degradation of the canister and fuel assemblies.

7.3.3.4 ^{14}C release due to metal corrosion in L/ILW

Objectives

Carbon-14 in metallic radioactive waste is produced predominantly by the thermal neutron activation of precursor species, mainly nitrogen, present in nuclear fuel components and reactor core structures. ^{14}C can be released in a variety of chemical forms, both organic and inorganic, as a result of dissolution or waste degradation processes. It can then be transported as dissolved species or in the gas phase in the form of volatile compounds. It is a safety-relevant radionuclide especially during the first few tens of thousands of years after repository closure. The broad aim is to develop understanding of the potential release mechanisms of ^{14}C from radioactive waste materials under conditions relevant to disposal in deep geological repositories. More specifically, it is to gain scientific understanding of the rate of release of ^{14}C from the corrosion of irradiated steels and Zircaloys under geological disposal conditions, the speciation of ^{14}C in the gas and liquid phase and how these relate to ^{14}C inventory and aqueous conditions.

Current state-of-the-art and progress since the 2009 RD&D Plan

The EU project CAST (CArbon-14 Source Term, CAST 2016), aimed at studying ^{14}C release mechanisms, rates and speciation in the context of geological disposal, has been initiated. Both PSI and Nagra are participating, while Nagra leads the activities dealing with activated steel. Within CAST, comprehensive literature reviews on the release of ^{14}C due to the corrosion of activated steel (Swanton et al. 2015) and Zircaloy (Gras 2014) have been completed and published.

The literature reviews have indicated that limited information is available on the release of ^{14}C from irradiated metals. The speciation of carbon released by corrosion will be determined both by the chemical form of the carbon in the metal and the corrosion conditions. There is considerable uncertainty concerning whether ^{14}C produced by irradiation will be present in the same chemical forms as the carbon present in unirradiated metals. Additionally, the reactivity of the different carbon species on contact with water varies considerably. Nevertheless, experiments on active and inactive steels and zirconium alloys have identified the release of C as organic and inorganic compounds in both the gas and liquid phase, although a higher proportion is released as small organic molecules.

A methodology has been developed to measure the speciation of ^{14}C in low molecular weight organic compounds in the liquid and gaseous phase at extremely low concentrations. These low concentrations are due to the low corrosion rate in a cementitious environment (Wieland & Cvetkovic 2016).

Independently from CAST but also contributing to the project, RWMC is currently performing measurements of ^{14}C release from the corrosion of metals (Yamashita et al. 2014).

Planned RD&D in the next 5 to 10 years

Nagra will actively contribute to the CAST project as a work package leader. Additionally, coordination will occur with PSI in which leaching experiments on activated stainless steel in cement porewater simulants will take place. Apart from this, the outcome of the other work packages in CAST includes the measurements of release rate and speciation of ^{14}C from activated Zircaloy, exchange resins and graphite. These results will be reviewed with a view to incorporating relevant information on ^{14}C behaviour into the safety assessment.

7.3.3.5 Gas generation from L/ILW

Objectives

The assessment of the impact of gas production in the repository (see section 6.5.3 and Diomidis et al. 2016) requires an adequate characterisation of the gas source term resulting from i) the corrosion of metals (H_2), and ii) the decomposition of organic materials (CO_2 , CH_4 , H_2 , H_2S). The main objective of RD&D in this context is to quantify the rate of gas generation from the L/ILW and to gain a comprehensive understanding of its evolution with time (corrosion and gas generation in the SF/HLW repository are discussed in section 7.5.2.1). In order to achieve this, substance-specific gas generation rates and a broad understanding of the relevant processes are required.

Current state-of-the-art and progress since the 2009 RD&D Plan

Metals

A review of the available literature on gas generation due to corrosion of metals (carbon steel, stainless steel and Ni-alloys, Zircaloy and aluminium) in repository-relevant conditions was completed (Diomidis 2014). The availability of new results, as well as Nagra's own experiments (see next paragraph), resulted in an increased confidence in the long-term anoxic corrosion rate of carbon steel in alkaline environments and, based on this, the reference value was revised down to 20 nm/a. At the same time, a refinement in the calculation of the local pH of the waste (Cloet et al. 2014) has allowed, for the first time, the provision of pH-dependent reference corrosion rates for carbon and stainless steel which are now representative of the local chemical environment.

An experimental campaign was initiated with the aim of measuring the corrosion and gas generation rate of carbon steel, the most abundant metal in the Swiss waste inventory, in conditions relevant to L/ILW disposal. The measurements are done using a high sensitivity hydrogen sensor, allowing an accuracy in derived corrosion rates of 0.1 nm/a. The experiments are ongoing but have so far exhibited very low corrosion rates of < 10 nm/a (Newman & Wang 2010 and 2013, Newman et al. 2013a and b, Wang et al. 2013, Newman et al. 2016). These

experiments provide the first measurements available in the literature on the corrosion of steel in anoxic and unsaturated cement grout, conditions expected to prevail for thousands of years in a Swiss L/ILW repository, exhibiting corrosion rates of only a few nm/a.

Organics

Organic materials represent only a minor proportion (1.8 %) of the total radioactive waste inventory (Nagra 2014d). They are almost exclusively (99.8 %) present in L/ILW compared with SF/HLW. Furthermore, 93 % of all organics are polymers. Given the minor proportion of organics in the wastes to be disposed of, gas production from the degradation of organics is significantly less important than the gas production from the corrosion of metals. Analyses of the literature on the degradation of organics, together with thermodynamic calculations and opinions of internationally recognised experts (Warthmann et al. 2013a and b), have shown that there are no clear indications for the biodegradation of synthetic polymers under anoxic conditions. More specifically, although degradation processes are theoretically possible, the available usable energy for microorganisms would suggest that such processes are improbable. High pH conditions and limited water supply might lead to further constraints on the degradation of organics.

Experiments performed in this context during the last decade in Finland (Small et al. 2008), Hungary (Molnár et al. 2010) and the US (Gillow & Francis 2006) under a wide range of conditions helped to improve the understanding of the degradation behaviour of different organic waste streams. Nevertheless, the experiments were either performed on a small scale (grams) or the conditions applied differed from the conditions expected in the L/ILW repository (i.e. waste streams, pH, gas phase composition, etc.). Since it is still of interest to gain more experimental data on rates of gas production from organic materials, a large-scale experiment for the determination of gas generation rates from organic waste streams was initiated in 2015 (gas monitoring experiment; see Fig. 7-12). The gas production due to the degradation of organics is investigated under repository-relevant conditions using non-sterile conditions and Opalinus Clay pore-water. The experiment consists of 5 hermetically sealed stainless steel drums including temperature, pressure and gas sensors as well as the possibility to take offline gas samples. The investigated materials (ion-exchange resins and PVC) are placed in these overpack drums, which are then heated to temperatures above 30 °C using drum heating jackets. The overall gas evolution and the gas composition are monitored by sensors and evaluation of offline analysis results.

Planned RD&D in the next 5 to 10 years

Metals

The experiments aiming to measure the corrosion rate of carbon steel in cement will continue with the objective of increasing confidence in the reference corrosion rates and increasing the understanding of critical parameters and the effects of local conditions such as cement degradation. Further measurements of the corrosion rates of other metals present in the waste inventory will be initiated if deemed necessary.

Organics

As mentioned in the previous section, gas generation experiments were initiated in 2015 (see Fig. 7-12). The degradation and gas production of important organic waste streams such as ion-exchange resins and PVC will be investigated over the next years. If promising, in the future experimental setups closer to reality might be considered, such as using conditioned waste, irradiated waste or also real waste drums.

Based on the results of the aforementioned experiments, the gas generation rates and modelling of degradation processes will be refined.

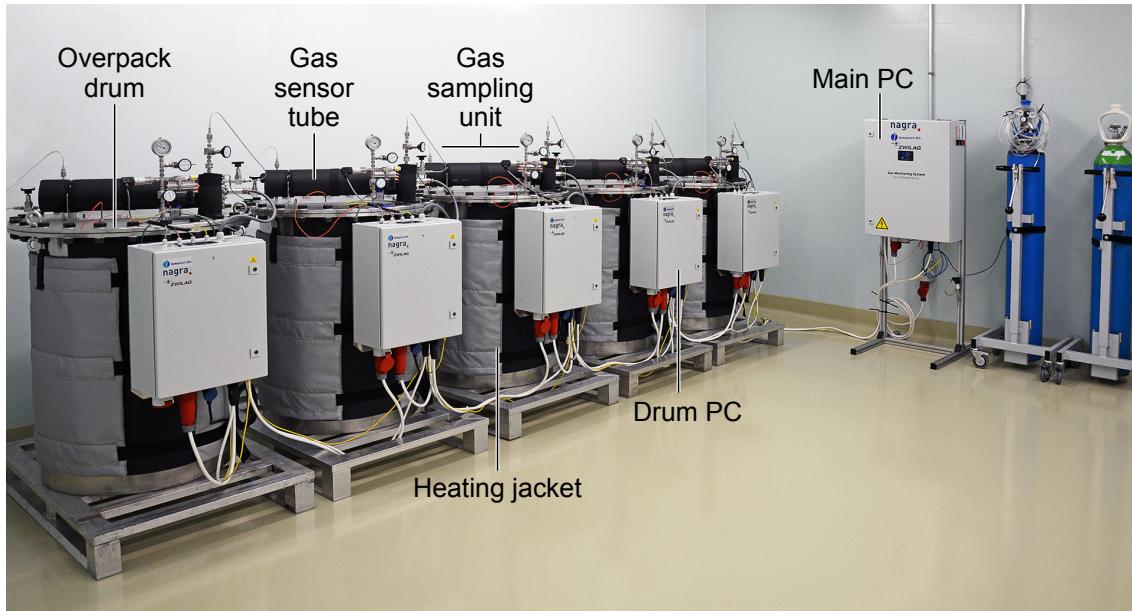


Fig. 7-12: Experimental setup of the Gas Monitoring Experiment.

7.3.4 Integrity of spent fuel and cladding during interim storage, transport and handling

Objectives

The spent nuclear fuel assembly (SFA) unloading/loading operations will be carried out in hot-cells in the surface encapsulation facility. Several docking stations dedicated to transport and storage casks and to final disposal canisters are planned to operate simultaneously. Nagra needs to ensure safe handling and encapsulation of the fuel assemblies.

In line with the decision by the Swiss Federal Council (Appendix A) and the ENSI Guideline (ENSI 2015d), the main objective of this research is to assess the integrity of SFAs during the interim dry storage of the transport and storage casks, their transport to the encapsulation facility and the unloading/loading and handling operations from the transport and storage casks into the final disposal canisters. While experience with fuel handling (e.g. at ZWILAG) and knowledge of degradation mechanisms confirm that the integrity of SFAs is to be expected, confirmatory data and analyses will help to validate the understanding of SFA degradation mechanisms that may affect their integrity and behaviour during handling in the encapsulation facility.

Current state-of-the-art and progress since the 2009 RD&D Plan

The behaviour of SFAs during dry storage has been the subject of investigation in several international programmes such as the IAEA programme SPAR II-III (Coordinated Research Project on Spent Fuel Performance Assessment and Research; IAEA 2012), aimed at developing the

capability to assess the impact of potential deterioration mechanisms on SFA and SFA storage components, and in studies coordinated by WENRA (West European Nuclear Regulators Association; Bare & Torgerson 2001, Peehs et al. 1998). The handling of SFAs after extended dry storage has already been successfully demonstrated (Sasahara & Matsumura 2008), although experimental experience and examination campaigns on this matter are infrequent. Hence, a final assessment for extended interim storage periods cannot be made for all SFA types and burnups with the data available. More specifically, aspects relevant to SFA cladding alteration such as hydriding, creep and stress-corrosion cracking are of particular importance for the further understanding of issues related to the transport and handling of SFAs.

A study on the integrity of SFAs during interim storage and transport was completed by the utilities in 2015 (Axpo 2015). The study aimed at assessing the integrity of the fuel assemblies from the Swiss NPPs in dry storage and during transport and handling. The report summarises the international state-of-the-art, including recent outcomes from a joint PSI-Axpo research programme on hydride reorientation investigation of high burnup PWR fuel cladding (Valance & Bertsch 2015). The basic conclusions of this study state that the fuel rod integrity during dry storage is to be expected, since:

1. Significant corrosion processes would not be expected to occur during extended dry storage (~ 100 years) in a transport and storage cask, because of the mainly inert atmosphere
2. Secondary damage from hydride reorientation is not expected in the absence of primary damage (i.e. a primary through-wall defect)
3. The impact of high burnup fuel as well as MOX fuel can be compensated for by a longer cooling period in a wet storage pool, which would reduce the fuel temperature

The study also points out that:

1. Even if unlikely conditions affect the rod integrity, this would not compromise the normal handling of SFAs foreseen in the hot-cell operations as SFA handling is principally determined by the fuel assembly superstructure and not by the fuel rods themselves
2. The consequences of a potential release of fuel material from rods could be managed without any impact on the environment, since adequate decontamination equipment will be available

Similarly, SFA structural materials are expected to exhibit nominal handling properties since i) the handleability is guaranteed by the fuel vendors and ii) operational experience further suggests that this is the case.

With respect to the SFA behaviour during transport of the storage casks, the study reports the status of international research (Cummings et al. 2012, Sorenson et al. 2015), which demonstrates that normal transport conditions should not affect SFA rod integrity.

Planned RD&D in the next 5 to 10 years

Several activities have already been initiated to further investigate the behaviour of SFAs during dry storage conditions:

1. A SF transport/storage cask ageing management working group (ZET²⁹ – Cask Ageing Sub Group) was recently established (2016) by the Swiss nuclear power plants, ZWILAG and Nagra to plan for systematic actions necessary to provide confidence that the storage and transport systems will perform satisfactorily and that specified requirements will be fulfilled (IAEA 2016).
2. Additionally, Nagra started developing an experimental programme together with the EPFL and the Joint Research Centre, Institute for Transuranium Elements (JRC-ITU), European Commission (Rondinella et al. 2013, Rondinella et al. 2015). The collaborative research arrangement between Nagra and JRC-ITU was signed in 2016, establishing a cooperation and related experimental campaign, with a duration of four years. JRC-ITU has hot-cell facilities to conduct load and impact tests on real SF rods and to perform relevant pre- and post-test characterisation. The agreement with JRC-ITU is intended to build on partnerships with many other organisations (e.g. Bundesanstalt für Materialforschung und -prüfung (BAM), Sandia National Laboratories, Pacific Northwest National Laboratory (PNNL) and Oak Ridge National Laboratory (ORNL)) and also to contribute to international programmes (e.g. the IAEA Coordinated Research Project SPAR-IV from IAEA), aiming to expand the scientific understanding of phenomena related to representative spent fuel types under dry storage conditions.
3. A US DoE/Euratom International Nuclear Energy Research Initiative (I-NERI) was established at the beginning of 2016 under the title: "Assessing the integrity of high burnup spent nuclear fuel in long-term storage and transportation". The I-NERI collaboration is based on cooperation between Sandia, PNNL, ITU, BAM and Nagra (e.g. I-NERI 2013). The duration of the programme is three years, with a possible extension of 1 year. The ultimate goal is to provide a final report assessing the ability of high burnup fuel to maintain its integrity during extended storage and normal conditions of transport.

The findings of the experimental programme and international cooperation are intended to serve as additional input for the detailed assessment of working procedures for the handling of spent fuel assemblies in the encapsulation facility (see section 7.4.9), as well as to provide a basis for safety studies and accident assessment in relation to operational safety (see also section 7.6.2).

7.3.5 Optimisation of spent fuel loading in final disposal canisters

Objectives

The aim of this work is to optimise the loading of spent fuel assemblies (SFA) from the transport/storage casks into the final disposal canisters that will be disposed of in the repository. This optimisation needs to take place in order to i) satisfy a maximum allowable heat limit of 1,500 W per canister at the time of emplacement in the repository, and ii) to minimise the number of canisters needed.

²⁹ 'Zwischenlagerung, Entsorgung, Transport von abgebrannten Brennelementen und Abfällen aus der Wiederaufarbeitung'.

More specifically, transport/storage casks will have to be docked and opened in a hot-cell and SFAs will have to be handled and transferred into the final disposal canisters. For this purpose, an optimum sequence for unloading the SFAs contained in different transport/storage cask types (e.g. TN 24) and loading them into the different final disposal canister types (e.g. 4 PWR SFA canisters, 9 or 12 BWR SFA canisters) has to be devised.

Current state-of-the-art and progress since the 2009 RD&D Plan

SIMAN (an acronym based on the underlying optimisation algorithm "Simulated Annealing") is a logistics optimisation programme that has been developed by Nagra since the beginning of the 2000s. It determines the optimum sequence of transport/storage cask unloading and final disposal canister loading operations under different boundary conditions (such as starting time of HLW final disposal operations, number of transport/storage cask docking stations for the encapsulation facility, encapsulation facility capacity, etc.). The input data for this programme include i) the full SFA database delivered by the utilities, ii) the transport/storage cask loading plans and iii) pre-calculated burnup and decay-dependent SFA heat outputs.

Since 2009, the SIMAN-I code version has been updated to SIMAN-II, which allows explicit simulation of the SFA operations inside the hot-cell. SIMAN-I is still a valuable code for performing parametric studies, whereas SIMAN-II is used to investigate in detail the effects of different transport/storage cask loading plans and types and the final disposal canister types on the final disposal canister loading efficiency (Vlassopoulos 2015).

Planned RD&D in the next 5 to 10 years

Future activities aim to update or replace the SIMAN sequence of codes with new features/ codes that will enable i) the investigation of potential changes in the boundary conditions (e.g. final disposal canister types, buffer storage options and surface facility design), ii) the improvement of the underlying mathematical optimisation algorithm, and iii) the integration of improved data on the heat output of SFAs (e.g. taking into account depletion calculations with SFA-specific Pu-vectors for MOX SFAs).

7.4 Design and technology development for the surface and underground facilities for the repositories and the engineered barriers

The conceptual design of the repositories and the concepts for the associated facilities and their operation are continually being developed and refined based on the overarching requirements arising from long-term safety and taking into account geological, spatial planning and environmental planning boundary conditions. For the general licence application, the conceptual design needs to be in place. This includes the basic size and location of the most important constructions as well as the waste categories and the maximum disposal capacity.

The conceptual design for the engineered barriers, the facilities and the operating concepts serve several purposes up to the general licence application:

- Evaluation of engineering feasibility within the context of the comparison of the sites and the site selection as part of SGT Stage 3
- Providing the information and data on the facilities required for conducting the safety assessment

- Providing additional background for evaluating the spatial compatibility and environmental impact assessments, operational safety, acceptance, cost-effectiveness and financial proportionality, as well as the required risk assessment, which has been gaining importance in the last years

The current concepts for the HLW and L/ILW repositories are described in section 4.2. The key elements of the HLW repository were defined as part of the '*Entsorgungsnachweis*' feasibility demonstration project based on the example of a site-specific project in the Zürcher Weinland (Nagra 2002a). The key components of the L/ILW repository are also based on a site-specific project, in this case for the general licence application for a repository at Wellenberg (GNW 2000).

The site selection procedure according to the SGT (SFOE 2008) required modifications to the concepts mentioned above, in order to take account of the wider range of geological and spatially and environmentally relevant boundary conditions that needed to be considered as a result of assessing several possible repository sites. Furthermore, given the early phase of the project, the aim is also to ensure as much flexibility as possible for future concept development.

The main modifications were:

- Consideration of additional rock support measures for the SF/HLW emplacement drifts and different sizes of L/ILW caverns to ensure flexibility given the uncertainties in geomechanical boundary conditions (depth, rock mass strength and stiffness, tectonic structures)
- Adaptation of the repository architecture to make optimum use of the available space in the host rock. This resulted in facility concepts with centrally located infrastructure installations at the base of the access structures at the disposal level with the disposal areas and rooms laid out around this in a "dead-end" tunnel arrangement
- Changing the number and layout of the underground access structures to ensure flexibility when taking into account potential geometric boundary conditions and the variability of the geological and hydrogeological boundary conditions in the rock formations overlying the host rock and to increase robustness concerning operational safety needs

Given the nature of the general licence, the early stage of the project and the large range of possible site boundary conditions, the designs and plans considered in the site evaluation process correspond to a planning level equivalent to a conceptual design. For this purpose, modular planning is assumed: the facility is divided into functional areas (modules) depending on functional requirements and a generic conceptual design is developed for each module (Nagra 2011a, 2014j). For the sites evaluated as part of the SGT Stage 1 and 2, these modules are used to develop a range of site-specific configurations which are supported by more detailed planning and design studies.

At the general level regarding the overall repository concept and design, overall requirements and principles are known (Chapter 4). During SGT Stage 3, there will be a continuous process to refine and further develop these in line with the envisaged level of detail for the general licence application documentation.

With respect to the engineered barriers, specific requirements on the individual engineered barriers are formulated from a long-term safety point of view as a first consideration. For certain topics, where this is most needed as it contributes significantly to demonstrating feasibility, these requirements have been developed and listed (e.g. Leupin et al. 2014). For other topics, particularly where these are related to site-specific aspects, these requirements are currently

under development. The different materials for the engineered barriers (e.g. the material for the HLW/SF canister) will be continually evaluated and the final decision will be taken at the time of the construction licence.

Similarly, the basic design for the repositories is to be completed for the construction licence after subsurface access has been established with the exploration shaft and/or the exploration tunnel and the construction of the facilities for underground geological investigations (Chapter 8).

Confirmation from the engineering point of view is needed to ensure that the requirements can be met and specifications can be formulated to ensure that the design target can be met. As only a conceptual design is required for the general licence application, specifications and detailed designs for many aspects will be developed at a later stage. This includes detailed requirements and specifications with respect to operational safety, worker safety, spatial and environmental compatibility and suitability for use.

The relationship between the RD&D activities regarding design and technology development for the repository and the engineered barriers is given in Fig. 7-13.

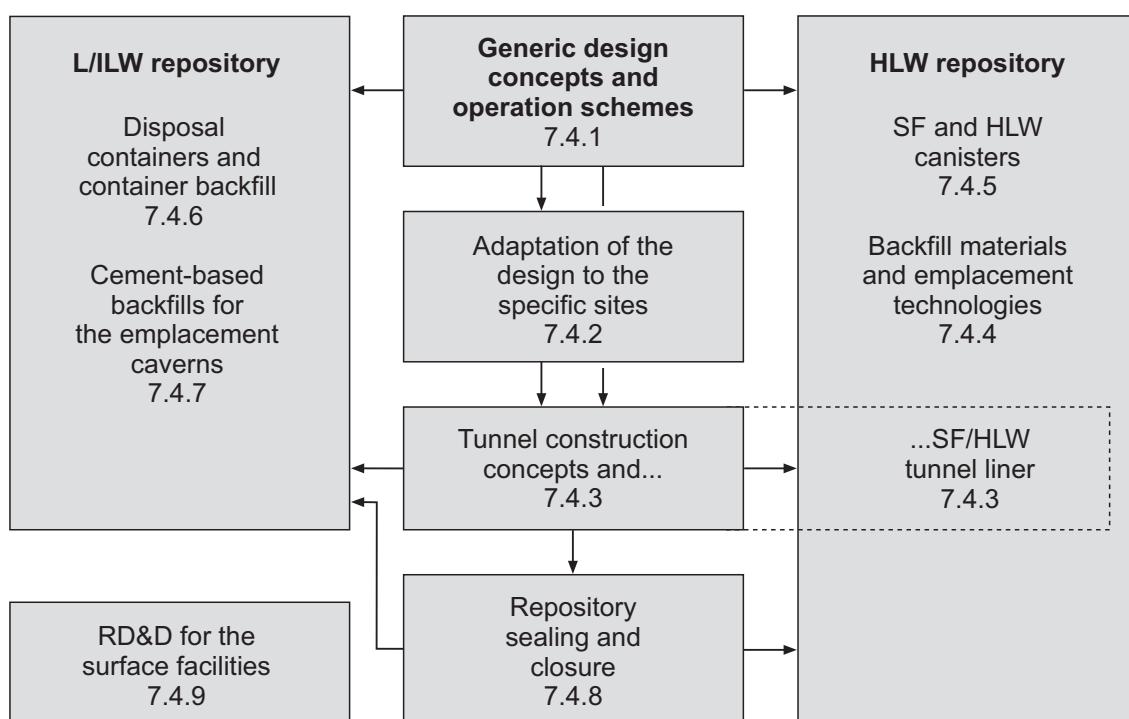


Fig. 7-13: Relationship between the RD&D activities regarding design and technology development for the repository and the engineered barriers.

7.4.1 Development of generic design concepts and operating schemes (including the pilot facility and potential retrieval of wastes)

Objectives

The objectives are:

- To develop reliable and robust generic facility modules (structures, systems, components) and corresponding layout concepts
- To provide the comprehensive design basis for the site-specific allocation of the wastes and basic layout concepts for HLW, L/ILW or combined repository

In general, the main functions of the deep geological repository within the waste disposal chain can be defined as:

- Waste receiving, packaging and encapsulation, transport to final disposal area and disposal, including concurrent backfilling and sealing
- Concurrent construction (option)
- Management and administration, facility services (supply, ventilation, drainage, etc.) and maintenance, exploration and observation, public information

The general facility breakdown structure comprises the following modules:

- Surface facility, including site infrastructure (waste receiving, packaging and encapsulation, management and administration, facility services and maintenance, public information)
- Access facilities (main access, ancillary access) to underground (transport, supply, connection)
- Underground facilities on the disposal level (exploration and observation, transport logistics, final disposal, auxiliary services, construction)

The modules provide the basis for the site-specific conceptual design to be developed as part of the general licence application.

The development of the generic conceptual designs or concepts is part of the staged design process in the context of the Sectoral Plan and the licence applications (Nagra 2016a).

RD&D topics relate primarily to the following aspects:

- The repository and its elements are a facility that is first of a kind. Specific are the unique requirements that are imposed by long-term safety (including limiting the host rock disturbance) and the need to combine nuclear activities with underground construction.
- The requirement that retrieval of wastes must be possible means that, in the operating licence of a repository, the feasibility of retrieving the wastes without undue effort has to be demonstrated. Concepts and technology for retrieval will be developed and a demonstration of retrieval will be performed in anticipation of the operating licence. For the period up to the general licence application, concepts will be refined with the objective of ensuring that the retrievability requirement is adequately integrated into the overall conceptual design.

Current state-of-the-art and progress since the 2009 RD&D Plan

Robust conceptual designs for generic modules and concepts including alternative configurations for the different facility elements have been developed for all functional requirements for both HLW and L/ILW, as well as for a combined repository. They provide the basis for the site-specific design concepts for the surface facilities as required in Stage 2 of the Sectoral Plan (Nagra 2011a).

An analysis of operational safety (nuclear and conventional safety), construction risks and environmental impact have been presented in various reports (Nagra 2013a, Nagra 2014i and 2014j). The description of the generic design and operating schemes forms an important part of these reports. Among other things, the preferred ventilation system, supply and mine water drainage scheme and transport routes are defined in these documents. Conceptual designs for generic transport systems for waste packages and canisters for various options have been carried out, assessing rack and pinion railway, cable car, shaft hoisting and trackless techniques (Sindern & Borowski 2014, Wieser et al. 2014, Messmer & Berger 2014, Ricca & Monti 2014). They confirm that access (shaft and access tunnel) to the repository are expected to be feasible and safe.

Based on geomechanical considerations to evaluate suitable repository depths (Nagra 2014k), various construction methods, cross-sections and rock support measures (liner) have been investigated for a wide range of rock mechanical conditions (Nagra 2009b, Nagra 2014k).

Regarding retrievability, international desk studies on retrievability concepts have been carried out in order to evaluate the consequences of the requirement of retrievability on disposal concepts (e.g. Bollingerfehr et al. 2014). At the more practical level, manual dismantling of dummy SF/HLW canisters from both the EB experiment at Mont Terri (after approx. 12 years of saturation) (Mayor & Velasco 2014) and the FEBEX heater experiment at the Grimsel Test Site (after approx. 18 years of saturation; García-Siñeriz et al. 2016) provide realistic experience concerning working conditions with saturated bentonite at high density (although not yet at elevated temperatures). Similar experience has been gained on an even larger scale (Prototype Repository dismantling; Svemar et al. 2016) in the URL at Äspö.

Planned RD&D in the next 5 to 10 years

The main topic within the scope of RD&D relates to retrievability. Design studies concerning retrievability at the *conceptual level* are needed in order to confirm the layout of the underground and surface facilities. This includes the development of generic concepts and strategies for the whole retrieval chain. They have to take into account the range of in-situ boundary conditions that may exist at various retrieval times within the repository operational phase (e.g. geomechanical stability, temperature, etc.). The requirement for retrievability of the canisters/containers is also incorporated into the basic requirements for future canister/container development and generic facility module planning.

A regular follow-up, especially of international programmes that are close to submitting or obtaining a construction licence, is foreseen to enhance overall feasibility and safety and reduce technological and design-related uncertainties up to the general licence application.

7.4.2 Adaptation of generic repository concepts to specific sites

Objectives

Each of the sites proposed by Nagra for SGT Stage 3 has a specific geographic and geological setting. The objective for the general licence application is to provide a site-specific conceptual design for the HLW, L/ILW or combined repositories.

Almost all of the work involves current engineering practice, including:

- Localisation of ancillary access facilities above ground (as part of final site selection)
- Evaluation of access options (e.g. ramp/access tunnel, shaft) and provisional selection of the access variant (this may be kept open up to the general licence application)
- Design study for a combined repository
- Adjustment of the provisional underground disposal perimeter based on exploration (3D seismics and deep boreholes) (see section 7.2.1)

Current state-of-the-art and progress since the 2009 RD&D Plan

Site-related repository conceptual design studies have been developed, which provide the basis for input from the affected regions for making the decisions needed in SGT Stage 2. As part of SGT Stage 2, the localisation of the surface facility and therefore the portal of the main access have been defined based on a broad participatory process.

In addition, as part of the comparison of the sites in SGT Stage 2, a risk assessment for the access facilities was performed. Based on the updated geological models, optimised corridors for the location of the potential ramps or main potential shaft locations have been presented (Nagra 2014i, Biaggi et al. 2014, Eisenlohr et al. 2014).

Planned RD&D in the next 5 to 10 years

Site-related repository conceptual design studies will be further developed to provide the basis for input from the affected regions for making the decisions needed in SGT Stage 3 concerning the localisation of ancillary access facilities. In anticipation of the general licence application, *conceptual design* studies will be produced, which will be progressively refined in later stages.

Certain activities may have some RD&D character based on the first-of-a-kind nature of the facility, although these are expected to be minor and are currently not yet identified.

7.4.3 Tunnel construction concepts and materials technology for the support of SF/HLW emplacement drifts

Objectives

The excavation of underground facilities at repository level will perturb the host rock and cause the formation of excavation-damaged zones (EDZ). The existence of an EDZ with properties different from those of the undisturbed host rock might affect the safety function of the host rock as required for the assessment of long-term safety as well as operational safety. The

objective of the construction concept studies is to evaluate suitable construction methods (excavation technique, sequencing, tunnel geometry) in combination with adequate rock support such that the following requirements are met (Nagra 2014a):

- To provide a safe working environment and serviceability during service life (construction, operation, final closure and retrieval)
- To preserve the excellent barrier properties of the Opalinus Clay on the long term by limiting host rock disturbance and damage. This is achieved by
 - Limiting the extent of the EDZ to preserve sufficient thickness of undisturbed Opalinus Clay host rock above and below the excavation (see e.g. Nagra 2008a, Appendix 5)
 - Limiting the extent and disaggregation of the EDZ around the tunnels to restrict permeability and advective flux along the tunnels (see Nagra 2014b, Poller et al. 2014, Alcolea et al. 2014)
 - Limiting negative impacts on the engineered barrier system by e.g. restricting the amount of sprayed concrete or other cementitious materials in order to limit cement-clay interactions; limiting quantities of steel and organic material to minimise the gas source term and providing smooth excavation surfaces (avoiding loose rock materials and hollows which might affect the as-built bentonite emplacement dry density)

While the RD&D regarding the geomechanical processes in the undisturbed host rock is described in section 7.2.3.3 and the overall evolution of the near-field in section 7.5, with the evolution of the EDZ and the mechanical evolution of the near-field in Section 7.5.3.4, the consequences for tunnel construction and for engineering of the tunnel support are discussed in this section.

The range of potential geomechanical boundary conditions and stress states for the candidate sites for the HLW repository will remain broad up to the point at which underground access is possible with an exploration shaft and/or exploration tunnel. This means that when designing tunnel support, a wide range of conditions must be accounted for. The geometry of the EDZ in indurated clays is controlled not only by the primary stress tensor, rock anisotropy (stiffness and strength) and the heterogeneity of the rock mass (facies variability and tectonic features), but also by the excavation technique, tunnel geometry, tunnel support and ground interaction. There is limited experience in tunnelling parallel to bedding in clay rocks at depths of 400 to 900 m (see Mont Terri, Meuse/Haute-Marne URLs; Armand et al. 2013 and 2014). Furthermore, in conventional mining and tunnel construction at great depths there are typically no constraints on material selection for tunnel support or requirements for limiting the EDZ, in contrast to the situation for SF/HLW emplacement drifts, for which the amounts of concrete and steel need to be kept to a minimum.

The current concept for the SF/HLW repository requires safe and reliable emplacement drift construction of 1.8 km a year, including equipment operation and assembly and disassembly of the tunnel excavation equipment. This means a tunnel construction method that is able to advance approximately 12 m per day, or alternatively 6 m per day if two tunnelling machines are working concurrently. A total of up to 20 km of emplacement drifts have to be excavated within 13 years. Ideally, a full-face tunnelling machine needs to be used to meet these performance criteria and to excavate the claystone with an adequate circular contour, avoiding significant overbreaks. The latter is required in order to avoid loosening rock close to the contour line. Furthermore, it would be beneficial to install the rock support or liner as close as possible to the face in order to control EDZ extent and deformations. Since this is not possible using an open-mode TBM, a balance needs to be struck. In principle, two potential concepts remain: either

conventional mining (e.g. using a roadheader and rock support close to the face) or a full-face TBM (either with a gripper TBM and sprayed concrete liner or a shield TBM with segmental liner).

The objective is thus to have a suitable excavation technology together with appropriate materials and application methods available for providing adequate support of the SF/HLW emplacement drifts.

The concept for the emplacement caverns for L/ILW foresees different options concerning size (clearance cross-sections between 58 m^2 and 110 m^2). Conventional mining using either a roadheader or drill and blast with single-shell sprayed concrete liner are considered as suitable methods. For the relatively large clearance cross-section of about 110 m^2 , a sequenced excavation method using top heading with subsequent enlargement (bench and invert) has to be applied (accessibility of equipment). If the geomechanical conditions are unfavourable for large cross-sections and sequenced excavation, smaller caverns in combination with full-face excavation needs to be applied, which will increase the required repository footprint compared to the footprint based on large caverns.

Current state-of-the-art and progress since the 2009 RD&D Plan

a) Tunnel construction

As part of the activities completed for SGT Stage 2, the analysis of construction parameters with respect to the behaviour of the rock mass has been deepened. The impact of various construction methods (excavation and reinforcement) has also been analysed in detail. In the case of minimum depth and favourable rock mass conditions, the choice of methods for tunnelling only minimally influences the damage to the rock. On the other hand, at greater depth and in unfavourable conditions, the choice of the tunnelling methods can considerably reduce the damage to the rock, for example if rock support with sufficient stiffness can be emplaced at the front (resistance principle). In the case of significant rock damage and the corresponding pressure response, this can lead to significant loading on the reinforcement and even overloading. In this case, a follow-up/additional tunnel reinforcement further down the tunnel away from the point of excavation is required that swiftly provides support for the rock mass, which reduces relying on the rock mass (ductile behaviour) but increases the damage to the rock. In the analysis, various methods with different levels of experience (combination of excavation and reinforcement) have been taken into account (Nagra 2009b, Nagra 2016d, Nagra 2016e).

In Mont Terri, several tunnels have been constructed in recent years using a roadheader. This includes the 1:1 scale FE tunnel. Due to the short length of the tunnel, the method of choice was not representative of industrial-scale methods. The accuracy (tolerances) of the profile and the rate of progress in particular are not in accordance with the requirements for real repository tunnel construction. As part of the Andra programme, in the Meuse/Haute Marne URL, which has similar (but not identical) geological and depth conditions compared to a repository in Opalinus Clay, test tunnels have been constructed in the past few years using various excavation and reinforcement methods. The results are described in Armand et al. (2013). These tunnel sections have only been partly constructed on an industrial scale but provide valuable experience which has been integrated into the Nagra knowledge base.

With respect to large galleries with a cross-section of 130 m^2 , experience in similar geologies exists in Italy at 500 m depth (Boldini et al. 2004) and from the works in the London Clay (Heathrow Express) at 30 m depth.

b) Materials and technology for support of SF/HLW emplacement drifts

Design concepts

Design concepts for the tunnel liner and the construction methods have been further developed. Unlike the feasibility study for HLW (Nagra 2002c), the present assessment assumes that the SF/HLW emplacement drift requires a liner. In Nagra (2009b), different design concepts and construction methods were presented, described and compared. The principal challenge in constructing SF/HLW emplacement drifts is the requirement to apply a liner preferably immediately upon excavation in a tight clearance situation with significant deformation of the rock.

In Nagra (2010a and c), the current design concept was proposed for the first time, consisting of a sprayed concrete liner (in conjunction with a prefabricated invert segment) in the section for canister emplacement and steel ribs with no liner in between at the location of intermediate seals as shown in Fig. 7-14. This ensures direct contact between bentonite and Opalinus Clay. In Nagra (2016d and e), this design concept has been further developed and alternatives (e.g. segmental liner) have been discussed.

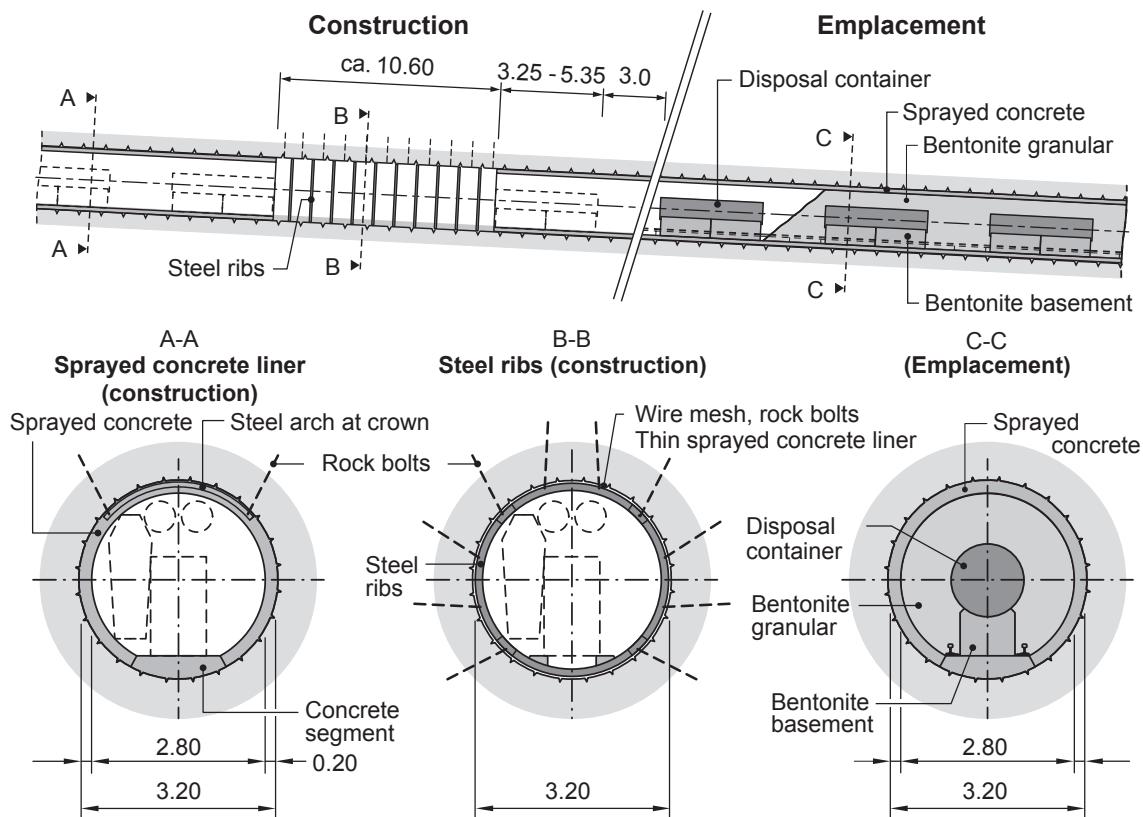


Fig. 7-14: Reference liner concept for SF/HLW emplacement drifts according to Nagra (2010a and 2014a).

URL experience

Several large-scale tests on tunnel support/liners have been performed in the Mont Terri URL, although it is acknowledged that the stress regime and the tectonic overprint in the Mont Terri URL are different from those anticipated at the selected sites. These tests are:

- The construction of Gallery 08 (Ga08) which passes through the three main facies (shaly, sandy and carbonate-rich, sandy facies) present in the URL and three tectonic faults (Burruis et al. 2010, Nussbaum et al. 2010, Lanyon et al. 2014b). Gallery 08 was excavated with a roadheader (hydraulic drum cutter Erkat ER 600) mounted on an excavator machine. Rock support consists of 15 cm of ordinary sprayed concrete with a flat concrete slab. The largest displacements and overstressing of the sprayed concrete liner occurred at the section parallel to bedding strike.
- The Mine-By (MB) experiment (Martin et al. 2015, Madritsch & Vietor 2010). The MB tunnel is oriented along the bedding strike. The tunnel with a 4.5 m diameter circular cross-section was excavated with a roadheader at a rate of 0.6 – 1.9 m/day. The tunnel was excavated with only limited support (15 cm sprayed concrete, 6 anchors) to maximise the ability to monitor the rock mass.
- The FE gallery of the Full-scale Emplacement (FE) experiment (see section 6.2). The gallery was designed with a 3 m diameter circular cross-section and 50 m length. It was excavated with a pneumatic hammer and roadheader. Support varied along the gallery, with "shotcrete only" and "arches only" sections (Lisjak et al. 2015).

Low-pH cement has been tested successfully for wet mix shotcrete applications during the ESDRED project in the laboratory and in field tests (Pettersson et al. 2007, Fries et al. 2007). Large-scale tests on tunnel support/liner have been performed during tunnel construction at the Mont Terri URL using wet mix (Ga 08 niche 4 and SR (low-pH concrete for rock support) experiment; Wetzig et al. 2011) and for the FE experiment (Daneluzzi et al. 2014) using dry mix. In principle, the suitability for rock support of low-pH shotcrete using wet or dry mix and based on common application technology is proven.

Planned RD&D in the next 5 to 10 years

a) Tunnel construction

Pre-engineering of tailor-made tunnel excavation equipment in combination with liner concepts will be studied. These studies will involve collaboration with leading manufacturers of tunnel machines. A review will be conducted to identify those excavation concepts which are likely to fulfil the requirements or which have been applied under similar conditions.

Based on these studies, it is planned to conduct more detailed pre-engineering of the suitable construction methods up to the level of definition of the design basis and evaluation of the main concepts.

The procurement and application of a tunnel boring machine on an industrial scale is foreseen later in anticipation of the construction licence (see Chapter 8), such that benefit can be gained from technological progress in the coming decades leading up to the construction licence. Furthermore, the transferability of the geomechanical rock response observed in the Mont Terri URL to the selected sites is limited because of differences in the tectonic history and the stress regimes, while the exact conditions at the selected sites are also still unknown. The results of such a new project would therefore not be conclusive with respect to the selected sites. How-

ever, it remains possible that specific aspects of tunnelling (e.g. ground response to gripper pressure) will be tested on the laboratory scale based on the results of the pre-engineering studies if this is required.

Currently, there are several tunnels under construction intersecting the Opalinus Clay (e.g. the third tube of Belchen road tunnel, new Bözberg rail tunnel). The lessons learned from these recent constructions will be collected and analysed.

b) Materials and technology for support of SF/HLW emplacement drifts

The following studies are in progress:

- An improved understanding of geomechanical processes and a database of geomechanical/rock support interactions are being developed in conjunction with site-specific exploration (see section 7.2.1) and RD&D activities concerning the formation and evolution of the EDZ (see section 7.5.3.4). Based on this, a reference engineering approach (design basis and engineering tools) will be developed, verified and established in order to apply this approach within Nagra's site selection programme.
- The constructability of the reference liner concepts (sprayed concrete liner only, steel ribs only) will be further improved. To do so, design studies will be carried out to develop preliminary designs for a liner concept taking into account new developments (e.g. lining stress controllers) and to improve details such as bedding of steel ribs. It is possible that the technology for some construction details will need to be further developed and tested in a URL (e.g. perfect bedding of steel ribs in order to avoid hollows) in later stages of the programme (underground geological investigations – see Chapter 8).

In the Mont Terri URL, the long-term behaviour of low-pH shotcrete with respect to durability will continue to be observed in niche 4 (Fries et al. 2016). With the FE experiment now started (section 6.2), there is the possibility on the longer term (15 years or more) to remove the buffer and heater in order to investigate the long-term behaviour of the liner and rock in the vicinity.

7.4.4 Buffer material selection and emplacement technologies for HLW emplacement drifts

7.4.4.1 Buffer material evaluation for HLW emplacement drifts

Objectives

The reference material MX-80 bentonite has been chosen by various waste management organisations and the status of characterisation and studies is correspondingly advanced. It is recognised, nonetheless, that bentonites other than MX-80 that have similarly high montmorillonite contents are likely to ultimately be used in the final repository for reasons related to availability and cost. The objective of the work is thus to identify various suitable bentonite materials for use as buffer material around the SF/HLW canisters in terms of the requirements (e.g. swelling, hydraulic conductivity) and to demonstrate how the knowledge base on MX-80 bentonite would be transferred to these materials. A reference material will be selected for the general licence application, while additional options will continue to be evaluated. The final decision on the material to be used will be taken in anticipation of the construction licence.

Current state-of-the-art and progress since the 2009 RD&D Plan

MX-80 sodium bentonite from Wyoming (USA) has been widely studied over the last decades (e.g. Madsen 1998, Karnland et al. 2006) and is presently considered as a reference material. However, other natural bentonites are also available and could be an alternative to MX-80 (Karnland et al. 2006, Laine & Karttunen 2010, Svensson et al. 2011, Wilson et al. 2011).

The requirements for the buffer material in the Swiss concept are discussed in section 7.5.3.3 and described in Leupin & Johnson (2013). These are related to safety-relevant properties (such as swelling capacity and hydraulic conductivity) and quantitative criteria have been established for several safety-relevant properties independently of the material used.

Cuevas et al. (2013) developed a method for the comparison of different bentonite materials by defining the bentonite properties to be measured. In Cuevas et al. (2014), the database available for the characterisation of 19 bentonites in order to establish a basis for their comparison with respect to MX-80 bentonite was documented. It was concluded that a simple test for the assessment of bentonites and their adequacy as a substitute for MX-80 bentonites as buffer material in a HLW repository is not trivial mainly because the safety-relevant properties of the bentonite result from a variety of parameters (e.g. octahedral charge, type and amount of accessory minerals, type of charge-compensating cation, etc.) and the interpretation of the results of standard methods (e.g. establishing the relevance of the amount and type of accessory minerals measured by XRD (X-ray diffraction) on the long-term stability of the bentonite). Nonetheless, an important conclusion from both Cuevas et al. (2013) and Karnland et al. (2006) is that there are bentonites of different origins that are likely to be appropriate for use as a buffer material.

Planned RD&D in the next 5 to 10 years

In order to keep maximum flexibility with respect to types of bentonites that fulfil the requirements, opportunities to enlarge the database for alternative materials and/or deepen the understanding of the close relationship between safety-relevant properties and measured parameters will be considered. Close collaboration with sister organisations (e.g. SKB) allows participation in field experiments such as the Alternative Buffer Materials (ABM) project (e.g. Svensson et al. 2011) and the Long-term Test of Buffer Material (LOT) project (e.g. Karnland et al. 2009), where different bentonites are tested under various conditions which enlarge the database and refine the method proposed by Cuevas et al. (2013).

7.4.4.2 Buffer emplacement technology

Objectives

The buffer includes granular bentonite material as well as pedestals made from pre-compactated bentonite blocks, the latter being emplaced together with the canisters (see section 4.2).

The buffer emplacement technology is an integral part of the waste emplacement concept, which envisages that the emplacement of each SF/HLW disposal canister on its bentonite support blocks is directly followed by filling the surrounding open space with buffer material. There is no industrial reference technology available from which basic technical feasibility can be justified. Hence, the objective of the work comprises technology development in order to demonstrate that the bentonite emplacement density satisfies long-term safety requirements for the buffer in SF/HLW emplacement drifts.

Further objectives to be addressed mainly beyond the general licence application will concern prototype development and optimisation aspects with regard to industrial application, quality control and quality improvement, as well as operational safety and radiation protection.

Current state-of-the-art and progress since the 2009 RD&D Plan

The buffer emplacement concept for SF/HLW focuses on the use of granular bentonite material to be backfilled around the disposal canisters and the pedestals. The major requirements relate to the completeness of the backfilling around, in front of and behind each disposal canister, allowing for:

- A target dry density of 1.45 t/m^3 for the entire bentonite backfill, a value that ensures the relevant requirements from a long-term safety point of view (Leupin & Johnson 2013)
- A reasonably homogeneous distribution of the backfilled granular bentonite material and thus of its dry density

Moreover, in selecting an appropriate backfilling method, the following engineering requirements have to be ensured:

- Continuous backfilling process in a retreating mode for each disposal canister with high reliability and continuous feeding of backfill material
- Sequential process harmonisation with the emplacement of disposal canister units incorporating pedestals made of highly compacted bentonite blocks
- Sufficient backfilling quality accounting for an irregular tunnel radius due to gallery excavation deviations and support elements (e.g. shotcrete lining, steel ribs, breakouts, etc.).

A screw conveyance technique has been identified as the most suitable method for granular bentonite backfilling with the desired quality, in comparison to pneumatic, tube drag conveyance, slinger stowing, belt conveyance methods and manual backfilling (Kennedy & Plötze 2004, Plötze & Weber 2007, Müller et al. 2017).

Major progress has been achieved with the implementation of the Full-scale Emplacement (FE) experiment at the Mont Terri Rock Laboratory and with corresponding pre-tests (Müller et al. 2017). To demonstrate the feasibility of the emplacement of the granular bentonite, a prototype machine for emplacing the material was constructed (Fig. 7-15) and successfully deployed.



Fig. 7-15: The backfilling machine in the FE tunnel (left) and a detail of the emplaced granular bentonite (right) and the contact with the liner (FE experiment – see also section 6.2).

The main conclusions from this project are as follows:

- The sectional dry density values in the FE tunnel at Mont Terri assessed by mass-volume balance varied between 1.444 t/m^3 (where low quality material was backfilled unintentionally) and 1.555 t/m^3 . With an average dry density of $1.489 \pm 0.003 \text{ t/m}^3$, the target dry density of 1.45 t/m^3 for the entire backfill was clearly met under conditions that were challenging compared to a representative repository environment, due to the presence of the instruments in the buffer and the fact that care had to be taken to avoid their damage. This was achieved by ensuring:
 - Optimisation of the buffer material production (highly compacted granular bentonite material)
 - Optimisation of backfilling technology using a machine with five screw conveyors
- Segregation during horizontal backfilling of the granular material was observed. Approaches for suppressing this effect have been evaluated qualitatively. Flexible slope coverage seems most promising in this regard.
- There seems to be potential for optimisation of the density of horizontal buffer emplacement with the horizontal screw conveyance method. Approaches to increase dry density have been evaluated (Behl & Bunge 2016), but making conclusive statements is not possible at this stage.
- Various methods for local dry density assessment were applied, especially in pre-tests at a surface industrial facility where access from outside to a dummy tunnel tube was possible. The tests comprised dielectric and gamma-gamma probe measurements as well as horizontal cone penetration tests. The resulting profiles of local dry density indicate higher values near the roof section and in the close vicinity of the screw conveyors' positions. Lower density was observed near the invert. Although certain open questions remain, e.g. regarding boundary effects with dielectric measurements of density, in general the results show good consistency with the average dry density derived from sectional mass-volume balance calculations (1.48 to 1.55 t/m^3 in the pre-test).

Planned RD&D in the next 5 to 10 years

Since the setup of the FE experiment has been successfully achieved, no further large-scale experiments are planned. Nonetheless, further development of QC measures for local density determination is being considered to identify the influence of segregation and the impact of countermeasures. The level of activities regarding this and the need for further activities to optimise the emplacement density is strongly related to the outcome of the work described in section 7.5.3.3 refining the requirements on the as-built properties of the bentonite and backfill barriers.

7.4.5 Development of SF and HLW canisters

Background and objectives

In order to achieve safe disposal of SF and HLW, it is necessary to provide long-term containment³⁰, which requires that both the structural and corrosion performance of the disposal canisters are adequate. The broad objective of the programme for the development of SF/HLW canisters is to ensure that a secure knowledge base is available for the selection of a suitable canister concept so that full-scale prototype development can proceed in the period around 2035. In order to reach this stage, it is necessary to assess the potential options for materials and designs, select suitable candidate concepts and ensure that the technology to implement these concepts will be adequately developed by this time.

In reviews of Nagra (2002c and 2008e), HSK (2005), KSA (2005) and KNS (2012) have commented on the desirability of selecting a canister material that would avoid gas production in the repository and on the need for minimum requirements for barriers. In this context, the discussion below notes the progress on the development of requirements, the consideration of copper as a canister material and on critical reviews of the feasibility of various canister materials. The associated studies that are needed to establish the understanding of corrosion performance of the materials under consideration are discussed in section 7.5.3.1.

Current state-of-the-art and progress since the 2009 RD&D Plan

Canister requirements

The basic requirements for the SF/HLW disposal canister are listed below and are discussed in more detail in Johnson & Zuidema (2013):

- Sufficiently low general corrosion rate under in-situ repository conditions.
- Low probability of localised damage processes (e.g. stress-corrosion cracking, pitting corrosion, etc.) under in-situ repository conditions.
- Well developed methodologies for predicting the long-term corrosion (chemical) and mechanical canister failure modes and their interactions.
- Adequate structural strength under in-situ repository conditions and under normal and off-normal handling operations of the operational phase, including possible retrieval from the emplacement position.

³⁰ ENSI G03 (ENSI 2009) requires that canisters provide complete isolation for at least 1,000 years.

- Reliable closure sealing; in addition, the method for sealing a canister must not result in the maximum temperature permitted for the waste being exceeded³¹.
- The canister design should be compatible with the size of spent fuel assemblies, which are up to about 4.5 m in length. From this requirement, it follows that a satisfactory method for fabrication of a canister must exist or be possible to develop at the scale of interest.
- Processes arising from the canister and its waste and their interaction with the barriers in the repository (e.g. gas production, radiation emission, corrosion products) should not cause significant damage over the long term to these barriers.

Depending on the material and canister design selected, the more detailed requirements derived may vary. An example of more detailed elaboration of requirements for the concept of carbon steel canisters for SF/HLW is given in a design study for carbon steel canisters by Patel et al. (2012).

Evaluation of options

For many years, Nagra has focused on assessment of canister concepts based on two options: carbon steel or copper shell/cast iron (Johnson & King 2003, Landolt et al. 2009, Patel et al. 2012). The former design option has been developed in some detail based on Nagra-sponsored studies (Patel et al. 2012, Pike et al. 2010). The copper shell/cast iron canister concept has been studied extensively by SKB and Posiva and many prototypes have been constructed (Raiko 2012). Other metallic materials such as titanium or nickel alloys have also been examined at varying levels of detail in other national programmes (Johnson & Zuidema 2013 and references therein). In addition, some studies have been performed to determine whether or not ceramics might prove a feasible option, at least for the smaller HLW canisters (Baroux 2013, Holdsworth 2013).

In order to develop a clear comparative overview of the prospects for metallic and ceramic options, a comprehensive review of relevant materials and designs was performed, covering aspects such as fabrication, structural performance, corrosion performance, impact on the barrier system and cost. The results showed that the most suitable solution would be a concept that combines a corrosion-resistant external surface that leads to a low or negligible gas production rate with an internal structure fabricated from steel or cast iron to provide the necessary structural strength. Examples of such a concept would be the copper shell/cast iron canister, a copper-coated canister, or even a Ti- or Ni-coated carbon steel canister. Based on the assessment of fabrication possibilities and the demanding design loads, ceramics are considered to be unable to meet the structural performance requirements and there is currently no technology available for final closure sealing (Holdsworth et al. 2014). Thus no further development work is proposed for a canister built out of ceramic materials.

Design and materials development

The results of the options study (Holdsworth et al. 2014), as well as those from other design development studies (Patel et al. 2012, Raiko 2012, Keech 2013, Keech et al. 2014, Boyle & Meguid 2015), provide the basis for canister concepts that have been actively developed. These include carbon steel canisters and copper-coated carbon steel canisters. Even though it remains a candidate solution, no active design work on the copper shell/cast iron concept is being performed, because the SKB and Posiva work is comprehensive and addresses all issues relevant to a repository in Opalinus Clay.

³¹ 450 °C for HLW and about 400 °C for spent fuel assemblies.

Nagra has established a long-term cooperation agreement with NWMO (Canada) to develop the methods for coating carbon steel canisters with copper (Keech 2013, Keech et al. 2014, Boyle & Meguid 2015). Both electroplating and cold spray methods have been studied, with electroplating considered for the canister body and lid and cold spray coating planned for covering the closure weld region of the steel canister after sealing (Keech 2013). High-quality electroplated and cold spray coatings up to 10 mm thick have been produced on large specimens, the applicability of both techniques on full-scale NWMO canisters has been demonstrated (see Fig. 7-16), and the process parameters have been optimised in view of critical coating properties such as porosity, ductility, adhesion to the substrate, microstructure, chemical composition, etc. Corrosion studies of electroplated and cold sprayed copper are discussed in section 7.5.3.1.

In the area of the design and development of a carbon steel substructure for copper-coated SF and HLW canisters, work was focused on closure weld designs and associated structural analyses (Bastid et al. 2015).



Fig. 7-16: Photograph of a NWMO full-scale copper-coated canister prototype (courtesy of NWMO).

Planned RD&D in the next 5 to 10 years

Evaluation of options

It is likely that one or more countries will have licensed repositories before Nagra applies for a construction licence in the timeframe 2040 – 2050. Switzerland will inevitably profit from the associated development work done. Therefore, close contact will be maintained with programmes in other countries, in particular Sweden, Finland, Canada, Belgium and France, all of which are developing copper- or carbon steel-based canister concepts.

Design and materials development

The principal focus of work for the next several years will be on the further development of copper-coated canister concepts through the continuing cooperation with NWMO (Canada). This includes the development of the electroplating and cold spray coating methods for depositing copper onto carbon steel, cast iron and the weld region, as well as characterisation of coating properties and demonstration of the technology at full scale. In parallel, the ongoing work on the corrosion of copper coatings will provide input to the refinement of the design of the canister (e.g. copper coating thickness).

A specific technology development need is the design and demonstration of a weld closure method for the carbon steel substructure of the copper-coated canister. Several closure concepts will be studied using finite element stress analysis to determine suitable weld and inspection

techniques, weld closure designs and overall canister structural performance under expected repository loads. The general objective is to establish a design that does not require post-weld heat treatment, a process that may have negative impacts on fuel element integrity (Patel et al. 2012). Once a weld closure design is developed, the concept will be tested by small-scale weld trials and by constructing the lid and upper section of a canister and performing the closure weld. Non-destructive and destructive testing of the weld, including measurement of post-weld stresses, will be performed. The sequence of weld design through finite element stress analysis, fabrication of welded joints and post-weld characterisation and inspection will be pursued until a suitable design is developed and the feasibility of sealing has been demonstrated. In conjunction with NWMO, Nagra will also pursue the preparation of large-scale copper-coated lids and sections of canisters in order to further refine and demonstrate the technology.

Development work will also be done to evaluate the feasibility of a cast iron substructure on which copper will be coated. The major challenge of such a concept is the development of an adequate methodology for sealing/welding. If successful, the development of the design of a cast iron-based canister body can follow. The feasibility of alternative corrosion-resistant external surfaces for carbon steel or cast iron canisters, such as Ni-, Ti- or ceramic-based coatings, will also be explored. In parallel, further refinement of the existing weld closure of the carbon steel canister will be undertaken.

7.4.6 Development of L/ILW disposal containers & container backfill material

Objectives

The main role of the L/ILW disposal containers is to provide suitable handling units for several waste packages and protection, mainly against mechanical damage. For the latter, the space between waste packages should be filled with backfill material.

Containers and backfill materials need to fulfil various requirements regarding long-term safety, handling, interim storage, operational safety, costs, retrievability, etc. One of the objectives related to L/ILW disposal containers and container backfill materials is to develop and establish these requirements. This includes the development of detailed requirements for preparing and handling backfill materials and for filling the containers such that requirements from long-term safety and operational safety are met.

It is the objective up to the general licence application to define the conceptual design for L/ILW disposal containers and for the backfill material, as well as to demonstrate their suitability. In particular, the containers should be designed (considering structural, fire protection and potential water exposure requirements) to cope with incidents (operational safety) and loading cases/integrity requirements during potential retrieval.

Current state-of-the-art and progress since the 2009 RD&D Plan

Since the 2009 RD&D Plan, the development of new L/ILW disposal containers was started in close cooperation with the waste producers, mainly because of transport considerations. New containers LC-84 (6 m³), LC-86 (9 m³) and LC-86H (11.3 m³) replace older concepts LC-1 (26 m³) and LC-2 (14.3 m³), which are no longer considered because they are difficult to handle for decommissioning and transport and are not suitable for interim storage. The concept of using cuboid concrete containers for L/ILW remained unchanged, and the fabrication of similar containers for disposal purposes has been demonstrated.

For the backfilling of the disposal containers, two cement-based mortars have been developed in the context of the technical studies for the Wellenberg repository project (Jacobs et al. 1994, Mayer & Wittmann 1996). The high permeability fluid mortar ("mortar-2", Mayer & Wittmann 1996) is no longer considered, mainly due to concerns regarding long-term stability, operational safety (e.g. H₂ generation) and handling (application). Nonetheless, the concept of backfilling the containers with cementitious mortar is still valid. The current reference backfill material consists of a monograin mortar ("mortar-1", Jakobs et al. 1994).

Planned RD&D in the next 5 to 10 years

Development and production of prototypes of L/ILW disposal containers in close cooperation with the waste producers will be completed soon, as the first decommissioning of a nuclear power plant in Switzerland is scheduled to start in 2019, and will thus be completed before the general licence application. The new disposal containers will be tested in order to demonstrate the fulfilment of all relevant requirements.

The use of activated and/or contaminated concrete from decommissioning as an aggregate for a mortar as container backfill is an interesting option and will be further investigated and possibly tested. Also, if this option is not further pursued, research and development work on backfill materials and procedures will be continued.

7.4.7 Cement-based backfills for L/ILW emplacement caverns

Objectives

For the general licence application, concepts for suitable backfill for L/ILW emplacement caverns must be available. The backfill materials will be cement-based since cement exhibits favourable long-term properties. Work will aim at confirming the suitability of the suggested materials with respect to the requirements.

Current state-of-the-art and progress since the 2009 RD&D Plan

Two cement-based mortars (monograin mortar "mortar-1" and high permeability fluid mortar "mortar-2") were developed for the Wellenberg repository project (Jacobs et al. 1994, Mayer & Wittmann 1996); "mortar-2" is no longer considered (as mentioned in section 7.4.6).

For the Wellenberg project, the requirements for cement-based backfill materials were defined qualitatively in order to ensure the long-term safety of the engineered barriers; the requirements comprised the following aspects (these will be revised in SGT Stage 3):

- The backfill material should exhibit favourable retention properties for radionuclides. This includes maintaining high-pH conditions (> 12) for a long time period, resulting in high sorption capacity and low solubility for many radionuclides.
- The backfill material should contribute to keeping gas pressure in the cavern at a minimum level and to minimising gas-induced expulsion of porewater containing radionuclides. This can be achieved by ensuring a significant porosity fraction (e.g. 25 %) for gas accumulation, maintaining high pH and thus low iron corrosion rates and by providing sufficiently high gas permeability to allow gas migration and thus avoid high pressure build-up.

- The backfill material should provide favourable conditions for the long-term mechanical stability of disposal containers. Material stiffness should be designed to provide support against geomechanical pressure and to ensure the functional reliability of the natural barrier. This can be achieved by using a mortar with high aggregate strength and grain-to-grain contact.

Planned RD&D in the next 5 to 10 years

Quantitative technical requirements for backfill mortars will be defined based on requirements derived from post-closure safety assessment, including the assessment of the impact of repository-induced effects which integrate the outcome of the investigations in section 7.5.3.2 on safety-relevant properties of cement barriers. Current construction standards and, in particular, processability and on-site QC of the mortar will be considered when defining the technical requirements.

Technical parameters that need to be addressed include:

- Uniform grain size distribution resulting in high porosity and high (gas) permeability
- Compressive strength, splitting tensile strength and low compressibility (Young's modulus) in order to assess (and limit) the effects from rock pressure
- Creep and shrinkage in order to assess the effects of long-term volume change
- Hydration heat emission in order to asses potential THM-related impacts on the geological barrier
- Minimal alkali-silica reaction (ASR) in order to meet the long-term durability requirement
- Slump flow in order to check for workability and flowability
- No use of materials that may cause serious health hazards or technical/operational problems under standard procedural operations

Activities will focus on confirming the suitability of the suggested mortar. Initially, this will comprise a desk study, which may be expanded to laboratory-scale investigations in a second stage if necessary.

The concept for the backfill mortar also must be compatible with the emplacement concept for the backfill as well as for waste containers and with the retrievability concept for waste containers.

7.4.8 Repository (sealing and) closure

Objectives

According to the Nuclear Energy Act (KEG 2003) Art. 3, closure means backfilling and sealing of all underground excavations and the access tunnel/shaft of a deep geological repository after termination of the monitoring period.

Seals are part of the redundantly designed EBS with the purpose of preventing water flow and permanently preventing pollutants/radionuclides from migrating from the disposal area into the biosphere through conceivable future pathways such as the (backfilled) tunnel system and disturbed rock zones. The sealing system includes various sealing elements and their associated

mechanical confinement, each of which has to expect different load scenarios and fulfil different functions. The specific sealing elements include: i) temporary seals³², ii) long-term seals of low permeability and iii) seals with sufficiently high gas permeability to keep gas pressures at an acceptably low level in emplacement caverns (L/ILW), while still maintaining sufficiently low solute transport.

Backfilled volumes comprise all other tunnels/drifts/shafts apart from seals within the host rock, as well as above it. All of these openings have to be backfilled to keep long-term convergence at acceptable levels so that the functional reliability of the natural and engineered barriers is ensured (ENSI 2009). Moreover, the separation of water-conducting rock layers above host rock level existing prior to the construction of the deep geological repository must be restored over the long term (KEV 2004).

The main objectives are the development of the design requirements for the different types of seals, with the focus on those derived from post-closure higher-level requirements. Methodological and technical options for construction will be discussed and QC measures proposed, ensuring that these design requirements can be met. Detailed specifications for the construction of the seals will be developed later, in anticipation of the construction licence.

Current state-of-the-art and progress since the 2009 RD&D Plan

The main sealing functions rely on bentonite as the basic raw material of all sealing objects due to its favourable properties and its demonstrated long-term stability under repository-relevant conditions (see section 7.5.3.3).

Recent experimental projects on sealing and backfilling can be divided into three types of work:

- Evaluation of alternative bentonite raw materials (section 7.4.4.1)
- Industrial procedures for material processing, such as production of high density granular bentonite mixtures (Garitte et al. 2015a and b, Bosgiraud et al. 2014) and of compressed bentonite blocks (Garitte et al. 2015a and b, Arvidsson et al. 2015)
- Implementation procedures for horizontal tunnel sections and vertical shafts, e.g. the manual installation of bentonite blocks in the "interjacent sealing section" of the FE experiment at Mont Terri (Garitte et al. 2015a and b); emplacing bentonite blocks in SKB's repository tunnel experiment with an industrial robot (Arvidsson et al. 2015); emplacing sand-bentonite mixtures (80:20 ratio) and pure granular bentonite in a horizontal tunnel section for the GAST experiment at the Grimsel Test Site (Rüedi et al. 2012); emplacing different granular bentonite mixtures by screw conveyance methodology (project LUCOEX/FE: Köhler et al. 2015, project DENSFILL: Behl & Bunge 2016)

Full demonstration of seal construction and performance has been undertaken in international experiments such as the Tunnel Sealing Experiment (TSX) (Dixon et al. 2009) and the Enhanced Sealing Project (ESP) (Martino et al. 2007). Both continue to provide valuable information. Kudla et al. (2013) state that, in comparison with seals in horizontal tunnel sections, the design and implementation in vertical shaft sections can be considered as feasible, although it must be acknowledged that little experience exists in clay host rocks.

³² According to regulatory Guideline ENSI-G03 (ENSI 2009), seals must be available that can be emplaced within a short time; however, these seals must not be permanent.

Regarding the Swiss sealing concept, major milestones are the design and construction of the full-scale gas permeable seal test (GAST) at the Grimsel Test Site and the implementation of the full-scale interjacent sealing section for the FE experiment at the Mont Terri URL (see section 6.1), which demonstrated the technical feasibility of building such structures at full scale. First results from these long-term experiments are expected to confirm the functional barrier properties, including technical parameters that had previously only been upscaled from laboratory scale to full scale. Nagra has been developing experience in full-scale seal construction through involvement in the EU DOPAS project, which involves construction of seals in crystalline and sedimentary rock, for instance the Full Scale Seal Experiment (FSS) at Saint Dizier (France) implemented by Andra (Bosgiraud et al. 2014).

Further optimisation took place with regard to the long-term safety of sealing and backfilling systems, by using an adapted reference repository layout as proposed in the past years, following the principle of a "dead-end" emplacement concept (Nagra 2011a). The emplacement rooms no longer connect two larger galleries as described in Sitz (2002) and Nagra (2002a), and all underground access routes are arranged centrally in the current concept.

A generic modelling study on radionuclide transport along the underground access structures based on the layout described above concluded that, for realistic parameter values, radionuclide release along the access structures of a deep geological repository is extremely low. Increasing the hydraulic conductivities that are assumed for the tunnel system and the seals (including the excavation damaged zone along these underground structures) increases all the calculated flows. Nonetheless, the increase becomes smaller with rising hydraulic conductivity, as the flow ultimately becomes controlled by the limited capacity of the host rock to supply water rather than by the hydraulic conductivity of the seals. The dose rate maxima due to releases via the access structures show the same asymptotic behaviour as the flow, and remain low in all cases. The results confirm that radionuclide release occurs predominantly through the host rock (Poller et al. 2014). These findings will be taken into account when revisiting the requirements on the seals from a post-closure point of view in the future.

Planned RD&D in the next 5 to 10 years

A comprehensive closure (sealing and backfilling) concept will be developed for the general licence application. This will be based on the current repository layout and associated long-term requirements. It will include topics such as the different functions of the various types of seal and the technical feasibility of their implementation, possibly including considerations with respect to raw material processing and construction methodology.

The results from generic modelling of radionuclide transport along the underground access structures in the HLW and L/ILW repositories (Poller et al. 2014) will play an important role in the derivation of long-term safety-related design requirements for the different sealing objects and backfills. This in turn yields the properties of appropriate sealing raw materials to be considered for suitability testing, setting the scene for specifying requirements for material processing and the preliminary design of each type of sealing structure.

Safety-relevant requirements for the sealing objects (e.g. swelling pressure, gas- and water-permeability, porosity, etc.) can be met by ensuring the values of characteristic design parameters that are suitable for QC during construction (e.g. dry density; Bucher & Spiegel 1984, Bucher & Müller-Vonmoos 1989, Karnland et al. 2007). This contributes to ascertaining technical feasibility and allows effective and reliable on-site QC methodology to be included in the closure concept.

The important technical fundamentals have been comprehensively developed and demonstrated as described above by setting up experiments at different scales, most of which continue to provide valuable information, particularly regarding performance at the 1:1 scale. Hence, the closure concept for the general licence application will be based on a desk study and continued monitoring and interpretation of ongoing large-scale sealing experiments.

7.4.9 Aspects of the packaging facilities (encapsulation facility and others)

Objectives

A prerequisite for the licensing of the geological repository is the development of the scientific basis to ensure, within specified safety margins, the handling of the spent nuclear fuel (SNF) and its encapsulation in disposal canisters. At the time of encapsulation, the fuel assemblies need to be verified with regard to, but not confined to, confirmation of burnup, dose rate and decay heat. Specific issues such as opening the transport/storage cask, handling of spent fuel in the repository surface facility and repackaging of the fuel into the disposal canisters must be properly addressed. Several safety-relevant issues need to be considered, from material ageing to possible release of radioactive substances from the cask/SNF. The objective for the general licence application is to consolidate the basic concepts to ensure the above. Detailed development for the design and the processes involved will be ensured by the construction licence application. Important aspects to be addressed with an RD&D component are:

1. Description of spent fuel assembly behaviour:
 - Description of long-term integrity of the spent fuel assemblies during interim storage (see section 7.3.4) and handling operations
 - Determination of the degree and the type of contamination/activation of the spent fuel transport cask (defining a reference and a worst case scenario)
2. Disposal canister loading optimisation (discussed separately in section 7.3.5)
3. Fuel handling and qualification for disposal canister loading (including operational safety):
 - Detailed assessment of work procedures for the handling of spent fuel assemblies (opening of transport cask, unloading of spent fuel assemblies, loading into the disposal canister, closing the disposal canister, maintenance operations, airlock operations) as a basis for safety studies and accident assessment regarding operational safety (see also section 7.6.2)
 - Evaluation of the handling equipment and design of the encapsulation facility with regard to operational safety (safety regime, systems and functions)
 - Evaluation of the experimental setup and measuring techniques required for spent fuel qualification and radiological monitoring
4. Decontamination and decommissioning:
 - Decontamination and decommissioning of handling equipment, encapsulation facility and transport/storage casks with regard to operational safety (safety regime, systems and functions)
 - Assessment of waste management procedures and of the equipment used for the different operating phases

Current state-of-the-art and progress since the 2009 RD&D Plan

Only certain aspects required for the conceptual design need to be developed in the next years. This is in contrast to several of Nagra's sister organisations which have detailed design concepts in place in anticipation of their construction licence (e.g. Sweden and Finland). International collaboration and exchange is thus essential as the know-how is largely available already.

In addition, several activities have been initiated:

- The potential degradation of SF during long-term interim dry storage and the impact of transport and handling during transport to the surface facility of the repository and loading into disposal canisters are being investigated as part of an agreement between Nagra, EPFL and Swissselectric concluded in 2015. As part of the project, radioactive contamination, neutron activation of transport/storage cask components after interim storage and decontamination techniques are also being investigated.
- A revised version of the existing disposal canister fuel loading optimisation programme (SIMAN³³) is being developed (see section 7.3.5).
- Preliminary design studies of the encapsulation facility and planning of operational procedures has been completed, including the compilation of basic requirements.

Planned RD&D in the next 5 to 10 years

The following activities are foreseen:

- Cooperation with international organisations and laboratories such as ITU/JRC-ITU Karlsruhe (Rondinella et al. 2013) regarding investigation of long-term spent nuclear fuel behaviour (see section 7.3.4).
- The following aspects of transport/storage cask management will be addressed within the framework of the Nagra/EPFL cooperation mentioned above:
 - Estimation of the atmosphere of the transport/storage cask. Estimation of possible gas release (helium, fission gases) and particulates due to opening of the cask and unloading of the fuel
 - Estimation of possible induced activation and contamination in the transport/storage cask
 - Decontamination techniques for the transport/storage cask
- Other issues related to the encapsulation facility operation with spent nuclear fuel need to be addressed at the conceptual design stage
 - Handling of fuel assemblies in the encapsulation facility: normal operations and handling incidents
 - Evaluation of requirements for the handling equipment
 - Measures/concepts for handling of damaged fuel assemblies
 - Estimation of possible induced activation and contamination in the encapsulation facility

³³ SIMulated Annealing: the computer software SIMAN, based on the method of simulated annealing.

- The disposal canister fuel loading optimisation programme (SIMAN II) will be further developed. A high level of optimisation reduces the number of canisters to be disposed of per year as well as the total number of canisters. This can impact both the design of the encapsulation facility and the required storage volume in the repository.
- Following up the state-of-the-art regarding measurement techniques and experimental characterisation (Caruso & Jatuff 2014) will be continued.

7.5 Evolution of safety-relevant properties and processes in the near-field

The repository near-field is expected to provide long-term containment and retention of radionuclides over the entire assessment time due to a range of favourable safety-relevant properties. Due to interactions between the repository components and the resaturation of the repository, the near-field will evolve over time and, for safety assessment, it is necessary to identify any processes or circumstances that could lead to significant adverse perturbation of these safety-relevant properties. This section describes the RD&D that is required with respect to the post-closure evolution of the repository and the near-field.

The RD&D needs regarding post-closure evolution are driven by the safety functions of the engineered barriers and the natural barriers and the requirements and indicators derived from them. In order to formulate sensible indicators, detailed understanding of the evolution of the repository and the near-field needs to be in place as the processes involved are taking place in a complex environment, they are strongly coupled and the impact over long timeframes needs to be sufficiently understood.

Thus, the development of the safety functions (their indicators) and the requirements on the engineered barriers from a post-closure point of view is a process that goes hand-in-hand with the description of the repository evolution and both undergo constant refinement. This is shown in Fig. 7-17, which also illustrates the structure of this section.

Nagra has developed specific requirements on the components of the engineered barrier system (e.g. for the canister and the buffer). In some cases, these requirements are qualitative, while in other cases quantitative requirements or preferred values are given for parameters such as hydraulic conductivity that quantify the main safety-relevant attributes of the components. Furthermore, Nagra has developed sets of indicators and criteria (Tab. 6-2) that can be used to assess the potential significance of potentially detrimental features, events and processes on the safety functions. If the criteria cannot unequivocally be shown to be met, then radionuclide release and transport calculations are carried out (or existing radionuclide transport calculations are re-examined) to evaluate the nature and extent of any detrimental effects and assess the implications in terms of overall safety indicators, principally annual individual dose (section 6.5 and Leupin et al. 2016a and b). These indicators and criteria are strong drivers for the RD&D activities planned in this area.

Section 7.5.2 provides a general description of the evolution of the near-field as well as the activities supporting enhanced understanding of saturation, temperature evolution and gas transport. These processes affect the entire near-field and cannot be discussed at the level of the individual barrier. This section thus provides an overview, while other more detailed sections describe the evolution and the needs for RD&D at the barrier level or at the interfaces between barriers. Specific aspects of evolution that are addressed include temperature evolution, saturation and gas transport, as well as the chemical and mechanical behaviour of the canisters for SF/HLW, containers for L/ILW and buffer and backfill materials. The focus here is on the early saturation times of the repository when strong gradients occur.

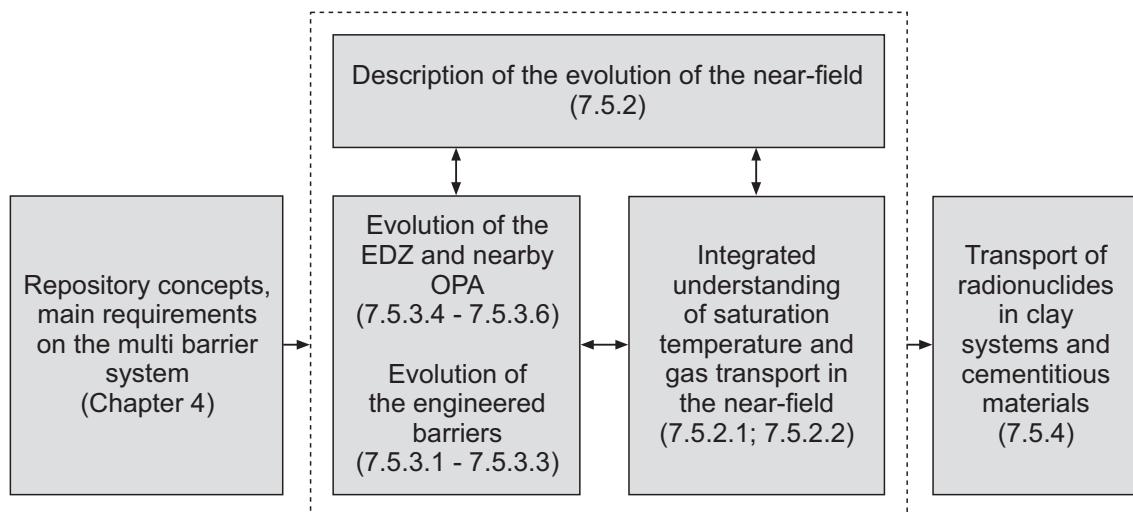


Fig. 7-17: Relationship between the description of the evolution of the near-field including its components and the development of the safety function indicators and requirements, illustrating the structure of section 7.5.

During the later repository evolution when the radionuclides are released, dose calculations require a solid knowledge of radionuclide immobilisation, retardation and transport behaviour in the near-field and in the undisturbed host rock. Key element-specific parameters describing these processes include sorption and diffusion coefficients and solubility limits. Planned RD&D addressing the development of near-field databases for these parameters is presented in section 7.5.4 (see section 7.2.3.1 for far-field host rock transport, retention processes and parameters).

Overall, the planned RD&D programme aims to develop the fundamental understanding, modelling capabilities and data needed to describe the near-field evolution, to evaluate the safety function indicators and to support the dose calculations needed to evaluate the consequences of any resulting radionuclide releases.

The latest full integration of the understanding of the near-field evolution took place as part of Nagra's safety assessment in 2002 (Nagra 2002c). The next full description of the repository evolution and the assessment of the safety-relevant aspects including the formulation of the requirements are planned for the safety case which will be part of the general licence application (around 2024).

While the focus here is on the current concepts, it is possible that, after evaluation of alternative repository concepts in the context of SGT Stage 3 (see section 4.2), supporting activities will be defined targeting the description and evaluation of the near-field specific to the potentially selected alternative concepts. While the RD&D related to the evolution of the copper-coated canister is included, other activities related to alternatives are currently not specified.

7.5.1 Description of the near-field evolution

As an introduction to the following sections, an overview of some of the main coupled processes that govern the evolution of the SF and HLW emplacement drifts in a HLW repository is given in section 7.5.2.1) (see Fig. 7-18) and for the L/ILW waste repository an overview is given in section 7.5.2.2.

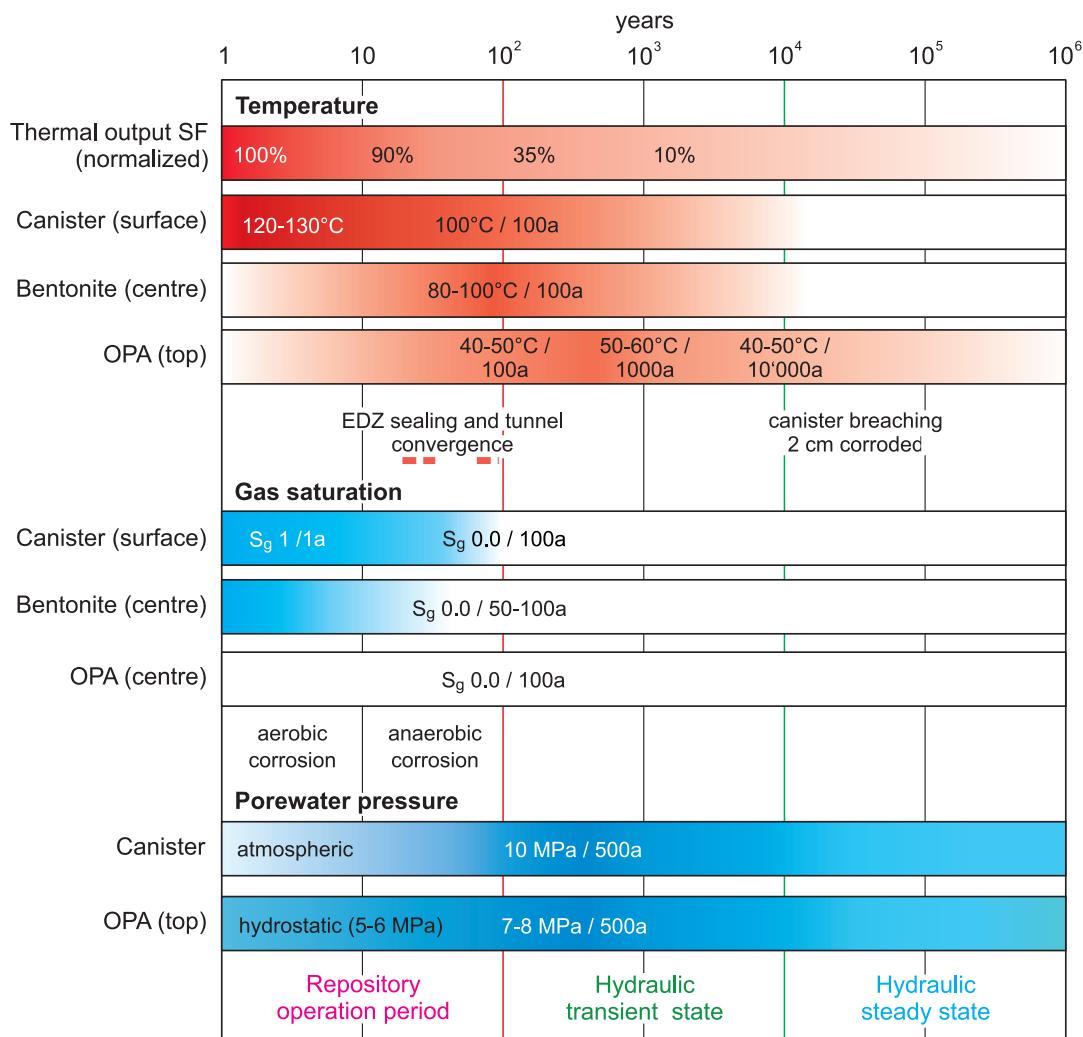


Fig. 7-18: Overview of the expected evolution of the main processes in a HLW repository based on a compilation of modelling reports and experimental data.

The colour intensity indicates in a qualitative way their expected importance over time. From Leupin et al. (2016a).

After waste emplacement, the development of the safety-relevant properties of the SF/HLW tunnel near-field is essentially controlled by the interplay of various thermal, hydraulic, mechanical and chemical (THMC) processes, including saturation of the backfilled emplacement rooms, heat and gas production from the waste, as well as the swelling of the bentonite buffer and the reconsolidation of the surrounding host rock.

Decay heat from SF and HLW will increase temperatures within and around the repository for long periods of time. The effects of this heat on the engineered and geological barriers cannot be completely eliminated, but can be kept low by ensuring sufficient duration of interim storage and suitable waste emplacement density. The bentonite backfill will become saturated within about 50 to 200 years (depending on the host rock properties), after which pore pressure in the buffer will increase to that in the surrounding host rock. Gas is generated through corrosion of the steel used in tunnel support and of the canisters, and migrates in the gas and water phase

through the engineered barriers or into the rock. The gas transport capacity of the Opalinus Clay is assumed to be sufficient to release the gas generated by corrosion of the SF/HLW canisters and tunnel installation materials into the surrounding host rock without causing damage.

Other potentially significant processes include:

- Degradation of the cementitious tunnel liner, migration of high-pH porewater affecting a thin section of the adjacent host rock and bentonite, where chemical interactions can occur (not shown in the figure)
- Canister breaching due to corrosion

Fig. 7-19 gives a similar overview for the L/ILW emplacement rooms. The construction of the emplacement rooms and emplacement of the waste will take around 15 years in total. The timeline for waste emplacement together with the adopted emplacement procedures will set the initial conditions for the thermal, hydraulic, mechanical and chemical (THMC) evolution of the L/ILW near-field. The period of thermal disequilibrium is restricted to the operational periods (cooling of the host rock due to tunnel ventilation) and the early post-closure period, after which the exothermic reactions in the cementitious backfill will cease. Thermal effects are expected to have a negligible effect on any chemical or physical processes.

Thereafter, the evolution of the L/ILW near-field is essentially controlled by the resaturation of the backfilled emplacement rooms, gas production by the waste and the physico-chemical interaction of the inflowing porewater with the cementitious backfill and the waste materials. Gas production will hinder saturation, which may take tens of thousands of years, and model calculations indicate that there could be a period during which gas will expel porewater from the rooms into the host rock and through the engineered gas transport system (EGTS). The EGTS is, however, designed to prevent the occurrence of potentially damaging gas pressures. The slow influx of water will initiate cement and waste degradation and could lead to cement-waste interactions, mineral precipitation and dissolution, with the potential for porosity changes and cement-clay interactions.

Overall, it is argued that the repository-induced effects can be adequately described based on present understanding and that the effects will remain below the identified criteria in Tab. 7-1 (Leupin et al. 2016a and b). However, further RD&D activities are foreseen to refine the assessment of the repository-induced effects, while new data and findings are being integrated into the understanding of the near-field evolution. This will also contribute to the refinement and justification of the performance criteria.

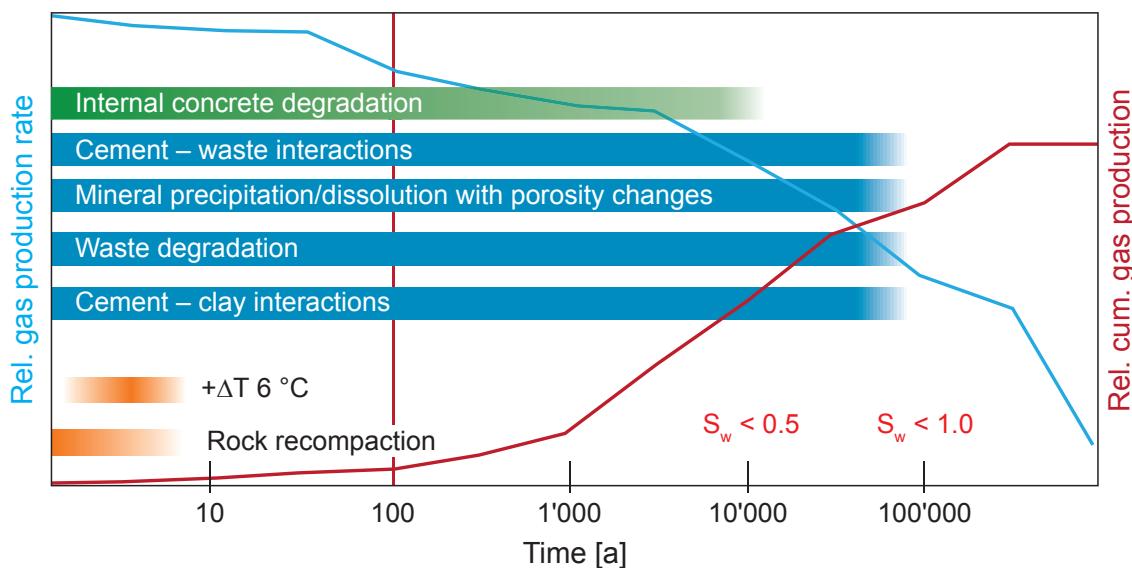


Fig. 7-19: Overview of the expected evolution of main processes in a L/ILW emplacement room based on a compilation of modelling reports and experimental data.

From Leupin et al. (2016b). The red vertical line indicates repository closure at 100 years and S_w indicates the degree of saturation of the emplacement room. The colour intensity indicates in a qualitative way the expected importance of the processes over time.

7.5.2 Resaturation, temperature evolution and gas transport in the near-field

7.5.2.1 The SF/HLW near-field

Objectives

The buffer in the SF/HLW emplacement rooms has the safety function that it provides a well-defined interface between the disposal canisters and the host rock, strong retention of radionuclides and a suitable environment for the disposal canisters and the waste forms over the time period to be considered, and that it is compatible with the favourable conditions in the host rock. The main objective is to further refine the description of the impact of the thermal pulse and the resaturation of the SF/HLW near-field on some of the key parameters describing the performance of the buffer and the host rock with respect to its safety function. Because of the coupled nature of the processes involved, an understanding of resaturation requires an understanding of temperature evolution, gas transport and geomechanical evolution and self-sealing of the surrounding excavation-damaged zone (EDZ). While work on these individual contributing processes is presented separately in sections 7.2.3.2 to 7.2.3.6, the combined impact of these processes from the URL scale to the repository scale is discussed in this section.

Particular focus is on the understanding of the temporal evolution of the conditions anticipated in the repository. Given the scale and timeframes involved, numerical (THM) modelling is an important aspect, but it needs to be supported by targeted laboratory and URL experiments. The ultimate objective is a reliable description of the evolution of the SF/HLW near-field in terms of safety-relevant parameters that underpins the derivation of safety function indicators for the near-field and demonstrates how the derived criteria can be met.

Current state-of-the-art and progress since the 2009 RD&D Plan

In Nagra's RD&D programme, the resaturation of the SF/HLW near-field has been a high priority for more than a decade. A synopsis of early experimental investigations and numerical studies as part of the Project Opalinus Clay was given in Nagra (2002c, 2004), providing an early quantitative assessment of the hydrothermal evolution of the repository near-field. Long-term monitoring of saturation, pore pressure evolution and swelling pressure provided an important new database for the evaluation of HM processes. Some studies of the EU NF-PRO Project were dedicated to the THM evolution of the SF/HLW near-field, ranging from the non-isothermal early post-closure phase to the processes and phenomena occurring at late times (Huertas et al. 2008). As an outcome of the project, a comprehensive document on the state-of-the-art was compiled, addressing phenomenology, conceptualisation and quantitative assessment of SF/HLW near-field evolution for a variety of repository concepts.

More recent work includes the follow-up project PEBS (Long-Term Performance of Engineered Barrier Systems), launched as part of the 7th EU Framework, which concentrated on the prediction and evaluation of THM processes in the SF/HLW near-field during the early and late resaturation phases. The experimental work included the dismantling of the Mont Terri EB (engineered barriers) experiment which demonstrated that dense bentonite pellets evolve to a swelled material indistinguishable from swelled block material from a hydromechanical perspective. It also demonstrated effective sealing through swelling of blocks and pellets with large initial density differences even under non-optimum emplacement conditions (Mayor and Velasco 2014). In a numerical benchmark exercise, different THM codes and models were evaluated by using them to extrapolate the short-term evolution of the SF/HLW near-field to the long term. The evolution of the relative impacts of different THM processes was examined, as was the propagation of uncertainties. Thus, important insight was gained into the capabilities and limitations of the different THM codes and models to capture the evolution of the SF/HLW near-field in terms of temperature, pore pressure and stress. Benchmark exercises with different THM codes and different modelling groups revealed that the thermal evolution of the near-field was modelled consistently and the thermo-hydraulic properties of the bentonite buffer could be constrained within narrow uncertainty ranges. However, significant discrepancies were seen in the simulation of pore pressure, water saturation and stress, indicating that the existing THM codes do not capture the full spectrum of relevant hydromechanical couplings needed for a reliable prediction of the hydromechanical evolution of the SF/HLW near-field.

Nagra modelling studies focusing on thermo-hydraulic (TH) near-field behaviour after repository closure have been carried out using a 3D model of a SF/HLW emplacement room (Senger & Ewing 2008). These dedicated sensitivity studies addressed the impact of resaturation, heat, gas transport and physico-chemical processes (Papafotiou & Senger 2014d, Senger et al. 2014a und b). Estimates of resaturation time, pressure recovery time and maximum temperature at the canister surface and at the tunnel wall were achieved for a broad spectrum of geological settings. First attempts were undertaken to simulate the impact of hydromechanical couplings on the evolution of stress and deformation in the repository near-field, including canister movements in response to the buffer saturation process (Dupray & Laloui 2016).

Finally, as part of the Äspö Task Force on Engineered Barriers, Nagra is continuing to participate in several modelling tasks with the focus on gas transport and homogenisation of the buffer system in the late resaturation phase (Senger & Marschall 2008, Dupray & Laloui 2016). Participation in these modelling tasks was motivated by the need to benchmark and complement Nagra's modelling toolbox for an integrated assessment of the repository near-field as a release path for radionuclides and gases, where the main components of the release path comprise the buffer, the EDZ, the backfilled access tunnels and the seal sections and shafts.

Planned RD&D in the next 5 to 10 years

Long-term gas percolation tests at the laboratory scale are planned in order to confirm that long-term gas transfer through the bentonite buffer does not impair its capacity to fulfil its safety function. Laboratory testing comprises phenomenological studies of gas-driven mobilisation of clay aggregates and gas/water permeability measurements at constant volume and fixed confining stress for the full range of relevant bentonite densities.

Long-term monitoring of the buffer resaturation processes in the HE-E and the FE experiments at the Mont Terri URL will produce additional data supporting the description of the evolution of the HLW near-field in the transitional phase, after the peak temperature at the canister surface has been reached. While the HE-E experiment has shown good agreement between models and measurements of TH parameters and temperature field in the EBS and host rock since its start in 2011, resaturation is slow (driven by host rock water supply) and it will require some years of monitoring to adequately validate models. The resulting databases will be supplied to international modelling task forces (e.g. EBS Task Force), allowing further model development and model validation.

A more rigorous assessment of the uncertainties associated with the thermal pulse and gas release from a HLW repository is foreseen.

Sensitivity analyses will encompass both gas transfer within individual repository components and the behaviour of the overall system. Of special emphasis will be the release paths along the EDZ of the backfilled SF/HLW tunnels and the seal sections. For this, the existing coupled HM approach (Alcolea et al. 2014) will be extended to account for the spatial variability of hydraulic conductivity along the EDZ (see also section 7.5.3.4). Such advanced simulation tools will allow a more balanced assessment of (i) the maximum gas pressure build-up in the backfilled repository structures and (ii) the expulsion of porewater from the saturated buffer.

A re-assessment of the thermal dimensioning of the repository will be completed once data from the field campaigns are available as the safety function indicator criterion related to hydraulic overpressures is likely to determine the optimisation potential with respect to the repository footprint.

7.5.2.2 The L/ILW near-field

Objectives

The safety function of the cementitious near-field within and around the L/ILW emplacement caverns is to provide a contribution to the overall retention of radionuclides and an environment that ensures low microbial activity and low corrosion (gas production) rates. Gas generation by the waste packages will slow down the resaturation of the near-field. The main objective of the work described below is to develop an improved description of the development of the ILW and L/ILW near-field during the resaturation phase and the subsequent formation pressure recovery, under conditions as close as possible to those anticipated in the repository.

A particular focus is the temporal evolution of the distribution of water saturation and pore pressure as basic input for the assessment of radionuclide transport within the engineered barriers and also the chemical and microbiological evolution of the ILW and L/ILW near-field. This latter aspect is covered in section 7.2.3.6, where the extent to which chemical and microbiological processes could provide a sink for gas is also addressed. The chemical evolution of the surrounding host rock (Opalinus Clay) is discussed in section 7.5.3.5.

Given that the processes are highly coupled and considerable timeframes are involved, the abstraction into a plausible evolution of the L/ILW near-field requires strong support from coupled models relying on an up-to-date experimental hydromechanical (HM) database to cover the full range of cementitious backfill materials under consideration in both pristine and altered states. Further improving the hydrochemical (HC) understanding needs to address processes such as water and hydrogen consumption, salt precipitation, iron and sulphate transfer in the unsaturated state and transfer of volatile gas components.

Overpressures generated by gas production in the near-field need to be constrained below a limit that is accepted as safe in that it does not affect the integrity of the barrier or cause induced seismicity. It is perceived as possible that generated pressures will lead to pathway dilation in the Opalinus Clay. This process is not thought to result in permanent damage to the favourable properties of the rock, since the microscopic dilated pathways are expected to close again once the gas pressure declines. However, if the process can be excluded, and thus pressures can be kept sufficiently low (e.g. through design measures), then this simplifies the analysis of the system and increases robustness. Finally, gas pressurisation could potentially lead to the displacement of porewater in the near-field and far-field, thus affecting the retention properties of the Opalinus Clay.

Current state-of-the-art and progress since the 2009 RD&D Plan

In Nagra's former RD&D programmes, the resaturation of the ILW and L/ILW near-field has been investigated with the main focus on the associated gas transport processes (Wiborgh et al. 1986, Senger et al. 1994). The emphasis of the research activities was mainly on the development of recipes for high-porosity mortar and on the characterisation of the gas transport properties of these materials (Jacobs et al. 1994, Mayer et al. 1998). As part of the GMT experiment at the Grimsel Test Site, a comprehensive survey of gas transport properties of cementitious material was elaborated and complemented with Nagra's own results (Lanyon & Rüedi 2008).

A comprehensive appraisal of gas release from a generic L/ILW repository was presented in Nagra (2008g), comprising a detailed assessment of the saturation conditions in a L/ILW cavern over the course of the repository lifetime. The simulations suggest that the maximum gas pressure in the emplacement caverns is reached in the period between 1,000 and 10,000 years after repository closure. Gas overpressures can be limited by an engineering solution, the so-called engineered gas transport system (EGTS). Additional sensitivity studies were initiated to investigate at greater spatial resolution the combined gas/water flow around the seal sections of the emplacement rooms (Senger & Ewing 2009), allowing for the optimisation of the seal design with respect to chemico-hydraulic phenomena such as pore clogging and mineral dissolution. Nagra (2008g) included a detailed discussion of the safety function indicator related to gas-induced porewater displacement. In the early post-closure phase (< 1,000 a), it was found that the maximum specific flux from the L/ILW caverns into the host rock may exceed the safety indicator criterion ($10^{-11} \text{ m s}^{-1}$), though by less than half an order of magnitude. On the other hand, no significant displacement of contaminated porewater is expected to occur as a result of gas release after maximum overpressure is past.

Nagra's participation in the Euratom FORGE Project (Shaw 2014) on the fate of repository gases was motivated by the need for an extended experimental database on gas migration processes in concrete materials, including high-porosity mortar, shotcrete and construction concrete. Particular focus was on the chemical alteration of the cement (Sellin 2014). The work has allowed identification and quantification of processes occurring during cement carbonation, indicating that the buffer/backfill remains intact during repository evolution, and some properties apparently improve (such as a reduction in permeability).

Finally, 3D sensitivity studies on gas release from a generic L/ILW repository were conducted as part of Stage 2 of the Sectoral Plan process, addressing the impact of resaturation, gas transport and chemical processes on the evolution of the L/ILW near-field after waste emplacement (Papafotiou & Senger 2014c, Senger & Papafotiou 2014). The studies revealed a pronounced sensitivity of gas pressure build-up to the variation of parameters associated with different geological conditions, the configuration of the EGTS and the uncertainty in gas generation rates. For the upper bounding gas generation rates, calculated gas pressures exceeded lithostatic pressures, thus violating the safety function indicator criterion related to gas fracturing. The sensitivity studies suggest that the reduction of gas generation rates together with design optimisation of the EGTS offer the most efficient way to constrain the gas pressure in the backfilled caverns.

It was concluded in Leupin et al. (2016b) and Diomidis et al. (2016) that the issue of gas pressure build-up can be addressed through the appropriate design of the L/ILW repository supported by additional engineering measures (e.g. the EGTS). Based on experimental evidence and theoretical considerations, it was shown that long-term corrosion-induced volume changes would not affect the mechanical integrity or porosity of the backfill.

Planned RD&D in the next 5 to 10 years

For a detailed site-specific assessment of the saturation conditions and gas pressure build-up around the waste containers, confidence in the gas-related database needs to be improved, comprising extended capillary pressure-saturation relationships and relative gas/water permeability relationships for the various cementitious materials and a robust estimate of the corresponding uncertainties.

Detailed knowledge of the geological setting will also allow for an optimised repository design with respect to gas release. This includes the integration of measured gas-relevant data from the field campaigns and the refined assessment of the anticipated overpressures, including the fate of the gas. Spatial variability of the gas transport properties in the Opalinus Clay will be characterised in-situ with state-of-the-art gas threshold pressure tests in deep investigation boreholes and in the laboratory by detailed analysis of core samples. These data will feed into site-specific gas release models, aimed at a refined assessment of the anticipated overpressures in the site-specific geological context.

For a detailed assessment of the saturation conditions and gas pressure build-up around the waste containers, supporting modelling of capillary pressure-saturation relationships and relative gas/water permeability relationships for the various cementitious materials are required.

Additional gas-related laboratory work will concentrate on these cementitious EBS components, particularly the waste immobilisation concrete and construction concrete. The gas-related laboratory tests on concrete alteration, which were started in the context of the FORGE programme, will be continued.

The improvement of advanced hydrochemical process models for the simulation of multi-phase and multi-component transport processes in the ILW and L/ILW near-field will be completed. Emphasis will be on a simplified representation of pore clogging by precipitation processes, sulphate transport associated with biogenic processes, corrosion processes around the disposal containers and transport of volatile gas components.

An assessment of the conceptual and parametric uncertainties associated with gas release in the ILW and L/ILW near-field will be conducted (see also section 7.2.3.2). Sensitivity analyses will include both gas transfer along individual repository components and the behaviour of the overall system. Uncertainty assessment will, if justified, include probabilistic elements as well as deterministic elements. With the integration of measured gas-relevant data from the field campaigns, a refined assessment will be made of the anticipated generated overpressures.

The elements above will refine and feed into a detailed description of the ILW and L/ILW near-field evolution in terms of safety-relevant parameters that underpins the derivation of safety function indicators for the near-field and demonstrates how the derived criteria can be met.

7.5.2.3 Evolution of a combined repository

A generic feasibility study for a combined SF/HLW/ILW and L/ILW repository aimed at assessing the potential interaction between the disposal system for SF/HLW/ILW and that for L/ILW has been described in Leupin et al. (2016a). The focus of this modelling exercise was on the pressure development associated with:

- gas generation from the degradation of radioactive waste material and corrosion of waste canisters, and
- heat generation from the decay of SF/HLW

since these are potentially the most significant causes of interaction between the two systems.

Based on this modelling study, it appears that the pressure regimes in the L/ILW and SF/HLW/ILW facilities evolve rather independently. Only the pressures in the vicinity of ILW caverns showed some interference from the other waste emplacement areas, being affected by the thermal and gas pressure build-up in the nearby SF/HLW emplacement rooms. The results suggest that a horizontal separation distance of a few hundred metres between the L/ILW facility and the SF/HLW/ILW facility is sufficient to avoid interference in the pressure build-up in these two parts of a combined repository.

7.5.3 Individual engineered barriers and the surrounding Opalinus Clay

7.5.3.1 Corrosion of SF and HLW disposal canisters

Background and objectives

The major safety function of the SF and HLW canisters is to provide complete long-term containment of the wastes³⁴. Eventually, a combination of mechanical and corrosion processes will lead to canister breaching, allowing the ingress of water and the release of radionuclides. Even after breaching, the canisters contribute to retarded release and retention of radionuclides through limited access of water and the favourable sorption capacity of corrosion products for many radionuclides.

The main objective of the work described below is to increase confidence in canister lifetime predictions by developing improved understanding of relevant corrosion mechanisms, by quantifying uniform corrosion rates under repository-relevant conditions, and by developing

³⁴ ENSI-G03 (ENSI 2009) requires that the canisters provide complete isolation for at least 1,000 years.

methodologies for predicting their long-term evolution. Furthermore, the risk of localised corrosion mechanisms such as pitting, stress-corrosion cracking and hydrogen-induced cracking needs to be evaluated. A critical aspect in the evaluation of corrosion processes is microbial activity in the near-field (see section 7.5.3.5), which can lead to acceleration of corrosion through the formation of biofilms or the production of corrosive species such as sulphide, but which can be mitigated by bentonite of sufficient density. This results in interplay between the different EBS materials. Other forms of interplay include interactions between corrosion products and bentonite or the generation of gas resulting from corrosion. Thus, corrosion rates provide input to the modelling of resaturation and gas transport in the near-field (see section 7.5.2.1) and the evolution of the bentonite buffer (see section 7.5.3.3). Corrosion and gas generation in the L/ILW repository are discussed in sections 7.3.3.5 and 6.4.3.

For the general licence application, it is foreseen that more than one canister material option will be considered in order to provide a better basis for selecting a final canister concept. These options are likely to include carbon steel and copper (see section 7.4.5), so the RD&D presented here includes work on both materials.

Current state-of-the-art and progress since the 2009 RD&D Plan

A literature review was conducted of corrosion and gas generation rates in repository-relevant conditions that aimed to substantiate the reference corrosion rate used for gas generation calculations (Diomidis 2014). The long-term anoxic corrosion rate of carbon steel in contact with bentonite or in relevant near-neutral porewater simulants was examined. Low corrosion rates of less than 1 µm/a are generally reported in the literature. However, due to the uncertainty introduced by the limited in-situ experiments in the presence of microbes, the reference corrosion rate used in Nagra's safety analyses has so far been cautiously maintained at 2 µm/a.

An experimental campaign that aims to measure the anoxic corrosion rate and to clarify the long-term corrosion mechanism for carbon steel in contact with anoxic saturated bentonite is ongoing (Diomidis et al. 2012, Diomidis & Johnson 2014, Smart et al. 2014). The measured corrosion rate after about 4 years of exposure is less than 0.5 µm/a, and is still decreasing. Currently ongoing analyses of the metallic samples and adjoining bentonite will provide an insight into the prevailing corrosion mechanisms and interactions between barrier materials. Additionally, an experimental campaign aiming to study the corrosion response of carbon steel and copper coating materials in conditions relevant to the early-stage development of the repository at high temperature and in unsaturated bentonite is currently ongoing.

On the other hand, in-situ experiments in relevant host rocks are exploring the interactions of canister materials with the local microbial populations. More specifically, the IC-A experiment at Mont Terri is measuring in-situ the anoxic corrosion rate of carbon steel, wrought copper and copper coatings in contact with bentonite saturated with Opalinus Clay porewater, and identifying the effect of microbial activity on corrosion (Bagnoud 2015). A similar in-situ experiment (MaCoTe) is currently running at the Grimsel Test Site, which also aims to study the influence of temperature. Additionally, corrosion coupons made of carbon steel, wrought copper and copper coatings have been installed in the FE tunnel at Mont Terri close to the heaters and close to the tunnel wall to examine the influence of the evolution of temperature and humidity on corrosion at full scale. Surface preparation of one of the heaters of the FE experiment will also allow investigation of the occurrence of localised corrosion phenomena at the interface between compacted blocks and granular bentonite.

The corrosion response of wrought copper and copper coatings under anoxic conditions is being actively studied in collaboration with NWMO (Keech 2013, Keech et al. 2014, Senior et al. 2013, Partovi-Nia et al. 2014). Considerable work on the corrosion of copper under disposal conditions has also been carried out by organisations such as NWMO (Kwong 2011, Scully & Edwards 2013), SKB (SKB 2010a, King et al. 2010, King 2010, Bashkaran et al. 2012, Johansson & Brinck 2012, King & Lilja 2013) and the Swedish Radiation Safety Authority SSM (Szakàlos & Seetharaman 2012, Apted 2014, Macdonald et al. 2014).

Planned RD&D in the next 5 to 10 years

The planned work for the coming years deals with two main issues: the study of corrosion processes on candidate canister materials and the quantification of the availability of corrosive species. The former is addressed by experimental corrosion work which will be concentrated on the study of carbon steel and copper coatings. The ongoing corrosion studies in anoxic saturated bentonite and in unsaturated bentonite at high temperature will continue in order to increase the understanding of relevant processes and to refine the reference corrosion rate values. Similarly, the currently ongoing in-situ experiments at Mont Terri and GTS will continue in order to obtain representative long-term corrosion data. Additional experimental campaigns will concentrate on the study of corrosion properties of candidate canister materials under simulated in-situ conditions and under irradiation. The specification of the work on corrosion is done in relation to the work on canister development (section 7.4.5) and, as a result, any new developments on candidate canister materials will also be reflected here. The second main issue is addressed by modelling and measuring the availability and migration of corrosive species (oxygen, sulphide) to the canister surface. The availability and consumption of oxygen will be addressed with in-situ and laboratory measurements and modelling within the FE-G gas monitoring experiment at Mont Terri. The migration of sulphide species, produced by sulphate-reducing bacteria in the EDZ, through the bentonite buffer to the canister surface will be assessed by modelling.

7.5.3.2 ILW and L/ILW disposal containers, container backfill material and cement-based barriers

Objectives

Cementitious materials will be present in the ILW and L/ILW repositories as part of the waste (cemented waste in concrete disposal containers) as well as the backfill of the repository. As noted previously, the safety function of the cementitious near-field within and around the ILW and L/ILW emplacement rooms is to provide a contribution to the overall retention of radionuclides and an environment that ensures low microbial activity and low corrosion rates. The cementitious materials also have a more practical function of providing mechanical strength to the repository (monograin concrete has grain-to-grain contact which provides maximum mechanical strength). Any chemical interactions that involve these materials, e.g. waste-cement interaction or interactions at the cement-clay/bentonite interfaces, which may affect the chemical environment and alter any of the safety-relevant properties of cement and concrete, must therefore be assessed. Supporting this assessment is the main objective of the work described below. The impact of other interactions on the host rock is addressed in section 7.5.3.5.

The heterogeneity of materials in the cement-based environment (different types of waste, disposal container, cement backfill) may induce a wide variety of different chemical reactions, which ultimately lead to variations in the local conditions (pH, Eh, porosity, salinity, water content). Currently, Nagra uses a mixing tank model to assess the evolution of the L/ILW near-

field. In this model, all materials present in the repository are represented as being homogeneously distributed. A better representation of the heterogeneity of the near-field environment and of its impacts on the safety-relevant properties of the (engineered) barriers will reduce excessively conservative assumptions made in the safety assessment and provide a more realistic view of L/ILW near-field evolution. It will be essential to demonstrate that high pH conditions are also maintained locally during the repository evolution to ensure low reactivity of waste materials (e.g. steel corrosion, microbial degradation of organic materials). The pH conditions are strongly dependent on the overall chemical composition of the waste, waste matrices, engineered barriers and water availability in particular.

Current state-of-the-art and progress since the 2009 RD&D Plan

Worldwide, there are currently many operating LLW repositories, leading to a mature state of knowledge regarding interactions between cement and waste or clay rocks. However, because there are no deep geological repositories for L/ILW, certain issues remain concerning the long-term evolution of such a repository.

An overview and assessment of the various chemical reactions that may occur in a L/ILW repository have been described in Nagra (2014f), Nagra (2014h) and Leupin et al. (2016b). Internal degradation of cement and cement degradation due to groundwater ingress are well studied and a degradation model is available (Berner 2009, Nagra 2014f). Other well described reactions include corrosion, carbonation of cement due to CO₂ production from organic waste degradation and the alkali-silica reaction (ASR) between silicate-rich aggregates and cement (Schwyn 2008, Cloet et al. 2014). Over the last few years, research on the interaction between corrosion products (Fe³⁺) and cement has been carried out at PSI and at the Swiss Federal Laboratories for Materials Science and Technology (EMPA) (Dilnesa et al. 2011, Dilnesa et al. 2014). This work investigated the incorporation of Fe³⁺ in the cement phases. It appears that Fe³⁺ can substitute for Al in Si-hydrogarnet by forming a solid solution of Fe-Al-Si-garnet. Fe might also be incorporated in monocarbonate phases. Less well-known are the organic waste degradation products and any impact of microbial interactions on cement stability.

In the current approach used in safety analysis, the temporal evolution of the cementitious near-field considers cement degradation through internal degradation and cement carbonation. As a result of the RD&D carried out since 2009, individual radionuclide sorption coefficients at each stage of the internal cement degradation process are used in dose calculations (Wieland 2014, Nagra 2014c). A bounding case assessment of the carbonation reaction is based on mass balance calculations, which leads to the division of the L/ILW into two different waste categories for which different sorption values in a cementitious environment are used, depending on the extent of carbonatisation (Schwyn 2008, Cloet et al. 2014).

A similar approach for safety analysis has been used by Andra (Andra 2005), where internal cement degradation (consisting of a hydrolysis phase and a carbonation phase) and sulphate attack are considered to degrade cement in long-lived intermediate-level waste disposal cells. In addition, any cement in the waste packages is considered to be attacked by acids and sulphates released from bituminised sludge is present.

Planned RD&D in the next 5 to 10 years

The RD&D that is currently planned includes a modelling study of heterogeneity in the L/ILW repository, lab-scale experiments to test the stability of organics under alkaline conditions and also some pilot-scale experiments to study the degradation products (mainly focusing on gas

production) of organics (see section 7.3.3.5). The aim of the modelling study is to develop a coupled model that represents the heterogeneity in the cementitious near-field sufficiently well to allow an assessment of the impact of heterogeneity on the safety-relevant properties of the cement barrier. The first major step will be to couple chemical reactions and mass balance calculations inside the waste packages with the saturation of the entire repository. The result of this modelling study could also provide a scientific basis for engineering decisions regarding cement barrier requirements, including the cement recipe (e.g. aggregates, low/high pH, organics), hydraulic characteristics, porosity, etc. Studies on the stability of organics under alkaline conditions and their degradation products should reduce uncertainties regarding gas production rates and the production of degradation products that may form complexing ligands for radionuclides. These aspects will allow a more realistic treatment of the L/ILW repository and its evolution in future safety analyses.

7.5.3.3 Bentonite-based barriers (buffer, backfill, seals)

Objectives

In the current repository concepts, compacted bentonite is used:

- In the form of compacted bentonite blocks and granular bentonites as a buffer surrounding the SF and HLW canisters
- In the form of a sand/bentonite mixture in the engineered gas transport system (EGTS)
- In the form of granular bentonite and/or blocks in other repository sealing and closure structures

Design and technology development related to these components are discussed in section 7.4.4.

The main objective of the work described below is the development of an improved understanding of the processes occurring during repository evolution that may affect the capacity of these components to fulfil their safety-related requirements over the relevant timescales (e.g. as set out for the buffer in Leupin & Johnson 2013). These requirements are formulated in terms of safety-relevant buffer attributes and preferred values for the parameters that quantify these attributes.

Specific areas where improved understanding and modelling capabilities will be sought are:

- THM evolution of the bentonite buffer and backfill barriers
- Stability of bentonite buffer at elevated temperatures
- Chemical and microbiological processes that might affect the safety functions of the bentonite buffer and backfill barriers, including interactions with other engineered materials
- The migration of repository-generated gases through the bentonite buffer and backfill barriers

A continuing RD&D objective is also to support the development of models and data used to evaluate radionuclide retention and transport in the bentonite buffer and backfill barriers in support of safety assessment.

Current state-of-the-art and progress since the 2009 RD&D Plan

TH/THM processes and modelling

TH modelling is required in order to analyse temperature evolution within a repository, as well as to investigate saturation behaviour and the fate of gases. Key areas of progress since the 2009 RD&D Plan includes:

- The HE-E experiment at Mont Terri, designed and constructed as part of the recent 7th Euratom PEBS (Long-term Performance of Engineered Barrier Systems) project, which has provided a first large-scale test (1:2 scale with temperatures up to 140 °C) of the understanding of TH behaviour of the Nagra near-field concept (Gaus et al. 2014b)
- Testing of THM model predictions for water uptake by a bentonite buffer against experimental observations as part of PEBS (Johnson et al. 2012)
- Measurements of the thermal conductivity of granular bentonite, bentonite blocks and bentonite/sand mixtures at ETHZ (Plötze & Valter 2011)
- Updated numerical analyses of combined heat transport, saturation and gas release from a SF/HLW emplacement room into the surrounding host rock using a non-isothermal two-phase flow and transport model (Senger et al. 2014a)

The evolution of temperature and saturation has been found to be fairly well described with current models, at least up to the time that maximum canister and buffer temperatures are reached. The PEBS project in particular has shown that current models can predict the saturation process well until around 90 % saturation is achieved. Thereafter, uncertainties are greater, but since the safety-relevant attributes of the buffer are already attained at 90 % saturation, these are not greatly relevant to long-term safety (Johnson et al. 2014). Nonetheless, improved accuracy in predicting temperatures and saturation in time and space is desirable and will be an objective when interpreting the FE experiment, a 1:1 full scale test of the Nagra concept that started in early 2015 at the Mont Terri URL. THM modelling is used to assess swelling pressure development and buffer homogenisation.

Since the 2009 RD&D Plan, key areas of progress in model development have been:

- Development of THM material laws for Opalinus Clay and bentonite
- Development of systematic process abstraction methods for safety assessment; and
- Non-isothermal insight modelling of the evolution of pore pressure and stress around the backfilled tunnels of a SF/HLW disposal system

Further modelling activities have been undertaken as part of the TIMODAZ project (EU 7th Framework Programme; Li 2011). In the Mont Terri EB experiment, which was studied as part of PEBS, it was observed that remaining heterogeneities predicted by HM modelling were broadly consistent with the observations during dismantling of the experiment (Johnson et al. 2014). The dismantling and interpretation of the FEBEX experiment, expected to be completed by the end of 2017, will provide further information on the HM behaviour of bentonite and contribute to the robustness of the existing dataset and models.

Discussion of THM phenomena in the context of integrated near-field models (bentonite plus host rock) is presented in section 7.5.2.1.

Thermal stability

A review of the current understanding of the thermal stability of montmorillonite³⁵ is given in Leupin et al. (2014). A comprehensive understanding of the impact of temperatures above 100 °C on THM properties, similar to that available at temperatures below 100 °C, is not yet available. Nonetheless, there is clear evidence that reasonable swelling pressure and low hydraulic conductivity are likely to be maintained during and after the thermal transient. In particular, since the 2009 RD&D Plan, several laboratory and field investigations of the changes in swelling, plasticity and hydraulic properties of thermally altered bentonite have been performed, including several long-term heater-buffer experiments that have been evaluated as part of the PEBS project (Johnson et al. 2014) and laboratory investigations performed at ETHZ at temperatures above 100 °C under partially saturated conditions (Valter & Plötze 2013). Evaluation of the combined data from these and other studies indicates marginal effects on swelling pressure and a less than one order of magnitude increase in hydraulic conductivity for exposure of bentonite to partially saturated conditions at temperatures up to 125 °C. It can thus be concluded that the impact on the performance of the bentonite will be minimal over the long term considering the short duration of the temperature peak and the limited amount of bentonite affected by temperatures over 100 °C when the requirement of maximum heat output of 1,500 W per canister is in place.

Chemical and microbial processes

Potential chemical interactions of bentonite with engineered components (canister metals, concrete tunnel liner, steel support mesh and arches, plus transport rails) in a geological repository for SF/HMW in Opalinus Clay have been assessed in Savage (2014). The current status is described below.

The main focus of Nagra's work regarding interactions with metal corrosion products since the 2009 RD&D Plan has been on the effects of adsorbed Fe(II) on retention of radionuclides and assessment of impacts on hydraulic and swelling properties, including work carried out in the context of PEBS and also collaborative work involving PSI and ETHZ (Hofstetter et al. 2014). Fe(II) migration and mineral transformation of the buffer due to Fe(II) have been found to proceed slowly; experiments of up to 6 years duration analysed in the context of the PEBS project indicate that no new iron silicates are formed and a penetration depth of Fe into the bentonite of only a few mm. Indications from models are that the interaction zone may be 1 – 10 cm after some tens of thousands of years (Bradbury et al. 2014), but further model development and testing is desirable to confirm this prediction.

Potential impacts of interactions with cementitious materials on the long-term properties of clay have been assessed using simple bounding assumptions, such as limitation by mass balance, kinetics and/or mass transport (Leupin et al. 2014). More detailed, reaction-transport simulations have also been carried out (Bradbury et al. 2014, Nagra 2014h). These and similar calculations carried out in the context of PEBS (Johnson et al. 2014) show that alteration of the bentonite due to an OPC concrete liner is quite limited, extending some 10 cm into the bentonite after a few tens of thousands of years. Bradbury et al. (2014) also showed that the interfaces between the concrete liner and both the Opalinus Clay and the bentonite have a strong tendency to clog after a few thousand years. However, it remains difficult to predict long-term behaviour and materials properties from short-term experimental data. A careful check of mechanistic models using experimental data is required in order to increase confidence in model predictions. A currently ongoing PhD project at LES/PSI (Shafizadeh *in prep.*) is investigating alterations at small montmorillonite – OPC interfaces. Specifically, changes in porosity resulting from dis-

³⁵ Montmorillonite is a swelling clay from the smectite group and the predominant mineral in bentonite.

solution and precipitation reactions and their effect on diffusion properties across the interfaces are observed by tracer diffusion experiments and neutron imaging. Such data can be used to check or to better constrain model simulations.

In order to limit the extent of chemical alterations in both the host rock and backfill material, a shotcrete liner with lower portlandite content, resulting in a reduced pH, can be used. For this material, a conservative mass balance model suggests that a maximum of only 4 cm of bentonite would be altered (Savage 2014). Since the 2009 RD&D Plan, the specific pH value in porewater in low-pH shotcrete has been determined (Cloet et al. 2016) and methods for studying interaction with clays have been developed. An integrated assessment of the knowledge of cement-bentonite interactions has been performed at the University of Bern (Dolder 2015). A low-pH shotcrete is the preferred option in view of long-term safety, provided that it also fulfils the operational safety requirements.

Microbial activity in compacted bentonite with a dry density of more than 1.45 g/cm³ is known to be low, due to the small size of the pores, their poor interconnectivity and the restricted availability of water (e.g. Stroes-Gascoyne 2011, Masurat et al. 2010). Since the 2009 RD&D Plan, studies of microbially induced effects have been performed at Mont Terri and in laboratories at EPFL to improve understanding of the conditions under which microbial activity can occur (rock pore sizes, availability of nutrients, etc.) and to assess possible implications for repository performance (see section 7.2.3.6).

Migration of repository-generated gas

Since the 2009 RD&D Plan, Nagra has participated in comprehensive laboratory and in-situ experiments in the 7th Euratom FORGE (Fate of Repository Gases) project (Shaw 2014), which contributed significantly to the understanding of gas flow through bentonite. As described in Villar et al. (2012), two-phase flow is expected to be the dominant gas transport mechanism in unsaturated or partially saturated bentonite. Strongly confined experiments have, however, shown that, at degrees of saturation of ~ 80 – 90 % or higher, no gas flow takes place unless the applied pressure is equal to or greater than the total stress, at which pressure dilatant pathways form that transport gas through the bentonite by advection. These pathways self-seal once the gas pressure falls, as has been demonstrated in small-scale experiments and large-scale mock-ups (Shaw 2014).

Two-phase flow is expected to be the dominant gas transport mechanism in the sand/bentonite mixtures used in the EGTS. The ongoing 1:1 scale GAST experiment at the GTS, representing a sand/bentonite seal which addresses water and gas migration through sand/bentonite, is described below under planned RD&D leading up to the general licence application. The possibility that interactions between sand/bentonite porewater and high-pH porewater in the ILW and L/ILW emplacement rooms could lead to pore clogging and reduced gas permeability has been investigated in Nagra (2014h), where qualitative reasoning and quantitative illustrative analyses are presented, indicating that, for an appropriately chosen EGTS design, the EGTS should function as required over a 100 ka timeframe.

Planned RD&D in the next 5 to 10 years

TH/THM processes and modelling

The HE-E experiment showed that a very dry zone will develop in the bentonite near the canister. This 1:2 scale experiment that started in 2011 is continuing and is expected to generate a solid dataset to increase confidence in the thermo-hydraulic models. Major confirmation of the

understanding of the early resaturation process is expected from the full-scale heater test (FE experiment), also at Mont Terri, which started in early 2015 and will continue to be monitored for the next 10 – 15 years. Confirmation of the THM behaviour close to full saturation is expected to be derived from the dismantling of the FEBEX in-situ experiment at the GTS (Fig. 7-20), which underwent 18 years of natural resaturation at a constant heater temperature of 100° C (Lanyon & Gaus 2013). These large-scale tests will be supported by smaller scale laboratory characterisation tests. In all of these experiments, international THM modelling efforts are foreseen with leading experts in the domain.

Thermal stability

The spectrum of experimental conditions described in Leupin et al. (2014) encompasses the range of thermo-hydro-chemical conditions in a HLW repository and in fact goes beyond it. The overall experimental findings confirm that montmorillonite is sufficiently stable over the transient thermal period to fulfil the safety requirements of the bentonite buffer. The repository near-field is expected to have a low water-to-solid ratio. Thus, the degree of alteration observed in the high water-to-solid ratio experiments typically performed is greater than that expected under repository conditions.



Fig. 7-20: Dismantling of the FEBEX experiment at the GTS in 2015 after 18 years of continuous heating at 100° C (García-Siñeriz et al. 2016).

Left: View of the bentonite, a few blocks behind the shotcrete plug. In front the dummy canister.

Right: After heater removal, view from the bentonite into the empty liner; clearly visible are block boundaries and oxidation-reduction zones around the upper part of the liner.

While the long-term bentonite performance at temperatures < 100 °C is largely established, the evolution of properties at temperatures up to 150 °C (and the underlying constitutive models) under partly saturated conditions is less well documented. However, current observations do not point to major impacts. Minor impacts (e.g. increased strength as a result of minor cementation) can be anticipated. In the future, activities will be undertaken to further enhance the existing dataset when the opportunity exists, e.g. through international collaboration or characterisation of samples taken from large-scale experiments at elevated temperatures.

Chemical and microbial processes

While there is evidence that the chemical impact of cementitious materials on bentonite performance is limited, international developments regarding bentonite-cement interactions will be followed carefully through the Horizon 2020 CEBAMA project (2015 – 2019) in which Nagra is participating as an end-user. Additional evidence illustrating the long-term impact is further expected from the dismantling of the FEBEX in-situ experiment and the continuation of the CI (cement-clay interaction) experiment at Mont Terri where undisturbed bentonite-cement interfaces can be analysed in detail, as well as from the ongoing PhD project at LES/PSI.

To better bound the alteration of bentonite resulting from the impact of heat and steel corrosion, existing samples from the ABM-2 test in the Äspö underground laboratory are being analysed at Uni Bern as part of a post-doctoral project. With the aid of the experimental data obtained, uncertainties regarding the evolution of the safety-relevant properties of bentonite, such as swelling pressure and retention capacity in the repository near-field, can be reduced. This will help to constrain the long-term safety functions of the clay barriers in safety assessment.

Although the impact on safety-relevant properties can, to some extent, be bounded by mass balance calculations, increased conceptual and parametric understanding would provide further confidence, especially regarding the metal corrosion-bentonite interactions.

A significant increase in understanding of microbial viability in bentonite at relevant dry densities is expected from the Horizon 2020 project MIND (MIND 2016), which specifically addresses the impact of microbial processes on the repository and its evolution. Nagra contributes as an end-user to this project, which will run between 2015 and 2018. Also as part of the FEBEX-DP (dismantling) project (Kober et al. *in prep.*), a microbial analysis package is foreseen which is expected to provide an insight into microbial viability at different temperatures, redox regimes and degrees of saturation in a naturally saturated bentonite that evolved over a timescale of 18 years. In the Mont Terri URL, experiments assessing the potential of bacterial H₂ consumption and SO₄ reduction in sand-bentonite or other barrier materials to contribute to limiting gas pressure build-up are in the feasibility stage and may be further developed in the future if promising results are obtained.

Performance of sand-bentonite seals in terms of gas transport

The continuation of the GAST experiment at the Grimsel Test Site (Rüedi et al. 2011) is examining the functionality of the EGTS on a 1:1 scale and contributing to the understanding of gas-water flow under repository-relevant conditions (see section 6.2). Resaturation of the seal will continue in the years to come until a sufficient degree of saturation is reached to start the gas injection. Small-scale tests will be conducted to aid the overall interpretation of the experiment and support the hypothesis made in the numerical models.

Evolution of the material heterogeneity in the near-field

If accepted by Euratom, a new project (BEACON) will evaluate the performance of an inhomogeneous bentonite barrier to support the safety case for SF/HLW repositories. This will be achieved by cooperation between design and engineering, science and performance assessment. The property evolution from an engineered barrier at the moment of installation up to a saturated functioning barrier will be assessed. This will require an increased understanding of material properties as well as of the fundamental processes that lead to homogenisation including improved capabilities for numerical modelling. The output will be a verification of the performance of current designs for buffers, backfills, seals and plugs and an improved understanding of the impact of potential density variations and their significance in long-term assessments.

7.5.3.4 EDZ and the mechanical evolution of the surrounding Opalinus Clay

Objectives

The excavation of tunnels and drifts in the host rock leads to stress redistribution that results in micro- and macro-scale fractures within an excavation-damaged zone (EDZ). The EDZ develops during the operational phase of the repository and consolidates after backfilling of the underground structures. The formation and evolution of the EDZ modifies safety-relevant properties of the host rock adjacent to the emplacement rooms, sealing zones and other underground structures. In particular, damage to the host rock results in an increased porosity, thus leading to higher hydraulic conductivity, gas permeability and thermal conductivity. After repository closure, stress redistribution in response to the consolidation process and pore pressure recovery affect the final properties of the near-field of both the L/ILW and SF/HLW emplacement rooms.

The main objective is to obtain an improved understanding of the development of the EDZ around the emplacement rooms, sealing zones and shafts and its impact on the safety functions of the engineered barrier system (L/ILW and HLW repository) under conditions close to those anticipated in the repositories. This is particularly relevant since the EDZ around backfilled underground structures represents a viable release path for radionuclides as well as a possible escape route for corrosion and degradation gases. The efficiency of this release path depends on the shape and extent of the EDZ and the degree of self-sealing that occurs during resaturation. In this context, a safety function indicator criterion has been developed that the effective EDZ hydraulic conductivity around the SF and HLW emplacement rooms (in an axial direction) and along the backfilled and sealed access routes, multiplied by the EDZ cross-sectional area, should remain below $10^{-8} \text{ m}^3 \text{ s}^{-1}$. Note that no criterion is set for the EDZ around the ILW and L/ILW emplacement rooms, due to the fact that the hydraulic conductivity of the interior of the emplacement rooms is in any case rather high ($\sim 10^{-6} \text{ m s}^{-1}$). There are also criteria concerning the potential impact of the EDZ on the barriers provided by the bentonite buffer and host rock (Leupin et al. 2016a and b).

There is a particular focus in the planned work on the temporal evolution of rock stress, pore pressure, (irreversible) strains and hydraulic conductivity in the near-field during the entire lifetime of the repository, extending from construction to the late post-closure phase. This entails:

- An extension of the empirical database concerning excavation-related fracture patterns and the corresponding fracture mechanisms
- Development and benchmarking of modelling approaches for the simulation of EDZ fracture initiation and propagation in heterogeneous and anisotropic media
- Development of a simplified representation of the EDZ, tailored to the requirements of safety assessment and engineering

The planned work also includes a balanced assessment of the conceptual and parametric uncertainties (see also section 8.2.3.2).

Current state-of-the-art and progress since the 2009 RD&D Plan

A comprehensive appraisal of the creation and evolution of EDZs in a HLW repository at a depth of 650 m was carried out in Project Opalinus Clay (Nagra 2002c). The work was based on empirical and experimental evidence from Mont Terri and provides a conceptual model of the creation and evolution of the EDZ (Martin & Lanyon 2004, Bossart et al. 2002). Further EDZ-related in-situ experiments were conducted as part of the Mont Terri research programme (Bossart & Thury 2008). The focus was on the hydraulic characterisation of the EDZ during the operational phase and on the investigation of chemico-osmotic and hydro-mechanical sealing mechanisms (disaggregation/slaking and fracture closure due to mechanical confinement). The results confirm the exceptional self-sealing capacity of the Opalinus Clay, indicating a reduction of the hydraulic conductivity of the EDZ by several orders of magnitude over time. The MB experiment (Martin et al. 2015) and the FE experiment (Lisjak et al. 2015) provided new insight into the deformation behaviour of the Opalinus Clay and the associated pore pressure evolution in the rock mass when tunnels are oriented along the bedding strike. Evidence was found of a significant increase in the size of the plastified zone, which may be attributed to a reduced bedding strength and stiffness anisotropy.

Work Package 4 of the EU NF-PRO project was dedicated to the characterisation and conceptualisation of the EDZ in different host rocks, covering crystalline rocks, clay-rich formations and rock salt (Aranyossy et al. 2008). The investigations related to indurated clays comprised EDZ initiation and short-term evolution, long-term evolution, self-sealing, gas transfer along the EDZ and geomechanical modelling of the tunnel near-field.

A recent synopsis of the state-of-the-art in EDZ-related research at Mont Terri has been compiled by Lanyon et al. (2014b). The databases from existing in-situ experiments with excavations oriented along the bedding and perpendicular to the bedding strike were analysed in terms of deformation behaviour and pore pressure evolution. The significance of the tectonic overprint (inventory of tectonic features) and sedimentary variability (facies inventory) was highlighted.

The hydro-mechanical phenomena associated with the creation and temporal evolution of the EDZ are highly complex, precluding the detailed representation of the EDZ in conventional safety assessment modelling tools. Thus, simplified EDZ models that are nonetheless able to mimic the safety-relevant functional features of the EDZ are required. Lanyon & Senger (2011) developed a sequential modelling approach leading to simplified representations of the EDZ with equivalent flow and transport characteristics, starting from a stochastic representation of the EDZ in terms of discrete fracture network (DFN) models, as illustrated in Fig. 7-21.

Further advances have been made by Geomechanica (2013) and Alcolea et al. (2014) with a new approach that emphasises a more realistic numerical simulation of the complex hydro-mechanical phenomena associated with the creation of the EDZ fracture network and the subsequent self-sealing processes. As part of a comprehensive sensitivity analysis, Alcolea et al. (2014) demonstrated that the above-mentioned safety function indicator values for the EDZ around the backfilled tunnels of a geological repository can finally be met for a wide range of geological settings if the appropriate engineering measures are taken (e.g. support measures adapted to the in-situ stress conditions and the rock mass strength, respectively). The new approach was successfully applied as part of a benchmark exercise for modelling in-situ data from the HG-A (gas path through host rock and seals) experiment at the Mont Terri URL (Geomechanica 2014).

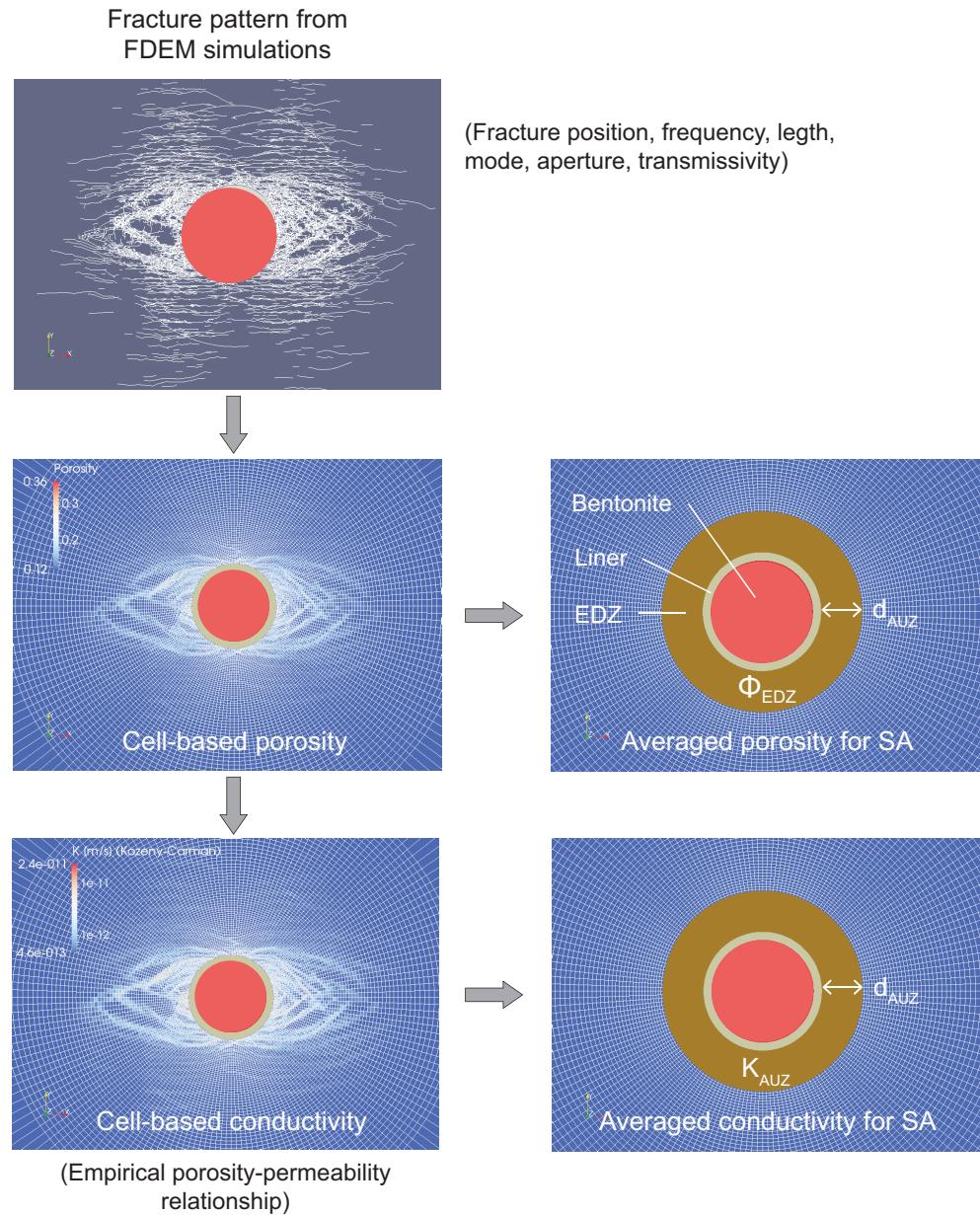


Fig. 7-21: Basic features of the EDZ abstraction process for a circular tunnel: representative fracture patterns are simulated for relevant repository configurations with a discrete fracture network model.

The resulting fracture patterns are converted into heterogeneous porosity and conductivity distributions. In a final abstraction step, the heterogeneous porosity/permeability distributions are converted to an annular shell of uniform porosity/conductivity for application in safety assessment (SA) calculations.

Planned RD&D in the next 5 to 10 years

Compilations of EDZ-related data from Mont Terri and from other underground laboratories (e.g. Meuse/Haute Marne site) will be completed, aimed at assessing in detail the impact of tectonic overprint and mineralogical variability on the development of the EDZ. Sensitivity analyses will be conducted, drawing on various alternative constitutive models and on comple-

mentary numerical codes (continuum models, distinct element models). Special focus will be on the impact of the variability and anisotropy of the elastic and plastic rock properties, including the assessment of lamination. Thus, geomechanical conditions can be investigated that are associated with extreme EDZ features, such as chimney caving and massive overbreaks. Logging data from deep boreholes will also be used to link borehole stability (as an indicator of an EDZ) to such properties. Examples are the correlation of clay mineral content and seismic velocity with indicators for rock strength such as borehole breakouts and unconfined compressive strength measurements on core samples. An integrated interpretation of evidence from independent data sources will allow a robust assessment of geomechanical rock mass behaviour on the tunnel and will feed into engineering models for tunnel design.

The model chain for simplified representation of the EDZ in safety assessment applications (Alcolea et al. 2014) will be expanded. For this, the spatial variability of the EDZ fracture network in the axial direction will be included, using a stochastic simulation approach. This will allow the simulation of the impact of spatial variability of hydraulic conductivity on radionuclide transport and gas release along the backfilled HLW tunnels and seal sections.

7.5.3.5 Chemical evolution in the EDZ and the surrounding Opalinus Clay

Objectives

Chemical reactions will occur at the interface between the Opalinus Clay and the engineered structures of the repositories, including the shotcrete liner in the HLW repository tunnels and the cement backfill in the ILW and L/ILW emplacement rooms. These reactions are of interest because they may directly affect the safety-relevant properties of the host rock. They may also influence other processes, such as transport of solutes and microbial activity, which may then impact the safety-relevant properties of the host rock. In the past, chemical interactions directly impacting the host rock have been studied in greater detail than processes that only indirectly affect it. It is, however, important to describe not only the individual reactions, but also their impact on other processes to which they are coupled, in order to derive an understanding of overall chemical evolution.

The main objective of the work described below is to assess the chemical evolution of the Opalinus Clay adjacent to the repository and to understand the impact of this evolution on safety-relevant properties of rock, including its self-sealing capacity and its radionuclide transport and retention properties. The focus is on coupled reactive-transport modelling to assess the interplay between chemical evolution and radionuclide, water and gas transport.

Current state-of-the-art and progress since the 2009 RD&D Plan

Several key reports on near-field evolution have been published since 2009. These include the reports on the evolution of the HLW and L/ILW repository near-field by Bradbury et al. (2014) and Nagra (2014f), which describe the chemical processes that can be expected in the near-field of a HLW and a L/ILW repository, respectively, including clay-cement interactions, waste-cement interactions, precipitation and dissolution of minerals and changes in pH and ionic strength. They also describe some of the couplings that exist between advective or diffusive transport on the one hand and the geochemical evolution of the near-field on the other.

The assessments of repository-induced effects (Leupin et al. 2016a and b) describe and assess THMC reactions in the repository near-field. These include, for example, the oxidation of pyrite during the construction phase, increased mineralogical transformations due to elevated tem-

peratures and delayed chemical interactions because of incomplete saturation associated with gas pressure build-up. Chemical interactions at the clay-cement interface might locally affect porosity and permeability (Fig. 7-22). Over the last 6 years, experimental and modelling work (e.g. within the CI experiment at the Mont Terri URL) has shown that interactions at cement-clay interfaces start almost immediately upon contact, but progress very slowly. For example, experiments involving 5-year old samples show only up to 100 µm of reacted materials (Jenni et al. 2014). Cement paste/shotcrete-clay interaction experiments at the Meuse/Haute Marne URL and at Tournemire in France, which are similar to the CI experiment at Mont Terri, come to the same conclusions regarding the high clay stability and the precipitation of secondary (poorly crystallised) minerals in concrete (Gaboreau et al. 2012 and 2011). The chemical effect of a degrading cement liner on the evolution of the EDZ must be considered when the self-sealing ability of the EDZ needs to be assessed. Modelling of the thermodynamics involved (e.g. Bradbury et al. 2014) and experimental data (e.g. Dolder 2015 and Shafizadeh et al. 2015) have shown that the degradation of a cement liner (pH plume) can result in a reduction of the porosity of the clay rock adjacent to the liner. The timing of the mechanical recompaction of the EDZ and consequent self-sealing and the chemical interactions in the EDZ due to the presence of the liner and how these affect each other remains uncertain, although impacts are unlikely to be safety-relevant based on current knowledge.

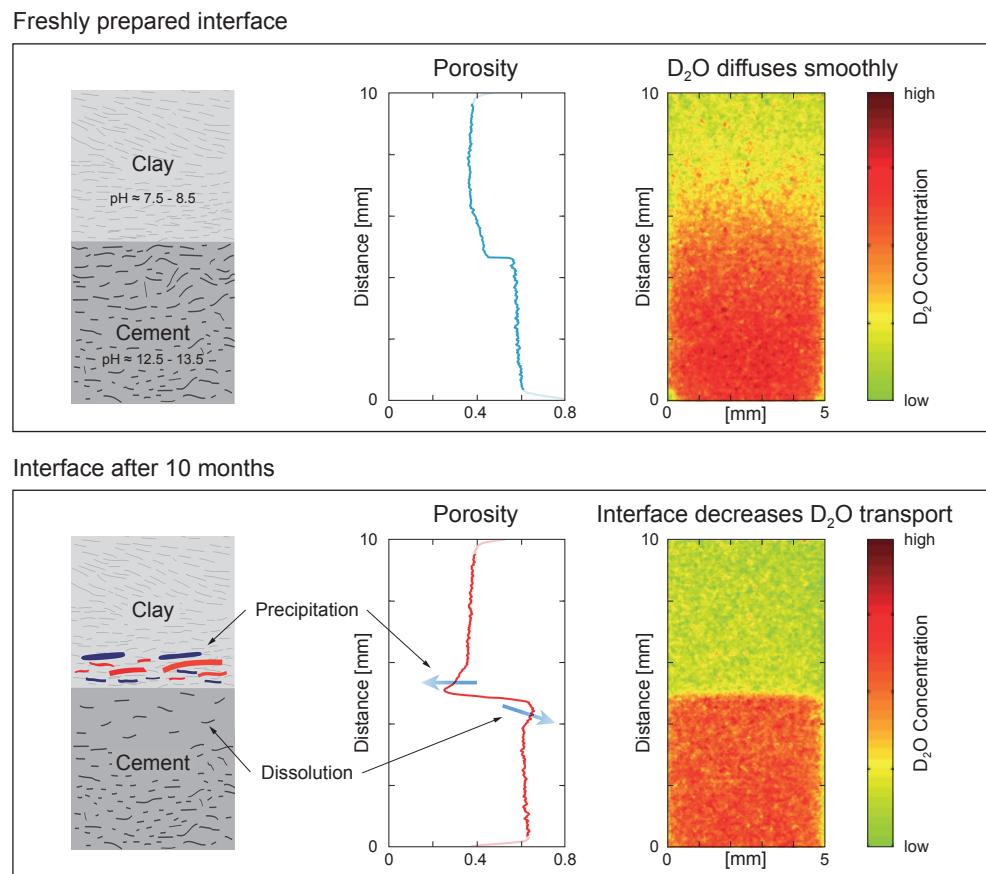


Fig. 7-22: Schematic representation of the cement-clay interactions (left), selected water content (porosity) profiles (middle) and transmission image of D₂O advancement (normalised to a reference time) across a fresh interface (top row) and an aged one (bottom row) measured using a neutron beam (right) LES (2015).

Higher values (in red) indicate higher relative D₂O concentration. The D₂O was introduced to the cement part of the sample.

Natural analogues such as Maqrarin in Jordan provide a valuable insight into the long-term interaction between an alkaline plume and clay minerals. Dissolution of clay minerals up to 40 mm from fractures in the clay rock has been observed. The alkaline plume – clay interaction was estimated to have lasted for at least 100,000 years (Pitty & Alexander 2011). Additional information on the long-term behaviour of cement-rock interactions is provided by studies of railway tunnels in Switzerland, but no major new findings have been made since 2009.

Other phenomena affecting the chemical evolution of the Opalinus Clay around the engineered structures are related to microbial activity in the EDZ, where microbes have been recognised to possibly consume hydrogen and reduce sulphate to sulphide (see section 7.2.3.6). Regarding microbial activity, significant progress has been made as a result of several experiments at the Mont Terri URL (e.g. MA (microbial activity): Leupin et al. 2017, PC (porewater chemistry): Wersin et al. 2011, HT (hydrogen transfer): Vinsot et al. 2014) and an extensive research programme at EPFL. In particular, several taxa of microorganisms that can be expected in the EDZ have been identified and their activity has been studied (Mauclaire et al. 2008, Stroes-Gascoyne et al. 2013). Sulphate-reducing bacteria have been recognised as an important type of microorganism that can consume H₂ if enough sulphate is present (Stroes-Gascoyne et al. 2008, Daumas et al. 2014), thus providing a potential sink for repository-generated gas. The impact of microbial activity has also been investigated by Andra, SKB and ONDRAF/NIRAS, for example in the BN (Bitumen Nitrate; Bleyen et al. 2017) experiment at the Mont Terri URL and in the microbial experiments at the Äspö URL in Sweden (e.g. Pedersen 2014).

As Opalinus Clay porewater contains sulphate that can be reduced to sulphide by micro-organisms (Leupin et al. 2017), it must be assessed if this has adverse consequences. The bentonite buffer around the canister, when emplaced at sufficiently high density, results in a strong reduction of the pore size and a significant swelling pressure when saturated. These conditions limit the likelihood of microbial activity in the buffer and at the canister surface, but might not fully exclude it in the EDZ. Sulphide produced in the EDZ may diffuse into the bentonite and potentially increase the canister corrosion rates. However, as the fractures that comprise the EDZ have a tendency to close over time (see section 7.2.3.5), these reactions are thought to be limited both in space and in time. Furthermore, compacted bentonite is an effective diffusive barrier that significantly limits the transport of sulphide that is potentially produced in the EDZ (Sellin & Leupin 2013). The potential impacts are considered in the assessment of canister corrosion rates in section 7.5.3.1.

The EDZ will play a significant role as an additional gas storage volume and a release path for corrosion gas, which slows down the pressure build-up in the near-field. Preferential gas pathways may develop in the EDZ.

Planned RD&D in the next 5 to 10 years

Even though cement – clay interactions are currently understood in reasonable detail, uncertainties remain. These concern particularly the relationships between porosity and permeability and between porosity and diffusivity at different saturations. Additional thermodynamic data on newly formed mineral phases in clay and cement could improve modelling of long-term evolution of the cement – clay interface. It is therefore planned to develop a better understanding of the kinetic and thermodynamic parameters of clays, zeolites and newly formed cement phases and thus address these uncertainties and improve the predictive capability of the models. To this end, the EC-funded CEBAMA project (Horizon 2020) will focus on improved understanding and modelling of the cement-host rock interface, considering both clays and crystalline rocks. Previous laboratory and field experiments have demonstrated that reactions at cement-clay or cement-silica interfaces are very slow and occur at sub-micrometre scale (Shafizadeh et al.

2015, Daehn et al. 2016). A dedicated experimental setup has been developed at LES/PSI, allowing characterisation of such material interfaces using X-ray synchrotron and neutron facilities. These approaches will be used in the follow-up PhD project at LES/PSI on characterisation of transport properties at cement-clay interfaces.

Further studies are also planned in collaboration with EPFL in order to test different backfill materials for their potential to host microbial activity. Microbial activity in different environments will be tested, including viability under different conditions of saturation, materials, nutrients, porosity, etc. in the new MA-A experiment at Mont Terri that started in 2016.

Finally, an enhanced assessment of the porewater evolution in Opalinus Clay and in buffer and backfill materials, taking into account changing redox conditions due to waste interactions and due to microbial alteration of hydrogen and methane, will be conducted. This will include coupled reactive transport modelling to assess the impact of mineral dissolution and precipitation reactions and will contribute to improving the assessment of repository gas generation and of the resaturation of the ILW and L/ILW emplacement rooms.

7.5.4 Transport of radionuclides in clay systems and cementitious materials

Objectives

In the past 20 years, extensive work, including both laboratory experiments and literature studies, has resulted in several databases of sorption coefficients, diffusion parameters and solubility limits being compiled by Nagra and other waste management organisations (e.g. Bradbury & Sarott 1994, Berner 1995, Bradbury & Van Loon 1997, Wieland & Van Loon 2002, Bradbury et al. 2010, Wang et al. 2009, SKB 2014b, Ochs & Talerico 2004, Posiva 2013, Andra 2005). These reports and the extensive scientific literature on which they are based provided a solid basis for dose calculations in the provisional safety analyses (Nagra 2014c). Although it has been shown using sensitivity analysis in safety assessment that, with the present range of uncertainties, repositories are safe by a significant margin, certain aspects require further investigation, for example the fundamental mechanisms for sorption and diffusion, radionuclide speciation and especially the speciation of ^{14}C . The objectives of the planned RD&D are to address these uncertainties and also to perform continuous updates of the databases to ensure they remain state-of-the-art.

Current state-of-the-art and progress since the 2009 RD&D Plan

Clay-based buffer and backfill

Diffusion and sorption are the dominant processes governing radionuclide transport in clay rock and in compacted clay systems. A description of the state-of-the-art diffusion modelling and sorption in clay rock can be found in sections 7.2.3.1 and 6.2 and this description is also applicable to compacted bentonite clay. The diffusion and sorption parameter values for safety-relevant radionuclides in bentonite, Opalinus Clay and the confining units have been intensely studied and reported in Van Loon (2014), Baeyens et al. (2014a) and Baeyens et al. (2014b). Solubility limits in compacted bentonite systems have been documented by Berner (2014a). An important reference work for these solubility limits is the PSI/Nagra thermodynamic database (Thoenen et al. 2014), which has been updated and extended over the last 6 years.

Cementitious materials

Diffusion and sorption are also expected to be the dominant processes governing radionuclide transport in the cementitious environment of the ILW and L/ILW emplacement rooms. Nagra's most up-to-date databases of sorption parameters and diffusion coefficients in a cementitious environment were published in 2014 by Wieland (2014) and, in the case of solubility limits, by Berner (2014b). The data are based on a combination of literature studies, experimentally determined sorption and diffusion parameter values, spectroscopic determination of uptake mechanisms on cement phases and evaluation of solid solution models to assess solubilities for those elements whose isotopes tend to dominate calculated dose rates (e.g. Ra).

Other waste management organisations have compiled databases for sorption and diffusion in cementitious environments using similar approaches (Andra 2005, SKB 2014b, Posiva 2013, Wang et al. 2009, Ochs et al. 2011). These databases were not derived entirely independently. In particular, SKB's cement sorption database is based mainly on the PSI/Nagra database, together with the ONDRAF/NIRAS database (Ochs et al. 2011, Wang et al. 2009). The latter is again partly based on PSI/Nagra database, but was extended using data from other researchers.

Although radionuclide sorption on cement phases and radionuclide solubility in a cementitious environment have been well studied in the past and good databases are now available, uncertainties still remain regarding certain radionuclide speciation and behaviour (^{14}C) and regarding coupled processes such as degradation of organics or microbial activity, which could lead to changing porewater conditions (pH, Eh, mineralogical changes) and an impact on the retention of radionuclides on cement phases.

Planned RD&D in the next 5 to 10 years

Clay-based buffer and backfill

As described above, the existing process understanding and databases for clay-based buffer and backfill at Nagra's disposal are already considered to be of high quality. Further RD&D is nevertheless planned to address residual uncertainties, potentially allowing more realism in the assumptions used in safety assessment dose calculations, while maintaining robustness. The most important uncertainties to be addressed are associated with the transfer of data measured in dilute systems to compacted systems, as well as issues of competitive sorption, radionuclide speciation, the behaviour of redox-sensitive elements (e.g. Se, U(IV/VI)) and the speciation, stability and retention of ^{14}C . These issues will be addressed by the long-term in-situ diffusion experiments in the Mont Terri URL (currently DR-B) and by the further development of mechanistic sorption models. Further details can be found in section 7.2.3.1.

Cementitious materials

The main issues to be addressed regarding retention and transport processes in the cement-based barriers comprise:

- The impact of cement degradation, arising for example due to interface reactions with clay and interactions with waste, on sorption and transport behaviour (see also section 7.5.2)
- The use of solid solutions as a basis for single radionuclide retention data where appropriate
- The speciation, stability and retention of ^{14}C
- The impact of changing porewater composition, due for example to microbial activity, on the immobilisation of radionuclides and on gas transport (see also section 7.5.2)

Among the planned projects that address these issues is the EU CEBAMA project, in which the impact of cement-clay interactions on radionuclide sorption and transport will be studied (CEBAMA 2016). Coupled modelling studies are also planned at PSI and at the University of Bern to elucidate the impact of degrading barriers on the retention of radionuclides (see also section 7.6.2.6). Uncertainties regarding speciation, stability and retention of ^{14}C are being studied in the EU CAST Project and by a swissnuclear-funded research programme at PSI, in which the aqueous and gaseous speciation of ^{14}C on release from irradiated metals is being analysed experimentally (see section 7.3.3.4). The impact of microbial activity on porewater chemistry is part of the MA-A experiment at the Mont Terri URL and of the EU-funded MIND project (see section 7.2.3.6).

7.6 Safety assessment

As presented in Chapter 4, safety assessment in the present context is the process of quantitatively and qualitatively evaluating the radiological safety of a deep geological repository. Safety assessment involves the application of a methodology for gathering and processing the required information about the disposal system and its environment. This information is then used to perform an evaluation of whether the disposal system as a whole meets the regulatory requirements on operational and post-closure safety as presented in ENSI (2009). The results of safety assessment along with additional evidence and arguments may then be synthesised into a safety case.

According to ENSI (2009), a safety case, and thus a comprehensive safety assessment, is a requirement for all major steps in repository development. In addition, safety assessment continuously provides feedback to repository implementation (e.g. within the framework of the site selection process, design studies or environmental impact studies, see section 7.8.1). Thus, specific RD&D activities are continuously needed to keep pace with international good practice with regard to safety assessment and with progress in the underlying scientific understanding.

Safety assessment also involves showing that the impacts of internal and external processes detrimental to the safety functions (section 4.2) are acceptable, or that design measures can be taken to reduce the impacts to an acceptable level. Understanding of internal processes is derived, for example, from the studies of coupled processes (e.g. thermal and gas pressure impacts on the hydro-mechanical state of the rock, see sections 7.2.3.2 to 7.2.3.5, and of the near-field, see section 7.5.2). External processes include geological and climatic phenomena (see section 7.2.2.5).

RD&D activities that focus on post-closure safety assessment (including aspects of repository implementation that affect the initial conditions for the post-closure period) are addressed in section 7.6.1 and those that concern operational safety assessment are described in section 7.6.2.

7.6.1 Post-closure safety assessment

Objectives

The main objective of RD&D work in post-closure safety assessment is to further develop the methodology and the necessary assessment tools so that the comprehensive post-closure safety cases that will support the general licence applications meet the requirements set forth by the regulatory authority in ENSI (2009). Particular focal points include FEP (features, events and processes) management and scenario development, as well as probabilistic safety and sensitivity analysis methods and tools. A special emphasis will be on the consistent treatment of uncertainty and risk.

Current state-of-the-art and progress since the 2009 RD&D Plan

Post-closure safety assessment is a key element of a repository safety case; a document on the nature and purpose of post-closure safety cases has recently been published by the OECD/NEA (OECD/NEA 2013). More specific examples of safety assessment methods used in the development of safety cases have been evaluated within the framework of the EU PAMINA project (PAMINA 2011a and b) and as part of the OECD/NEA MeSA initiative (OECD/NEA 2012a). These methods concern safety strategy, safety functions, scenario development, modelling strategy, sensitivity analysis, uncertainty management, safety indicators and the like. The OECD/NEA is also maintaining a FEP database for deep geological disposal to support safety assessments conducted internationally (OECD/NEA 2006); an update of this international database is planned for the near future.

The state-of-the-art in safety assessment is also reflected in the latest post-closure safety assessments conducted by other national waste management organisations. It should, however, be noted that some of these assessments have been made in the context of a construction licence application or for existing disposal facilities. Thus, the level of technical detail is, in some cases, beyond that of the post-closure safety assessments needed to support the general licence applications in Switzerland.

Nagra has developed a structured approach for carrying out safety assessments and for safety case development. The most recent safety case developed by Nagra was in the context of *Project Entsorgungsnachweis* (Nagra 2002c), which was extensively reviewed by several regulatory bodies (HSK 2005, KSA 2005, KNE 2005) and also internationally by the OECD/NEA (2004). All review comments were collected subsequently in Nagra (2008b), including statements about how the various comments would be considered in future safety assessments.

Since *Project Entsorgungsnachweis*, Nagra has carried out generic (Nagra 2008e) and site-specific (Nagra 2010a, Nagra 2014a and c) safety assessments in the context of the ongoing site selection process, as part of the Sectoral Plan (SFOE 2008). Both the generic and the site-specific safety assessments included a qualitative and a quantitative part. The qualitative part was based on criteria and indicators that are relevant in light of the site selection process. Methods for multi-criteria-decision-analysis (MCDA) were also explored and applied (Nagra 2014a, Appendix D). The quantitative part focused on dose calculations for the reference scenario, which is radionuclide release via the groundwater pathway under the expected evolution of the different repository systems.

Significant improvements have been achieved in quantitative assessment methodology and in the computer codes for evaluating radionuclide release and transport and for the evaluation of effective dose rates and risk. Together with the information flows between them, the assessment computer codes, often referred to as the model chain, are illustrated in Fig. 7-23.

The computer codes STMAN and PICNIC-TD are used, respectively, for near-field release and transport calculations and for geosphere transport calculations. These codes have recently been refined (Robinson 2013, Robinson & Watson 2013) to provide the capability to model radionuclide transport in transient groundwater flow-fields (see Nagra 2009a, 2008a) and also to represent diffusive radionuclide transport in a heterogeneous geological environment more realistically. In addition, the VPAC code for modelling radionuclide release and transport for the L/ILW repository (Holocher et al. 2008, Nagra 2009a, 2008a) has been extended to account for anisotropic diffusion. More details on these developments and a brief overview of each code are given in Nagra (2014e). Further development work has dealt with methods and tools to analyse a scenario involving radionuclide transport in solution along the underground access structures of a deep geological repository (Poller et al. 2014, Smith & Poller 2012).

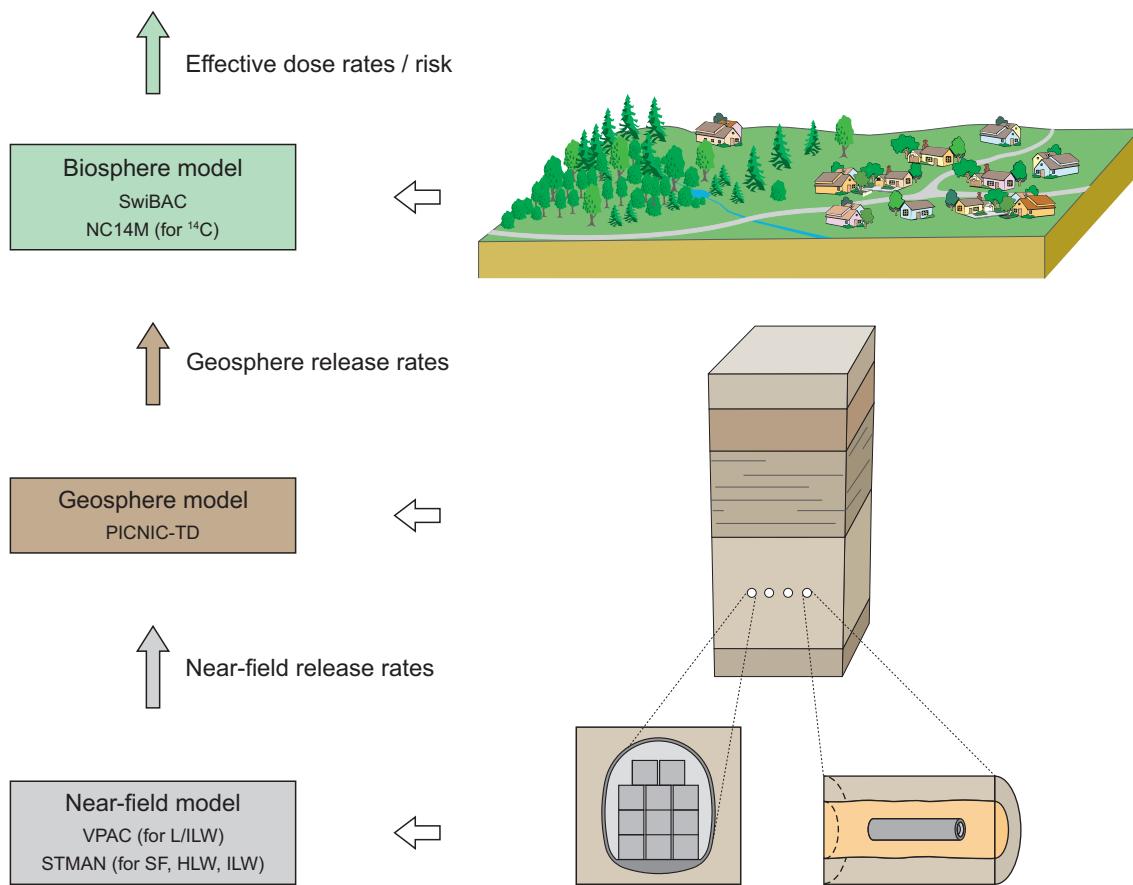


Fig. 7-23: The post-closure safety assessment model chain and the individual codes used in dose and risk calculations.

Major improvements in quantitative safety assessment have also been achieved in biosphere modelling. Biosphere modelling is required to convert radionuclide releases from the barrier system of a deep geological repository into dose and risk measures in order to evaluate compliance with regulatory protection criteria. Biosphere models are stylised models of possible future surface conditions (climate, landscape, water regime) and of how humans would be exposed to radiation in such environments due to radionuclide release from a repository.

The improvements in biosphere modelling concern (i) the re-implementation of the earlier biosphere model TAME (Klos et al. 1996) into the new code SwiBAC (Walke & Keesmann 2013), (ii) the revision and updating of generic biosphere data (Walke et al. 2013a, Nagra 2009a), (iii) the hydrological and hydrogeological characterisation of potentially affected areas (Haldimann & Schatzmann 2014, Nagra 2009a), and (iv) the development of a specific biosphere model for the radionuclide ^{14}C (NC14M, Walke et al. 2013b, Nagra 2009a). The latter was largely based on the results produced within the framework of the BIOPROTA forum (biosphere aspects of assessment of the long-term impact of contaminant release associated with radioactive waste management). Finally, the updated biosphere models and data were used for generic and site-specific biosphere modelling (Nagra 2014g).

In addition to safety assessment activities in the context of site selection, Nagra has been participating in international activities, including:

- OECD/NEA's Integration Group for the Safety Case (IGSC) and initiatives and projects such as MeSA (Methods for Safety Assessment for Geological Disposal Systems for Radioactive Waste) and INTESC (International Experiences in Safety Cases for Geological Repositories)
- IAEA projects such as MODARIA (Modelling and Data for Radiological Impact Assessments)
- EU projects such as PAMINA (Performance Assessment Methodologies in Application to Guide the Development of the Safety Case), NF-PRO (Understanding and Physical and Numerical Modelling of the Key Processes in the Near Field and their Coupling for Different Host Rocks and Repository Strategies) and FUNMIG (Fundamental Processes of Radionuclide Migration)
- The review of safety cases developed by sister organisations

As part of PAMINA, Nagra carried out a formal FEP analysis and subsequently developed an integrated radionuclide release code (IRRC), which can deal with transient two-phase flow conditions in a probabilistic context (Nagra 2010b and 2009a) and which provided valuable insight into coupled safety-relevant phenomena and their numerical modelling.

Planned RD&D in the next 5 to 10 years

In the years leading up to the general licence applications, two types of post-closure safety assessment will be undertaken. Firstly, there will be specific assessments for the geological siting regions proposed for SGT Stage 3. These assessments will be based on the results of detailed field investigations in the respective siting regions. The results of these assessments will eventually underpin Nagra's proposal of sites for the general licence applications (comparison with other siting options with respect to post-closure safety, see Tab. 7-4). Secondly, comprehensive safety cases, involving detailed safety assessments, will be developed for the repositories at the proposed sites as part of the technical documentation for the respective general licence applications.

With respect to the safety assessments that will support the siting proposals, no detailed requirements on the methodology have been set by the regulatory body. It is expected that the methodology will – both in quantitative and qualitative terms – be similar to that applied in Stage 2 of the Sectoral Plan, so no major RD&D activities are ongoing or planned in this area.

With respect to the safety assessments that will support the general licence applications, a number of RD&D activities are currently underway or planned:

- The current state-of-the-art of post-closure safety assessment, as described in the previous section, will be examined in detail to consolidate Nagra's overall safety strategy and safety assessment methodology. The reporting structure for the safety assessments (main reports and pertinent reference reports) will closely follow the safety assessment methodology that is finally adopted.
- A handbook on uncertainty management (scenario uncertainty, conceptual uncertainty, parameter uncertainty, probability of occurrence, correlations, uncertainty propagation through nested models), for both deterministic and probabilistic system/safety analyses, will be developed for use within Nagra and its supply chain (see Nagra 2008a).

- The FEP management methodology will be updated, with input from the OECD/NEA's (updated) international FEP database, FEP management approaches in other repository programmes (e.g. SKB 2010b, SKB 2014a, Posiva 2014) and Nagra's own development work (see Nagra 2009a and 2008a). The resulting methodology will then be applied to obtain a comprehensive FEP catalogue for each of the repository systems to be proposed in the general licence applications. Special emphasis will be on the potential interaction of FEPs (see Nagra 2008a).
- The procedures for identifying scenarios and defining corresponding assessment cases will be developed further in accordance with international good practice (see Nagra 2009a). In this context, Nagra is participating in an OECD/NEA initiative that aims to produce a report summarising the current status of scenario development methodologies.
- The method for quantifying risk, a requirement associated with Protection Objective 2 in ENSI (2009), will be further developed (see Nagra 2009a and 2008a). This involves the study of how different types of information could be assigned probability values for subsequent use in risk analyses. It also involves the examination of how risk conversion factors can be defined in accordance with national and international requirements and standards. The possibility to use complementary safety indicators in addition to dose and risk (e.g. comparison with natural radionuclide concentrations and fluxes) will also be re-examined (see Nagra 2008a).
- The methods for assessing the consequences of future human actions will be further developed. For instance, the possibility of accidental human intrusion (e.g. by means of a deep borehole) into the repository will be analysed in greater detail. Plausible scenarios through which intrusion might occur will be examined, as well as the range of situations that could be encountered at the time of intrusion (e.g. pressurised emplacement rooms, see Nagra 2008a). The results will be used to further optimise the repository concepts.
- The regulatory guideline (ENSI 2009) requires that the impact of geological processes that may lead to an exposure of the repository to influences from the surface beyond the timeframe of safety assessment as defined in Nagra (2008b) be evaluated in terms of regional radiological consequences. Along with the refinement of the existing models and methods that deal with such situations (see Nagra 2009a and 2008a), it is intended to apply them also to assess the radiological consequences of a hypothetical deep glacial erosion of the repository prior to the end of the timeframe for safety assessment (see Section 7.2.2.5).
- The methods for assessing the effects of repository construction, operation and closure (e.g. desaturation of parts of the host rock, formation of disturbed zones, effects of monitoring installations, potential retrieval activities, fire protection measures, accidents, safeguards, radiation protection measures, etc.) on post-closure safety will be refined (see sections 7.6.2, 7.4 and 7.5; see also ENSI 2009).
- The methods and tools used for biosphere modelling will be developed further. This includes the refinement of the conceptual models for different conceivable surface conditions (climate, landscape, water regime), based on RD&D activities in the field of long-term geomorphological and climatic evolution (see section 7.2.2.5), as well as considerations of how humans would be exposed to radiation in such environments due to radionuclide release from a repository (human habits and agricultural systems). Sensitivity analyses and information from natural analogues will be used to ensure that the range of biosphere models used to evaluate post-closure safety is sufficiently broad (see Nagra 2009a and 2008a).

- The above-listed RD&D activities along with new knowledge arising from site investigation and RD&D activities in other areas (particularly those mentioned in section 7.2.3.1 and section 7.5) will lead to further refinement of the existing safety assessment codes (including the conceptual models) and the concurrent development of the input datasets. It is, however, not expected that new safety assessment codes will need to be developed or acquired to meet the requirements on post-closure safety assessment in the period up to the general licence applications.

Work with international groups will continue in order to maintain a state-of-the-art capability in assessment strategy and methodology (see Nagra 2008a). Safety strategy aspects are discussed and further developed within the context of participation in the OECD/NEA Integration Group for the Safety Case (IGSC). Methodological aspects are discussed and further developed in international activities, such as the OECD/NEA's project on scenario development, the planned update of the OECD/NEA FEP database, BIOPROTA, the IAEA's project on Modelling and Data for Radiological Impact Assessments (MODARIA), or within the framework of IGD-TP (Implementing Geological Disposal of Radioactive Waste Technology Platform).

Further RD&D activities may be initiated following the regulatory review of the safety assessments carried out in Stage 2 of the Sectoral Plan and from new or modified regulations that may come into force in the period up to the general licence applications.

7.6.2 Operational safety assessment

Objectives

Operational safety reports are required for the general licence applications (KEV 2004, ENSI 2009) containing:

- A comprehensive accident assessment with the main focus on potential radiological impact and potential consequences for post-closure safety
- A description and discussion of the potential radiation doses to which personnel inside the facility and the general public in the surrounding area could be exposed during normal operations as well as in the event of an accident

In order to meet this requirement, the know-how for operational safety assessment has to be developed, including:

- The formulation of relevant accident scenarios
- The preparation of the required information and data for the corresponding dose calculations, including the development of an adequate concept for the classification and characterisation of spent fuel and radioactive waste, as well as nuclide- and accident-specific release fractions and retention factors

Both the accident assessment and the dose calculations provide constant feedback for optimisation of design measures and safety procedures to reduce the likelihood of accidents or mitigate their effects, which is ultimately expected to lead to safe repository design and to safe operating procedures. Hence, operational safety is closely connected with RD&D related to repository design and technology development for the repository and the engineered barriers, see section 7.4.

Despite the increasing attention given to operational safety assessment, it does not require extensive RD&D efforts on the part of Nagra, since advantage can be taken of the well-developed and highly relevant methods, knowledge and experience that already exist in the nuclear community (e.g. related to the operation of nuclear power plants, interim storage facilities, research facilities and repositories). The RD&D that is planned has the broad objective of further developing the operational safety assessment methodology and the associated assessment tools so that they lead to comprehensive safety assessments supporting the general licence applications that meet the requirements set out in ENSI (2009) and other regulatory guidelines.

Current state-of-the-art and progress since the 2009 RD&D Plan

A complete operational safety assessment for a L/ILW repository was conducted in connection with the general licence application for the Wellenberg project (Nagra 1993b, Nagra 1994a and b, Nagra 1996a and b). No such assessment has been performed as yet for a HLW repository, although a generic and qualitative operational safety analysis was carried out as part of *Project Entsorgungsnachweis* (Nagra 2002c). Furthermore, systematic and mainly qualitative and generic operational safety assessments were conducted for the repository surface facilities (Nagra 2013a) and for the underground facilities (Nagra 2014c) as part of SGT Stages 1 and 2. The objective was the characterisation and optimisation of measures and safety systems, based on the internationally recognised concept of defence-in-depth (IAEA 1996). The evolution of conditions following the occurrence of an accident was systematically investigated, including different potential damage states of the system components from the perspectives of:

- Nuclear safety and radiation protection
- Personnel safety and protection of life and health
- Post-closure safety
- Environmental impact

Some conservative estimations and calculations of radiation doses in normal operation and in the case of accidents were performed as part of these assessments, although the concepts, scenarios, models and data that were used were based on the Wellenberg project. For the general licence application, these will need to be updated to account for the selected preliminary repository designs and the current state-of-the-art.

Nevertheless, the findings indicate that a deep geological repository can be operated safely in line with the protection objectives specified by law (ENSI 2009, KEG 2003, KEV 2004, UVEK 2009, StSG 1991, StSV 1994). Furthermore, the requirement for safe operation of such a repository was found to have no bearing on site selection (except for the event of flooding, which is ruled out by appropriate selection of the site for the surface facility and shafts). Another outcome is the derivation and definition of requirements for the repository design and layout, waste package design and operational procedures with a view to the minimisation/exclusion of malfunctions and accidents.

Planned RD&D in the next 5 to 10 years

Two main areas of RD&D are considered necessary:

- Waste characterisation: a classification concept for spent fuel and radioactive waste tailored to the needs of operational safety assessment. The characterisation includes the determination of waste type- and waste package-specific release fractions for normal operation and in the case of accidents. Moreover, safety-relevant requirements for the disposal canisters and transport casks will be defined in order to determine their retention properties.
- Safety concepts: safety concepts and associated requirements will be further developed with a view to the minimisation/exclusion of malfunctions and accidents, so as to ensure (i) personnel safety and protection of life and health and (ii) environmental protection. The concepts to be considered include the radiation protection concept (including the allocation of controlled zones), the fire protection concept, the ventilation concept and the escape and rescue concept. These will be refined in parallel with, and will further constrain, the refinement of repository designs (and are thus strongly connected with other RD&D topics: repository design and technology development, see section 7.4).

International collaborations (e.g. EGOS - Expert Group on Operational Safety, GEOSAF II) will be continued to remain state-of-the-art (international good practice, scientific and technological understanding, methodology and tools as well as lessons learned from other nuclear facilities, e.g. WIPP).

7.7 Development of the concept for repository monitoring

Objectives

One of the basic design principles is that long-term safety is provided through passive safety with a multibarrier concept (KEV Art. 11 and ENSI 2009). Monitoring should not compromise the performance of the passive barriers after closure.

In the early stages, however, monitoring features prominently in the development and implementation of a geological repository, because it can provide repository implementers, expert reviewers (e.g. safety authorities) and lay (e.g. public) stakeholders with in-situ data over the different phases of the repository project. The observed data may be used to confirm the predicted very early repository evolution, contribute to operational safety and provide input for the staged repository implementation and closure process (construction, operation and closure). Comparison of the monitoring results with prior performance assessments and process models contributes to increased stakeholder confidence regarding the disposal system.

The objective for the next RD&D phase is to develop a concept, and eventually detailed methods and techniques, for reliable surface-based and underground monitoring of a repository. Surface-based monitoring will ultimately have to cover the radiological and environmental monitoring of the surface facility and its surroundings, the groundwater, surface water, soil, and atmosphere (ENSI 2009), as well as surface movements in the region of the repository. Underground monitoring covers the following phases of repository implementation: detailed site investigation, construction of exploration tunnels and shafts, construction and operation of the facilities for underground geological investigations (later test area), construction and operation of the pilot and main facility and the observation period (post-waste emplacement monitoring). A key feature of the underground monitoring concept is the monitoring of a pilot facility containing a representative amount of waste, as defined by EKRA (SFOE 2000) and ENSI (2009). In the pilot facility, underground monitoring will comprise monitoring of the engineered and

geological barriers as well as seal sections. In the far-field rock, repository-induced effects can be monitored using surface-based observation methods such as boreholes for hydrological changes in deep aquifers or temperature changes.

The first monitoring concept to be developed for the general licence application will cover base-line monitoring of the initial state and monitoring during construction of the access facilities, as well as first considerations regarding monitoring planned for the facilities for underground geological investigations and the pilot facility.

Current state-of-the-art and progress since the 2009 RD&D Plan

Studies since the 2009 RD&D Plan have focused on monitoring concepts, strategic aspects and the link to safety analysis, as well as practical work on the development and testing of monitoring techniques and sensors.

Monitoring concept and international research

Valuable knowledge transfer to Nagra was provided by European projects and other bi- and multilateral projects. Basic considerations regarding the development of monitoring concepts, equipment and methods were completed in the project "Monitoring developments for safe repository operation and staged closure" (MoDeRn) within the 7th EU Framework Programme. Conceptual research was done on monitoring concepts and the link to safety analysis and the concerns of lay stakeholders (MoDeRn 2013a). Within MoDeRn, several state-of-the-art monitoring techniques and technologies (e.g. wireless data transmission, non-intrusive monitoring techniques, fiber-optic sensing) were identified as suitable for a repository and were further developed (MoDeRn 2013b). Moreover, Nagra participated in two further research projects within the 7th EU Framework Programme, namely the international project "Full-scale Demonstration Of Plugs And Seals" (DOPAS), where knowledge about plug and seal monitoring is currently being generated, and the international "Large Underground Concept Experiments" (LUCOEX) project, where state-of-the-art and novel monitoring techniques are being successfully used (e.g. Sakaki et al. 2015).

Use of monitoring techniques and sensors in URLs

State-of-the-art monitoring techniques and prototype sensors have been used successfully in a large number of in-situ experiments in underground laboratories. Some experiments were dedicated to further developing, evaluating and testing different sensor and monitoring technologies.

At the Mont Terri Rock Laboratory, the Full-Scale Emplacement (FE) experiment, which is a long-term full-scale heater test, will provide valuable information for the monitoring concept of the pilot facility, because different monitoring technologies were implemented to compare and evaluate their performance under repository-like conditions (Vogt et al. 2015). The heating phase started in December 2014, but initial valuable experience was obtained during sensor installation, tunnel construction, the ventilation period, emplacement and backfilling (Vogt et al. 2013). A special method used in the FE experiment is fiber-optic sensing for THM monitoring. Different distributed fiber-optic sensing systems for temperature and strain measurements as well as point and quasi-distributed systems were installed. Monitoring during tunnel construction in the Opalinus Clay was done successfully with state-of-the-art equipment in the "Mine By" (MB) and FE experiments at Mont Terri. Non-intrusive geophysical monitoring techniques are being tested and further developed at the Grimsel Test Site in the "Test and Evaluation of Monitoring Systems" (TEM) experiment and at Mont Terri in the "Gas path through host rock

and along seals" (HG-A) and FE experiments (Marelli et al. 2010). Wireless data transmission is being tested in the long-term TEM experiment at the GTS (Breen et al. 2012). At Mont Terri, the long-term evolution of hydraulic heads in Opalinus Clay around the URL was investigated by the "Long-term monitoring of pore pressures" (LP) experiment, designed to better understand construction-induced effects and the evolution of water flow (Ababou et al. 2012). In addition, similar to dismantling of the Swedish prototype repository (Nilsson 2014), the dismantling of the remaining part of the FEBEX experiment at the Grimsel Test Site and the dismantling of the "Engineered Barriers" (EB) experiment at Mont Terri allowed the evaluation of the durability and reliability of typical sensors after decades of varying and challenging monitoring conditions (Martínez et al. 2016).

In addition, close cooperation with partner organisations, some of which are more advanced in their disposal projects, resulted in valuable knowledge transfer to Nagra. Close collaboration with Andra on fiber-optic sensing provided knowledge transfer with respect to installation and operation (Delepine-Lesoille et al. 2015), as well as the development of radiation- and hydrogen-resistant optical fibers.

Monitoring projects implemented in the siting regions

Since the 2009 RD&D Plan, two surface monitoring projects, namely the permanent broadband seismic monitoring network (Plenkers 2014) and the permanent GNSS network (Studer & Zanini 2013; Fig. 7-24), have been implemented to monitor recent neotectonic movements. In the siting region Zürich Nordost, the Benken deep borehole was equipped in 2009 with a new long-term monitoring system for observations of hydraulic heads in Opalinus Clay and its surrounding formations and aquifers (Jaeggi & Frieg 2010).



Fig. 7-24: Example of a GNSS station.

Planned RD&D within the next 5 to 10 years

The development of a concept for repository monitoring is a stepwise procedure. Therefore, the planned RD&D monitoring activities are closely linked to standards set by the regulator as well as international research activities and their results. While Nagra has to develop a monitoring plan for the pilot facility at the conceptual level in the first instance, decades will pass until the monitoring of the pilot facility starts, and significant technological development on monitoring techniques is expected, especially for fiber-optic sensing, wireless data transmission and non-intrusive monitoring techniques.

Regulatory requirements and international research

In the near future, ENSI will complete two research projects directly dedicated or linked to monitoring. ENSI is leading the Swiss Federal Workgroup for Nuclear Waste Disposal (AGNEB) research projects "Monitoringkonzept und -einrichtungen" (monitoring concept and installations) to clarify the regulatory monitoring requirements, as well as "Auslegung und Inventar des Pilotlagers" (design and inventory of the pilot facility), which also influences the monitoring concept for the pilot facility.

Participation in international research projects as well as bi- or multilateral projects and close cooperation with partner organisations, which are more advanced in their disposal projects, are ongoing and will allow learning from their experience. In 2015, the monitoring project Modern2020, which is the follow-up project of Modern, was launched within the Horizon 2020 framework (Euratom). The Modern2020 project aims at providing the means for developing and implementing an effective and efficient repository monitoring programme, taking into account the requirements of specific national programmes, e.g. a pilot facility. Within Modern2020, and based on *Project Entsorgungsnachweis* (Nagra 2002c), Nagra will identify EBS and host rock parameters to be included in the monitoring programmes to be developed at different stages of repository implementation. After Modern2020, these basic concepts will be further developed to provide a comprehensive monitoring concept for the general licence application. Further RD&D needs in the field of monitoring technologies were identified in MoDeRn (2013b). Therefore, Modern2020 will conduct research on what should be monitored, the design of monitoring systems and the improvement and further development of innovative monitoring techniques, including their demonstration in full-scale experiments. Within Modern2020, Nagra will further develop fiber-optic monitoring techniques.

Generic URLs

Progress in technological and methodological developments as well as feasibility testing for repository monitoring is expected from several experiments that are already initiated or will be implemented in the Swiss rock laboratories. Current long-term experiments in which monitoring plays an important role are running at the Grimsel Test Site, namely TEM and GAST, and at Mont Terri, namely the FE, HE-E, HG, LP and the "deep borehole" (DB) experiments. The FE experiment (see section 6.2) will provide valuable information as THM processes are investigated at a 1:1 scale under realistic conditions and state-of-the-art as well as novel monitoring systems are implemented to compare and evaluate their performance (Vogt et al. 2015). The temperature distributions over time along the tunnel which contains three heaters that were switched on during the first few months of 2015 are shown in Fig. 7-25. In addition, the gas composition in the sealed section of the FE experiment will be investigated by in-situ gas sensors and sampling campaigns.

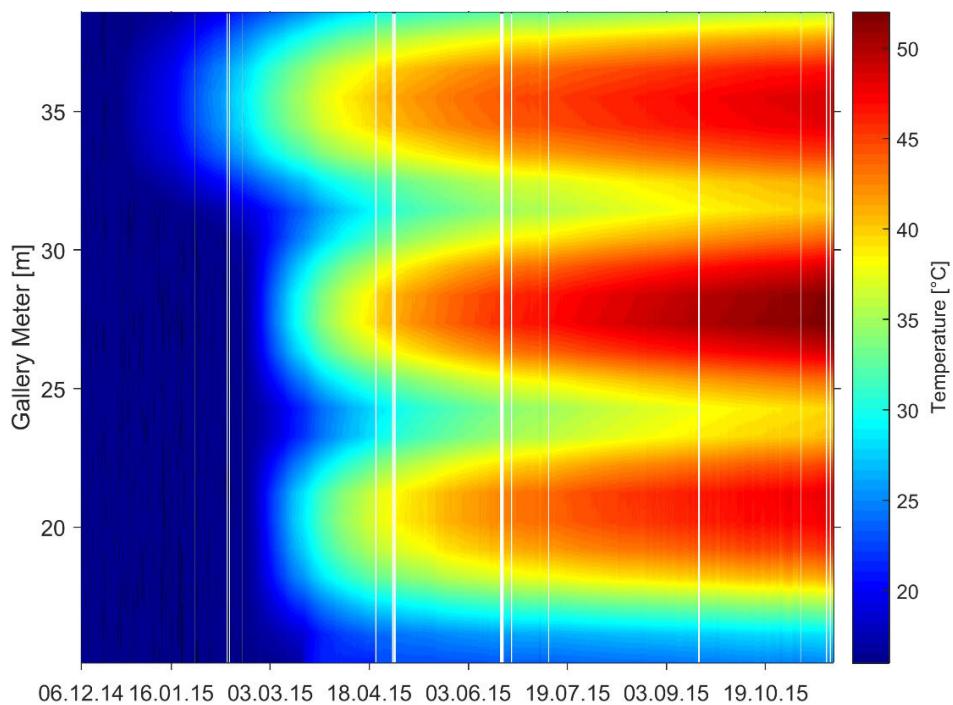


Fig. 7-25: Evolution of the temperature distribution along the tunnel wall of the FE experiment measured by means of distributed temperature sensing along a fiber-optic cable, which is installed at the 5 o'clock position in the tunnel cross-section.

The tunnel contains three heaters that were switched on during the first few months of 2015.

Baseline monitoring

Baseline monitoring will start with the detailed site investigations that will begin after granting of the general licence and will be intensified before construction work (access tunnel and shaft construction) begins. The RD&D activities up to general licence application with respect to environmental baseline monitoring are performed as part of the joint activity of the IGD-TP, which focuses on development of programmes for monitoring the environmental reference state. Meteorological measurements and a radiological monitoring programme will be set up according to the specifications of the authorities. These programmes will be similar to the already existing radiological monitoring networks MADUK and NADAM. For surface monitoring of ground movements and seismicity, the first GNSS and seismic stations are already installed in the siting regions and further stations and remote sensing techniques will be added for the selected site(s). New technological developments in this field will be regularly assessed. Moreover, Nagra's current monitoring activities in the siting regions, e.g. groundwater monitoring during 3D seismic campaigns, will be transferred to the baseline monitoring programme.

For baseline monitoring of the subsurface, a network of shallow and deep observation boreholes, mainly from the earlier site investigation phase prior to the general licence application, will be established and equipped with long-term monitoring systems. Monitoring targets and planned equipment for the exploration boreholes will be periodically updated in the light of new technical developments when existing systems have to be replaced, e.g. fiber-optic pressure sensors.

Underground monitoring concept for the facilities for underground geological investigations

The underground monitoring concept for construction and experiments related to the on-site facilities for underground geological investigations will focus on engineering feasibility, operational safety and long-term safety. For excavation work and THM characterisation tests, state-of-the-art equipment as well as experience from other URLs will be used. Until the application for the construction licence, the focus will be on concept development and technology screening for both surface and underground monitoring.

7.8 Other topics

7.8.1 Socio-economic and environmental impact of a repository

In the context of the Sectoral Plan process, the Swiss Federal Office of Energy (SFOE) is responsible for carrying out socio-economic and environmental studies in the potential siting regions. The conceptual part of the Sectoral Plan (SFOE 2008) states that socio-economic and spatial planning aspects should be taken into account in site selection when the sites are equivalent in terms of safety. These aspects are, in any case, relevant for the economic development of a siting region and the optimum arrangement of the surface facilities and the accesses to the repository. The analysis of the spatial planning situation and socio-economic impacts thus provides an additional basis for decision-making.

The procedure for analysing the economic, ecological and social impacts of deep geological repositories was described early in the process in connection with the spatial planning methodology for comparing sites in Stage 2 (ARE 2010). The methodology is based on a system of objectives and indicators that specifies which impacts are to be assessed and how they are to be evaluated. Quantifiable indicators are used to the greatest possible extent. Image-related impacts are to be examined in a separate study. Each socio-economic and environmental study should focus on the whole siting region and encompass the full period from the construction of the facilities for underground geological investigations through to the sealing of the facility, for which a duration of approximately 100 years is proposed.

In SGT Stage 2, therefore, socio-economic and environmental studies were prepared together with the siting regions defined in Stage 1 and the social, demographic, environmental and economic impacts of a geological repository were evaluated. The results were published in November 2014 (SFOE 2014b). With respect to the environmental impact assessment for the deep geological repository, chemotoxic characteristics of radioactive wastes were estimated (Häner et al. 2014). The study has shown that there is no chemotoxic risk expected due to the disposal of the materials in the SF/HLW and L/ILW repositories.

In Stage 3 of the process, socio-economic implications will be analysed in greater depth by the SFOE and the siting regions. The data, information and decision-basis will be improved with a view to monitoring the socio-economic and environmental impacts. The siting regions will also propose a strategy, measures and projects for sustainable regional development and compile the background information necessary for determining compensation measures.

7.8.2 Preservation and transfer of information across generations

Preserving information on the deep geological repository over long timescales is required not only to contribute to safety by, e.g. preventing human intrusion, but also to facilitate retrievability and more generally respond to social expectations and to allow future generations to make their own informed decisions about the waste. However, long-term projects of any nature are known to be vulnerable to risks of loss of information, knowledge and, ultimately, memory.

In line with these observations, the Swiss legislation includes provisions on the preservation of the relevant documentation in archives (Art 40 KEG, Art. 71 KEV), as well as on the marking of the disposal site (Art. 69 KEV). Compiling documentation on the repository is an activity that covers the whole lifetime of the facility and must be initiated early in the process. Nagra keeps an extensive archive of scientific and technical documentation covering forty years of research, as well as other documents relevant to decision-making.

The marking of a deep geological repository, on the other hand, has strong local components and can only be addressed in detail after a site has been selected. According to the ENSI Guideline G03 (ENSI 2009), the corresponding concept is therefore expected as part of the construction licence application. In preparation for this, the SFOE has already commissioned a literature study on the topic of marking strategies (SFOE 2010).

Like Switzerland, other national programmes are actively seeking to improve their understanding of the preservation of information across generations. In 2011, the Nuclear Energy Agency of the OECD therefore launched the initiative "Preservation of Records, Knowledge and Memory across Generations" (RK&M) as a platform for exchanging information and fostering reflection in this area, including formulating common approaches. Nagra has been an active member of the RK&M project since its early stages and will continue, together with 18 other organisations from 13 countries, to work on guiding principles and practical solutions for implementing information preservation in the long term.

Important findings of the first phase of the project include the fact that there is no single mechanism or technique that, by itself, could achieve the preservation and transfer of RK&M over centuries and millennia. Rather, an integrated system of mechanisms and techniques – technical, administrative and societal – is needed to address the various timescales. This system should offer a variety of transmission mechanisms that are either integrated with, or complement, one another. Archiving policies and marking strategies have been found to be important components of such a system, but other mechanisms need to be developed and implemented in order to maximise information accessibility, understandability and survivability over the timescales considered.

7.8.3 Monitoring of technological advances in partitioning and transmutation

The aim of this work is to monitor international advances in technologies that could lead to the further processing/use of Swiss spent nuclear fuel, and result in the reduction of the inventory of actinides or other long-lived isotopes. Such technologies could have the potential of reducing the volume and radioactive decay time of materials that are to be disposed of in the repositories, and include:

1. Partitioning technologies (e.g. aqueous reprocessing and pyroprocessing)
2. Transmutation technologies (e.g. Critical or sub-critical reactors and systems designed to destroy actinides such as types of Generation IV reactors and Accelerator Driven Systems)

Nagra follows up on international efforts in transmutation such as the development of the TransAtomic Power molten salt reactor, the GE Hitachi PRISM sodium-cooled fast reactor and the progress of the MYRHHA accelerator driven system project in Belgium. Additionally, Nagra follows international developments on both aqueous and pyroprocessing partitioning programs. This will be continued in the future with the aim to assess the potential impact of such technologies on the Swiss radioactive waste management framework (i.e. impact on repository safety considerations and radioactive waste management costs).

8 Broad overview of the technical work programme for programme stages beyond the general licence application

In Chapter 7, the RD&D activities for the next 5 to 10 years, encompassing the target general licence application date of 2024, are described in terms of objectives, current state-of-the-art and identification of the remaining uncertainties and how to deal with them. For the general licence application, the entire knowledge base and the many RD&D activities feeding into it will be integrated into the argumentation and decision-making supporting the safety case for the selected sites, which is an integral part of the licence application.

Chapter 8 describes the anticipated evolution of the RD&D programme beyond the general licence application. In the first instance, the focus will be on the continuation of the programme between the submission of the general licence application by Nagra (foreseen for 2024) and its granting after review and approval by the regulator and the government. It is anticipated that this will take approximately 7 years (up to 2031; Nagra 2016a). In this period, the licence for the facilities for underground geological investigations will be prepared. It is assumed that preparatory borehole drilling at the location of the exploration shafts as well as all surface-based preliminary investigations for subsurface construction will have largely taken place before the submission of the general licence application.

After the granting of the general licence, the RD&D programme enters a new phase, where technology development and engineering will become a major part of the activities, next to subsurface characterisation and the scientific programmes in the facilities for underground geological investigations.

8.1 Activities foreseen up to the granting of the general licence for the selected sites

In the process up to the granting of the general licence, it is anticipated that addressing questions from the regulator and the stakeholders regarding the documentation of the safety case will contribute to the definition of the RD&D activities to be undertaken as it will be required to gradually refine the argumentation for future steps.

Geological information and investigations

Following the submission of the general licence application for the selected sites, preparations for the construction of the facilities for underground geological investigations at the sites will start. Prior to the field and construction work, baseline monitoring programmes will be put in place. Regional monitoring will be continued (geodetic measurements, operation of a micro-seismic network) to further complete the datasets, with the aim of distinguishing natural from repository-induced effects (e.g. induced vs. natural seismicity or surface uplift).

State-of-the-art geodatasets and site descriptive models for detailed planning of site exploration, repository construction and future safety assessment programmes will remain a key element in later steps. In this sense, site descriptive modelling will be a continuous process in all stages of the future repository programme.

Experience from international waste disposal programmes and from other geoscientific disciplines will be monitored and it is anticipated that, before the granting of the general licence, certain European countries will have operating deep geological repositories.

Waste inventories, characterisation and databases

The inventory will be further refined with advanced calculations to support further operational safety, design and logistics considerations for the repository and related facilities.

When definitive waste acceptance criteria are in place, it has to be confirmed that each individual waste package fulfils these criteria. In the event that a waste package type is not accepted, reconditioning methods might need to be developed to ensure compliance with the definitive waste acceptance criteria.

Improvements in the understanding of processes associated with HLW and spent fuel will be pursued. The spent fuel dissolution and release model will be further refined by integrating new developments in the field. Specific experimental projects may be planned at PSI or in collaboration with KIT and JRC-ITU if deemed necessary. The ^{14}C reference release rates and speciation will be refined in accordance with experimental data as they become available.

With respect to gas production, the reference corrosion rates will be continuously refined in accordance with available experimental data and increasing understanding of the evolution of conditions in the repository. The currently ongoing corrosion experiments can be extended to further increase confidence in the reference corrosion rates. The gas generation experiments at ZWILAG are designed for long-term operation, also beyond the general licence application, and the programme can be further expanded if necessary. This may be useful because existing experimental data on the degradation of organic polymers indicate that these materials are hardly degradable and potential gas generation from their degradation will be very low; long-term datasets may thus be required to obtain reliable gas generation rates.

A continued follow up on international efforts in transmutation and partitioning is foreseen to evaluate the potential impact of such technologies on the Swiss radioactive waste management framework (i.e. impact on repository safety considerations and radioactive waste management costs).

Design and technology development

Preliminary and basic design work will continue after submitting the general licence application. The initial focus will be on the construction of the access and infrastructure for the facilities for underground geological investigations as well as developing adequate monitoring programmes. This information will form the basis for the licence application for the facilities for underground geological investigations.

With respect to the buffer materials for HLW emplacement drifts, alternative materials will be further evaluated to ensure that options are available for obtaining material that meets the requirements over the coming decades. The final materials will be selected in anticipation of the construction licence.

The emplacement concept will be further optimised based on new information and alternatives will be evaluated as they become available. Regarding the backfill emplacement technology, the focus will be on ensuring a homogeneous sufficiently high density, including innovative process engineering with regard to further improvement of the buffer and backfill quality.

A reference recipe for cement-based backfill for L/ILW emplacement caverns will be developed for the general licence application, although the possibilities to use alternative materials will be continuously evaluated and the final selection is expected to remain open until the construction licence application.

The decision regarding the material for the SF/HLW canisters will also be taken in anticipation of the construction licence. Before this, the evaluation of the options will continue with the steel canister, the copper-coated canister and the copper canister as options developed to a high technology readiness level. Other options will also continue to be examined as significant progress in material performance and coating techniques can be anticipated in the next decades.

Alternative EBS concepts will continue to be evaluated initially at the conceptual level, but this can involve substantial RD&D efforts in the case where optimisation in terms of safety and feasibility can be shown when assuming alternative engineered barrier materials and/or repository layouts.

The state-of-the-art regarding concepts for preservation of information and marking of the repository will be maintained. Measures for temporary closure in case of unfavourable boundary conditions will be evaluated and developed, allowing emplacement of closure elements within a couple of months and the ability to function for a few decades up to a few centuries.

Evolution of safety-relevant properties and processes in the near-field, the engineered barriers and compacted clay systems

The improvement of understanding of the behaviour of safety-relevant processes in the near-field is an ongoing activity with the objective of supporting the safety analyses performed for the various decision points.

The experiment programme in the Mont Terri URL will be continued with the focus on long-term characterisation of safety-relevant parameters. This will include the continuation of the FE experiment, the continuation of the tests characterising the corrosion rates of canister materials and the characterisation of the chemical interactions at material interfaces (cement, bentonite, Opalinus Clay). In this period, the excavation of the HE-E (heater) experiment is also foreseen, which will allow the performance of the bentonite barrier subjected to high temperatures under natural saturation conditions to be assessed, including a final assessment of the THM models applied during the course of the experiment. Continued characterisation of rock mechanical processes will allow improvement of constitutive models and complete the site-specific data obtained during the field activities.

Continued monitoring of in-situ corrosion rates of copper and steel, and possibly other materials, in the laboratory will allow corrosion models to be further refined.

Site-specific model analyses of the performance of the ILW and L/ILW near-field will be continued, possibly also beyond the general licence application, and these will need to be adapted to future layout modifications and changes to the waste inventory. Advanced process models will be implemented where required from an optimisation point of view.

The experimental plans for the facilities for underground geological investigations will be developed and certain aspects might be pre-tested in the existing generic URLs or in surface laboratories.

Safety assessment and operational safety

Beyond the general licence applications, RD&D activities for post-closure safety assessment will continue as the repository projects progress in a stepwise manner, guided by regulatory requirements as in ENSI (2009). This may include, for example, the development of methods and tools:

- To further optimise repository configurations (e.g. repository layout and design, grouping of waste types), construction and operation from the perspective of post-closure safety
- To guide the design, construction and operation of the pilot facility
- To derive more specific requirements on individual components of the multibarrier system
- To assess the effects of technical and operational measures for temporary closure, retrieval, security and the control of fissile materials on post-closure safety
- To assess post-closure consequences of monitoring and retrieval activities, both in normal operation and in case of incidents (which may in theory lead to the decision of waste retrieval)

Regarding operational safety, a broad description of repository design and sequences of operations is needed to support the general licence applications (KEV 2004). Thereafter, these aspects are expected to be further developed, resulting in increasingly refined descriptions.

Concepts for monitoring

The monitoring concept for the pilot facility, as well as the operational and post-closure phases of the repository will be further developed. The activities will focus on technology screening as well as further technology developments and testing in areas where national or international collaboration can be established. Testing of certain techniques in the Mont Terri URL will take place.

8.2 Construction of the facilities for underground geological investigations and tests therein

8.2.1 Introduction

It is anticipated that, with the granting of the general licences in 2031, the construction of the facilities for underground geological investigations will start soon after.

At the same time, the subsurface rock characterisation programme will be initiated. Depending on the access (exploration shaft or tunnel), a construction time between 2 and 4 years needs to be foreseen to complete the first access. The time during construction will also be used to characterise the rock sequence and update the datasets. Once the repository depth is reached, a service area will be constructed at depth.

At that point the facilities can be fully constructed. This could occur in two phases to allow the test programme to start as soon as possible:

- A first phase would lead to the construction of a first zone with niches foreseen for hosting tests that either require minimal space or require a longer lead time to obtain results, or to characterise parameters that are required at an early stage.
- A second phase would subsequently lead to the construction of a second zone with larger niches where larger-scale or more complex tests sensitive to host rock disturbances can be placed.

While results from the tests (apart from the demonstration tests) are required to be included in the construction licence, several tests can be continued beyond the granting of the construction licence and also during the operation of the repository, if this is deemed useful to further confirm the understanding and/or reduce remaining uncertainties.

8.2.2 Rock characterisation during construction of the access

Together with the construction of the facilities for underground geological investigations, a rock exploration and characterisation programme will be conducted. The objectives of the programme are to confirm the geomechanical, hydrogeological and hydrogeochemical understanding of the site by acquiring new data, including their spatial variability, and to integrate these data into the existing conceptual understanding and the numerical models of the site.

In order to achieve these objectives, the following activities are foreseen:

- Drilling of a vertical borehole at the anticipated location of the exploration shaft (if this is not already in place)
- Characterisation of the geological sequence during the exploration shaft and tunnel construction (mapping and sampling), including geotechnical, hydrogeological and hydrogeochemical aspects
- Monitoring of the state parameters (temperature, hydraulic pressure, stress, etc.)

8.2.3 Rock characterisation and experiments during construction and operation of the facilities for underground geological investigations

Once the service area at the repository depth is in place, the experimental programme will be initiated. The objectives of the programme and the planned tests, including a broad assessment of the time required to conduct them, are indicated below.

8.2.3.1 Enhanced characterisation of relevant host rock properties

Enhanced characterisation of the relevant host rock properties and their spatial variability (geomechanical, petrophysical, mineralogical, hydrogeological and thermal parameters) is needed to improve the site descriptive models and reduce remaining uncertainties. This involves repeated measurements characterising the rock volume of the facility and defining spatial patterns for the whole repository area, also taking into account the information from the boreholes already in place. Characterisation of the porewater will also be performed.

8.2.3.2 Performance confirmation of the host rock and engineering applications

The main objective of the performance confirmation is to ensure that the anticipated performance of the rock as described in the safety case for the general licence can be confirmed and refined at the selected sites at repository depth. It has two main aspects.

Performance confirmation from a post-closure safety point of view

Performance confirmation from a post-closure safety point of view involves repeating various experiments that have already been conducted in the laboratory and in the Mont Terri URL. The underlying phenomena have been investigated in detail and are sufficiently understood to support the safety case for the general licence application. The objective is to demonstrate that the understanding can be applied at the repository site and to confirm that the safety-relevant parameters lie within the anticipated ranges such that the impact of the consequences of repository-induced effects can be bounded. It concerns the following key safety-relevant properties.

Self-sealing processes

This refers to understanding the development and the geometry of the EDZ and the evolution of its hydraulic properties over time. It probably requires a mine-by test to be conducted (which can be combined with the construction of the facilities for underground geological investigations). A load-plate test could be foreseen to estimate the evolution of the hydraulic properties with time. Similar experiments (SELFrac experiment) already conducted in the Mont Terri URL indicate that an experimental timeframe of 2 – 3 years has to be foreseen.

Thermal impact on the host rock and the EBS (HLW repository only)

With the thermal properties already characterised at the sample scale, a heater test will allow confirmation of the heat dissipation capacity of the host rock at the large scale. This experiment can be conducted at borehole scale. Current understanding based on the HE-E and FE experiments at Mont Terri suggests that maximum overpressures will be generated 1 – 3 years after heating starts. However, it is worthwhile continuing these experiments over longer timeframes.

Gas transport capacity in the host rock

The gas transport capacity will be assessed using a gas injection test to establish the dominant gas transport mechanism in the undisturbed Opalinus Clay under the anticipated pressure regimes. The potential impact of the spatial variability of gas transport parameters also needs to be assessed. Based on experience with similar experiments (e.g. HG-A, Senger et al. 2014b) at the Mont Terri URL, these are anticipated to require 1 – 2 years.

Radionuclide migration

While the radionuclide sorption and transport parameters will be confirmed in the laboratory based on samples taken from the sites and the upscaling of these parameters to the URL scale has already been demonstrated in the Mont Terri URL, confirmation of in-situ migration using proxy species can be considered (although not deemed absolutely necessary) for the site where the HLW repository will be constructed. Based on the Mont Terri experience, these experiments require a timeframe in the order of 5 years, after which overcoring is carried out to obtain the results. Longer experiments can also be foreseen beyond the submission of the construction licence to confirm more short-term observations.

Performance confirmation and optimisation from an engineering point of view

These activities address specific construction issues that are strongly dependent on the in-situ conditions at the repository depth of the selected sites.

Tunnel construction and support confirmation (HLW repository)

Based on surface characterisation, a tunnel construction and support concept will be developed, including alternative options to account for different stress regimes at the repository depth and the anticipated geomechanical conditions. During the construction of the facility for underground geological investigations and possibly thereafter, these concepts will be tested and refined. This will require the development of a geomechanical test sequence which needs to be conducted in different directions depending on the prevailing stress tensor and rock properties. Mine-by tests, which can partly be conducted as part of the construction of the facility for underground geological investigations, will contribute to this. Experience has been gained during mine-by tests (e.g. Vietor et al. 2010) in the Mont Terri URL, although it must be acknowledged that the rate of excavation for the construction of the repository tunnels needs to be considerably higher than during previous tests, while the method of excavation also differs from the one anticipated for the repository. A semi-industrial prototype tunnel boring machine will be developed off-site for this purpose. The excavation rate consequently determines the duration of the experiment. This testing ultimately needs to provide the basis for the method for repository construction. It can be further optimised after the granting of the construction licence (also accounting for spatial variations in the rock properties).

Construction of a cavern calotte with different levels of support (L/ILW repository)

Based on surface characterisation, a construction and support concept will be designed, including alternative options to account for different stress regimes at the repository depth and the anticipated geomechanical conditions. A first test will involve the construction of the service area immediately after reaching the repository depth. During the construction of the facility and possibly thereafter, further concepts at the semi-industrial level can be tested if this is required (e.g. for the L/ILW waste repository).

8.2.3.3 Performance confirmation of the components

Seal test (major elements)

The major elements of a representative seal will be emplaced at reduced scale and sealing performance will be monitored. The size of the experiment will be selected taking into account the materials for the sealing element (e.g. sand/bentonite, pure bentonite) such that performance can be monitored (borehole size) within the available timeframe. This test has many similarities to the GAST experiment (Spillmann et al. 2015), which is a 1:1 scale experiment and thus larger than the performance test anticipated. While a representative bentonite sealing element will be considered in the facility for the HLW repository, which is also representative for certain seals in the L/ILW repository, a proxy for a sand/bentonite-based gas permeable seal is envisaged in the facility for underground geological investigations for the L/ILW repository. During this test the performance of the EDZ in contact with the sealing element will also be evaluated. Depending on the size of the experiment (which influences the saturation times), performance confirmation is expected to be acquired after 5 – 7 years. The experiments can also contribute to the confirmation of self-sealing (see above).

While major experimental results are anticipated to be available for the construction licence, certain further confirmation might be obtained in anticipation of the operating licence.

8.2.3.4 Demonstration

Demonstration of emplacement and retrievability of the HLW canister and L/ILW container

Once the technology for emplacement and retrieval is developed, in anticipation of the operating licence it will be demonstrated that this can be realised safely and according to the requirements in the subsurface environment. Both tests can be combined in one experiment if this is considered advantageous. The actual experiments will be preceded by a detailed testing programme in surface laboratories, first of the individual components and then of the entire experimental sequence to reduce the experimental risk underground.

- In the case of the canister for the HLW repository, the demonstration will include the emplacement of the pedestal with the canister and the granular bentonite using remote handling if the current concept is to be pursued. Retrieval will require removing the canister also by remote handling. It will be checked if all requirements are fulfilled.
- In the case of the container for the L/ILW repository, the demonstration will include the emplacement of the container and the filling of the open space with porous concrete if the current concept is to be pursued. Retrieval will require removing part of the porous concrete and the container. The feasibility demonstration of the emplacement of the L/ILW container is expected to be less complex as remote handling will not be required.

Demonstration of the construction feasibility of a seal

Demonstration of the construction feasibility of a seal at the 1:1 scale according to the requirements (to be defined at a later stage) is foreseen. Off-site surface-based testing is envisaged before conducting the experiment in the facility for underground geological investigations. Given adequate off-site preparation, this demonstration experiment can typically be completed in 1 – 2 years (as no long-term performance demonstration and thus full saturation is required).

It will be evaluated whether this demonstration can also ultimately contribute to performance confirmation of the sealing elements already foreseen at borehole scale as mentioned above.

A final activity that might require demonstration is the testing of emergency measures for operational safety (e.g. tunnel closure).

8.2.3.5 Monitoring

Monitoring will be an essential part of the construction and operation of facilities for underground geological investigations, with an eye on the development of the monitoring strategy for the pilot facility and the strategy for the construction, operation and closure of the repository. This also includes evaluation of next-generation instrumentation to support the objectives of the monitoring strategies.

8.2.4 Optimisation of the test programme and its timing

The test programme in the facilities for underground geological investigations needs to be optimised for the following reasons:

- The facility has limited space as construction of additional tunnels requires a significant effort and the repository area should be preserved
- Elevated levels of safety and QA will be imposed as the facility is likely to become part of a nuclear facility at a later stage
- The disturbance of the host rock (drilling, chemical substances, materials) should be kept to a minimum to preserve its barrier function
- The time schedule needs to be respected to be able to integrate the results into the safety case and feasibility assessment supporting the construction licence application.

Therefore, activities that can take place off-site (Mont Terri URL or surface laboratories) should be conducted off-site. Extensive off-site testing should also take place to reduce the risk of experimental failure in the facilities. This applies especially to the EBS testing and the emplacement and retrievability tests. Where possible, experiments will be combined to serve multiple objectives.

Important synergies can be expected in the case where the geologies for the facilities for underground geological investigations are similar; this concerns the rock characterisation programme and the testing of rock performance (both from a post-closure safety and an engineering point of view, including the sealing experiments).

An illustration of the sequence of activities in the facilities for underground geological investigations supporting the L/ILW repository and the HLW repository is shown in Tab. 8.1 and 8.2 respectively.

Tab. 8-1: Illustration of a potential test programme in the facility for underground geological investigations for the L/ILW repository.

This is based on the objectives defined above and the time planning as described in Nagra (2016a) and assumes the following conditions: geological expectations confirmed during the exploration shaft and service area construction, the facility can be constructed in two phases and experiments can be initiated concurrently with the construction of the second phase, the experiments confirm the anticipated results, the geology encountered in the facility shows little spatial variability and is representative for the entire repository.

| Date | Description | Experimental programme in this timeframe |
|---------------|--|---|
| 2032 – 2035 | Start of the construction of the facility by exploration shaft | <ul style="list-style-type: none"> - Initiation of the rock characterisation programme |
| Starting 2035 | Construction of the service area and the facility and initiation of a first series of experiments | <ul style="list-style-type: none"> - Enhanced characterisation of the relevant host rock properties and their spatial variability - Performance confirmation from a post-closure safety point of view, e.g. gas transport capacity, self-sealing load test - Monitoring |
| 2036 – 2044 | Finalisation of the construction of the facility and initiation of a second series of tests for the construction licence (submission 2041) | <ul style="list-style-type: none"> - Enhanced characterisation of the relevant host rock properties and their spatial variability - Tunnel/cavern construction (mine-by) and support confirmation - Performance confirmation from a post-closure safety point of view: self-sealing load test, mine-by - Performance confirmation of the sealing components - Demonstration of seal construction feasibility - Monitoring |
| 2045 – 2049 | Continuation of tests and new demonstration tests in anticipation of the nuclear operating licence (submission 2046) | <ul style="list-style-type: none"> - Demonstration of emplacement and retrieval - Monitoring - Testing of emergency measures for operational safety - Continue and/or conclude the above-mentioned tests |

Tab. 8-2: Illustration of a potential test programme in the facility for underground geological investigations for the HLW repository.

This is based on the objectives defined above and the time planning as described in Nagra (2016a) and assumes the following conditions: geological expectations confirmed during the exploration shaft and service area construction, the facility can be constructed in two phases and experiments can be initiated concurrently with the construction of the second phase, the experiments confirm the anticipated results, the geology encountered in the facility shows little spatial variability and is representative for the entire repository.

| Date | Description | Experimental programme in this timeframe |
|---------------|--|--|
| 2032 – 2037 | Start of the construction of the facility by exploration shaft | <ul style="list-style-type: none"> - Initiation of the rock characterisation programme |
| Starting 2035 | Construction of the service area and the facility and initiation of a first series of experiments | <ul style="list-style-type: none"> - Enhanced characterisation of the relevant host rock properties and their spatial variability - Performance confirmation from a post-closure safety point of view, e.g. gas transport capacity, self-sealing load test, diffusion test. - Monitoring |
| 2038 – 2048 | Finalisation of the construction of the facility and initiation of a second series of tests for the construction licence (submission 2045) | <ul style="list-style-type: none"> - Enhanced characterisation of the relevant host rock properties and their spatial variability - Tunnel/cavern construction (mine-by) and support confirmation - Performance confirmation from a post-closure safety point of view: self-sealing load test, mine-by, heater test - Performance confirmation of the sealing components - Demonstration of seal construction feasibility - Monitoring |
| 2044 – 2059 | Continuation of experiments and new demonstration experiments in anticipation of the nuclear operating licence (submission 2056) | <ul style="list-style-type: none"> - Demonstration of emplacement and retrieval - Monitoring - Testing of emergency measures for operational safety - Continue and/or conclude above-mentioned experiments |

8.3 RD&D supporting later stages in the programme

8.3.1 Activities supporting the construction licence

Once the general licence has been granted, the RD&D programme will focus on the activities required to support the construction licence.

Geological information

The construction of the facilities for underground geological investigations will allow subsurface characterisation for the first time, bringing a substantial gain in data to support and validate the geological models and datasets. A detailed rock characterisation programme starting with

the construction of the facility will be conducted (see section 8.2). Regarding the geomechanical behaviour at the site, hands-on excavation experience and instrumented (mine-by) testing in-situ will aid optimisation of the tunnelling and support construction.

Additional surface-based site investigations to be carried out after the granting of the general licence will provide a better understanding of the host rock mass geometry (e.g. the presence of disturbed zones that might affect the repository layout and construction procedure) and, to a minor extent, additional information concerning rock mechanical properties and in-situ stress.

The whole body of information will allow a further refinement of the site descriptive models.

Design and technology development

Demonstration of the tunnel design at full scale will take place in the facility for underground geological investigations. Also, the design of the liner will be finalised based on the in-situ characterisation of the rock performance. A prototype tunnel boring machine, tailored to the conditions encountered at the site, will be developed and tested.

The orientations of the horizontal stress magnitudes may impact on the final repository layout and the absolute values of the stress magnitudes may require adaptation of the support design planned prior to going underground. Detailed cavern and drift layout and support design will have to be adapted according to the results obtained.

The final canister design will be selected in anticipation of the construction licence. The materials and prototypes will be developed and tested at full scale.

Further testing and optimisation of backfilling materials, including their detailed characterisation, will also take place. However, the main principles and methods will have been established earlier. The backfilling technology will have to be designed for industrial application in a repository, involving a more robust design as well as further mechanisation of the backfilling process. The design will include a feeding device for buffer material supply in the emplacement drifts.

Once the container design and the handling requirements are established, appropriate tools for container handling in the surface and underground facilities will be developed and tested.

The emplacement of the HLW canisters and the buffer emplacement in the repository will have to be designed to allow for remote handling due to radiation protection requirements.

In anticipation of the construction licence, Nagra will develop a plan for the closure of the repository. In order to demonstrate the technical feasibility of implementing reliable long-term seals, sealing structures have to be designed, built and tested by means of full-scale demonstration experiments under realistic conditions. Feasibility demonstration of sealing and backfilling at full scale is foreseen in anticipation of the operating licence (see section 8.2).

Measures for temporary closure of the facility will be developed (feasibility of construction of temporary plugs with a performance of a few decades to a few centuries).

A detailed design for the surface facilities with the encapsulation facility, including the equipment and procedures, needs to be in place in line with operational safety requirements.

For the construction and operating licence, other aspects also need to be considered, including security, and, for the HLW repository the issue of safeguards. A concept for the preservation and transfer of information across generations as well as a concept for marking the disposal site will be developed.

Evolution of safety-relevant properties and processes in the near-field, the engineered barriers and compacted clay systems

The rock characterisation programme and the planned experiments in the facilities for underground geological investigations will allow confirmation of the safety-relevant properties and processes in the near-field. Extensive testing (see previous paragraphs) will aim at confirming understanding and refining the process models.

This includes repeating heater tests to confirm the observations and the overall assessment of the impact of the heat pulse on Opalinus Clay at the selected repository site. At this stage, the requirements (see Chapter 7) with respect to the maximum temperature allowed in the engineered barriers and the host rock and the maximum allowed overpressures can be re-confirmed and the thermal loading of the repository will be established (canister pitch).

Long-term monitoring of the deformation behaviour of the host rock will be performed during and after completion of the excavation of the facilities and specific EDZ-related experiments will be conducted.

By the time of the construction licence application, results from long-term in-situ corrosion experiments that will have been in place for 15 – 20 years will be available.

The interaction with the French programme will be further maintained. Before the submission of the construction licence application, a significant return of experience is expected from Andra, which will by then have concluded its pre-industrial testing phase and associated monitoring and started operation.

Safety assessment and operational safety

RD&D activities for post-closure safety assessment will continue as the repository projects progress in a stepwise manner. The final repository design will be based on the subsurface characterisation and testing in the facilities and will be subject to optimisation in terms of the layout and design. The safety concepts and assessment of potential accidents will need to be continuously updated in line with these developments, also taking into account any more general improvements in scientific and technical knowledge in Switzerland and internationally.

Concepts for monitoring

At the time of submission of the construction licence application, the monitoring strategy for the construction phase needs to be in place, including a description of the technology that will be used. It will have to be demonstrated that the objectives can be reached with the proposed technology.

The monitoring concept for the pilot facility, as well as for the operational and post-closure phases of the repository, will be further refined. The knowledge regarding the technologies that might be applied for these will be progressively deepened and the approach developed in more detail.

8.3.2 Activities supporting the operating licence

The safety case will be refined again in anticipation of the operating licence. This is likely to require RD&D activities driven by experience derived from test programmes, new technological developments and questions formulated by the regulator.

The constructability of the sealing elements will be demonstrated and the return of experience will feed into the specification and refinement of the construction method.

Technology for emplacement and retrieving will be developed before submitting the construction licence application and demonstration of emplacement and retrievability will be performed in the period prior to the repository operating licence.

Innovative mechanised procedures will be considered with the aim of enhancing working safety and optimising construction efficiency as well as the expected performance of the sealing and backfilling structures.

8.3.3 Licence for closure of the repositories

Finally, monitoring in the pilot facility, after construction has started, aims at providing the confirmation of the performance of the engineered barriers during the entire construction phase up to the closure of the repository.

The closure concept including the sealing and backfilling of the main tunnels will be assessed again in anticipation of the licence for closure foreseen for the next century.

It is clear that the activities described in Chapter 8 can only be a broad indication of the RD&D programme lying ahead, as the repository programme is expected to adapt to future developments (of scientific or societal nature) during the current and following generations.

9 References

- Atomic Act (1959), further elaborated in the Federal Government Ruling on the Atomic Act (1978) and the Radiation Protection Act (StSG 1991).
- Ababou, R., Fatmi, H., Matray, J.M., Nussbaum, C. & Bailly, D. (2012): Statistical Analyses of Pore Pressure Signals in Claystone During Excavation Works at the Mont Terri Underground Research Laboratory. Chap. 17 in "Radioactive Waste", InTech – Open Access Publisher (<http://www.intechweb.org>), ISBN: 979-953-307-274-5, 2012, 373-430.
- Abrahamson, N.A., Coppersmith, K.J., Koller, M., Roth, Ph., Sprecher, C., Toro, G.R. & Youngs, R. (2004): Probabilistic Seismic Hazard Analysis for Swiss Nuclear Power Plant Sites (PEGASOS Project). Final Report, Vol. 1, UAK/UeW, Bern, 358 p.
- Aimoz, L., Kulik, D.A., Wieland, E., Curti, E., Lothenbach, B. & Maeder, U. (2012): Thermodynamics of AFm-(I₂,SO₄) solid solution and its end-members in aqueous media. *Appl. Geochem.* 27/10, 2117-2129.
- Alcolea, A., Kuhlmann, U., Lanyon, G.W. & Marschall, P. (2014): Hydraulic conductance of the EDZ around underground structures of a geological repository for radioactive waste – A sensitivity study for the candidate host rocks in the proposed siting regions in Northern Switzerland. Nagra Working Report NAB 13-94.
- Alcolea, A., Kuhlmann, U., Marschall, P., Lisjak, A., Grasselli, G., Mahabadi, O., de La Vaissière, R., Leung, H. & Shao, H. (*in prep.*): A pragmatic approach to abstract the EDZ around tunnels of a geological radioactive waste repository – Application to the HG-A experiment in Mont Terri. Geological Society, London, Special Publications.
- Alcoverro, J., Arnedo, D., Olivella, S. & Alonso, E.E. (2013): Simulation results of the HG-A test. D4.23 Final report – simulation results (HG-A). FORGE EU-FP7 PROJECT.
- Akçar, N., Ivy-Ochs, S., Alfimov, V., Claude, A., Graf, H.-R., Dehnert, A., Kubik, P.W., Rahn, M., Kuhlemann, J. & Schlüchter, C. (2014): The first major incision of the Swiss Deckenschotter landscape. *Swiss Journal of Geosciences*, 107/2, 337-347, DOI 10.1007/s00015-014-0176-6.
- Andersson, J., Skagius, K., Winberg, A., Lindborg, T. & Ström, A. (2013): Site-descriptive modelling for a final repository for spent nuclear fuel in Sweden. *Environ. Earth Sci.* 69, 1045-1060. DOI 10.1007/s12665-013-2226-1.
- Andra (2005): Dossier 2005: Référentiel des matériaux d'un stockage de déchets à haute activité et à vie longue. Tome 1: Matériaux à base d'argiles gonflantes. Collection les rapports. Andra, Châtenay-Malabry, 2005.
- Apted, M. (2014): Workshop on general corrosion of copper. SSM Technical Note 2014-43. Strål Säkerhets Myndigheten, Sweden.
- Aranyossy, J.F., Mayor, J.C., Marschall, P., Plas, F., Blumling, P., Van Geet, M., Armand, G., Techer, I., Alheid, A.J., Rejeb, A., Pinettes, P., Balland, C., Popp, T., Rothfuchs, T., Matray, J.M., De Craen, M., Wieczorek, K., Pudewills, A., Czaikowski, O., Hou, Z. & Fröhlich, H. (2008): EDZ Development and Evolution (RTDC 4) – Final Synthesis Report (D. 4.5.3). FP6-EURATOM/NF-PRO, F16W-CT-2003-02389.

- ARE (2010): Raumplanerische Beurteilungsmethodik für den Standortvergleich in Etappe 2: Methodik für die sozioökonomisch-ökologische Wirkungsstudie SÖW. Schlussbericht von ECOPLAN im Auftrag des Bundesamtes für Energie (BFE) und des Bundesamtes für Raumentwicklung (ARE). UVEK, Bern.
- Areva (2010): Spaltgasfreisetzungsdaten aus dem Kernkraftwerk Gösgen für Studien zur Endlagerung abgebrannter Brennelemente. Nagra Working Report NAB 10-32.
- Areva (2012): Spaltgasfreisetzungsdaten aus dem Kernkraftwerk Beznau, Block 1 und 2 für Studien zur Endlagerung abgebrannter Brennelemente. Nagra Working Report NAB 12-01.
- Armand, G., Noiret, A., Zghondi, J. & Seyedi, D.M. (2013): Short- and long-term behaviors of drifts in the Callovo-Oxfordian Claystone at the Meuse/Haute-Marne Underground Research Laboratory. *Journal of Rock Mechanics and Geotechnical Engineering* 5/3 (June): 221-230. doi:10.1016/j.jrmge.2013.05.005.
- Armand, G., Leveau, F., Nussbaum, C., Vaissiere, R., Noiret, A., Jaeggi, D. & Righini, C. (2014): Geometry and properties of the excavation-induced fractures at the Meuse/Haute-Marne URL drifts. *Rock Mechanics and Rock Engineering* 47/1, 21-41. doi:10.1007/s00603-012-0339-6.
- Arvidsson, A., Josefsson, P., Eriksson, P., Torbjörn, S. & Ojala, M. (2015): System design of backfill – Project results. SKB Technical Report TR-14-20. Svensk Kärnbränslehantering AB, Stockholm.
- Axpo (2015): Langzeitstabilität von abgebrannten Brennelementen während der Zwischenlagerung. Axpo Technical Report BT-KN-T 0070.
- Baeyens, B. & Bradbury, M.H. (1997): A mechanistic description of Ni and Zn sorption on Na-montmorillonite. Part I: Titration and sorption measurements. *J. Cont. Hydrol.* 27, 199-222.
- Baeyens, B., Thoenen, T., Bradbury, M.H. & Marques Fernandes, M. (2014a): Sorption data bases for argillaceous rocks and bentonite for the Provisional Safety Analyses for SGT-E2. Nagra Tech. Rep. NTB 12-04.
- Baeyens, B., Marques Fernandes, M. & Bradbury, M.H. (2014b): Comparison of sorption measurements on argillaceous rocks and bentonite with predictions using the SGT-E2 approach to derive sorption data bases. Nagra Tech. Rep. NTB 12-05.
- Bagnoud, A. (2015): Microbial metabolism in the deep subsurface; case study of Opalinus Clay. Ph.D. Thesis, EPFL Lausanne (<http://dx.doi.org/10.5075/epfl-thesis-6727>).
- Bagnoud, A., de Brujin, I., Andersson, A.F., Diomidis, N., Leupin, O.X., Schwyn, B. & Bernier-Latmani, R. (2016a): A minimalistic microbial food web in an excavated deep subsurface clay rock. *FEMS Microbiology Ecology* 92/1, fiv138 (<http://dx.doi.org/10.1093/femsec/fiv138>).
- Bagnoud, A., Leupin, O.X., Schwyn, B. & Bernier-Latmani, R. (2016b): Rates of microbial hydrogen oxidation and sulfate reduction in Opalinus Clay rock. *Applied Geochemistry* 72, 42-50.

- Bagnoud, A., Chourey, K., Hettich, R.L., de Bruijn, I., Andersson, A.F., Leupin, O.X., Schwyn, B. & Bernier-Latmani, R. (*in press*): Reconstructing a hydrogen-driven microbial metabolic network in Opalinus Clay rock. *Accepted by Nature Communications*.
- Bare, W.C. & Torgerson, L.D. (2001): Dry Cask Storage Characterization Project – Phase 1: CASTOR V/21 Cask Opening and Examination, INEEL/EXT-01-00183 Rev.1.
- Baroux, C. (2013): Summary report of the preliminary feasibility study for ceramic HLW over-packs (2007-2012). Andra CG.NT.ASCM.13.0004.
- Bart, G., Zwicky, H.U., Aerne, E.T., Graber, Th., Z'Berg, D. & Tokiwai, M. (1987): Borosilicate glass corrosion in the presence of steel corrosion products. Mat. Res. Soc. Symp. Proc. 84, 459-470.
- Bashkaran, G., Carcea, A., Ulaganathan, J., Wang, S., Huang, Y. & Newman, R.C. (2012): Fundamental aspects of stress corrosion cracking of copper relevant to the Swedish deep geologic repository concept. SKB Technical Report TR-12-06. Svensk Kärnbränslehantering AB, Stockholm.
- Bastid, P., Blackwell, S. & Punshon, C. (2015): Finite element stress analyses of copper-coated Nagra BWR Spent Fuel Canister with partially penetrating weld detail under circumferentially variable swelling pressure. Nagra Working Report NAB 15-18.
- Beaud, F. & Flowers, G.E. (2015): Implementation of glaciofluvial erosion and sediment transport processes in models of subglacial hydrology. Nagra Working Report NAB 15-19.
- Beaud, F., Flowers, G.E. & Pimentel, S. (2014): Seasonal-scale abrasion and quarrying patterns from a two-dimensional ice-flow model coupled to distributed and channelized subglacial drainage. Geomorphology 219, 176–191.
- Beaud, F., Flowers, G.E. & Venditti, J.G. (2016): Efficacy of bedrock erosion by subglacial water flow. Earth Surface Dynamics 4, 125-145. doi:10.5194/esurf-4-125-2016.
- Becker, J.K., Lindborg, T. & Thorne, M.C. (2014): Influence of climate on landscape characteristics in safety assessments of repositories for radioactive wastes. Journal of Environmental Radioactivity 138, 192-204.
- Behl, M. & Bunge, R. (2016): Abschlussbericht DENSFILL. Nagra Working Report NAB 15-11.
- Berner, U. (1995): Kristallin-I: Estimates of solubility limits for safety relevant radionuclides. Nagra Tech. Rep. NTB 94-08.
- Berner, U. (2009): Modelling hydrated HTS cement and its pore water. PSI Internal Document, AN 44-09-10. Paul Scherrer Institute, Villigen.
- Berner, U. (2014a): Solubility of radionuclides in a bentonite environment for provisional safety analysis for SGT-E2. Nagra Tech. Rep. NTB 14-06.
- Berner, U. (2014b): Solubility of radionuclides in a concrete environment for provisional safety analysis for SGT-E2. Nagra Tech. Rep. NTB 14-07.

- Berner, U., Kulik, D.A. & Kosakowski, G. (2013): Geochemical impact of a low-pH cement liner on the near field of a repository for spent fuel and high-level radioactive waste. *Physics and Chemistry of the Earth, Parts A/B/C* 64, 46-56.
- Bernier, F., Li, X.L., Bastiaens, W., Ortiz, L., Van Geet, M., Wouters, L., Frieg, B., Blümling, P., Desrues, J., Viaggiani, G., Coll, C., Chancholle, S., De Greef, V., Hamza, R., Malinsky, L., Vervoort, A., Vanbrabant, Y., Debecker, B., Verstraelen, J., Govaerts, A., Wevers, M., Labiouse, V., Escoffier, S., Mathier, J.-F., Gastaldo, L. & Bühl, C. (2007): Fractures and Self-healing within the Excavation Disturbed Zone in Clays (SELFRACT). Final report, Euratom 5th Framework Programme, Contract No: FIKW-CT2001-00182. Euridice Report, EUR 22585.
- Biaggi, D., Rust, S., Montani, S. & Wüthrich, E. (2014): Sachplan geologische Tiefenlager – Etappe 2: Standortspezifische Baugrundmodelle für die Zugangsbauwerke. Geologische Profile nach SIA 199 (Rampen und Schächte). Nagra Working Report NAB 14-72.
- BIOCLIM (2003): Simulation of the future evolution of the biosphere system using the integrated strategy: Continuous climate evolution scenarios over western Europe (1000 km scale). Deliverable D7 available on www.andra.fr/bioclim
- Birkhäuser, Ph., Roth, Ph., Meier, B. & Naef, H. (2001): 3-D Seismik: Räumliche Erkundung des mesozoischen Sedimentschichten im Zürcher Weinland. Nagra Tech. Report NTB 00-03.
- Bläsi, H.R., Deplazes, G., Schnellmann, M. & Traber, D. (2013): Sedimentologie und Stratigraphie des 'Braunen Doggers' und seiner westlichen Äquivalente. Nagra Working Report NAB 12-51.
- Blechschnitt, I. & Vomvoris, S. (2015): The fourth decade of underground research at the Grimsel Test Site – What we have learned and where we go from here. WMSYM WM2015 Conference "Achieving Results through Technology and Innovation on a Global Scale" March 15-19, 2015, Phoenix, AZ, 7, Paper 15075.
- Bleyen, N., Smets, S., Small, J., Moors, H., Leys, N., Albrecht, A., de Cannière, P., Schwyn, B., Wittebroodt, C. & Valcke, E. (2017). Impact of the electron donor on in situ microbial nitrate reduction in Opalinus Clay. *Swiss Journal of Geosciences* (submitted).
- Bock, H., Dehandschutter, B., Martin, C.D., Mazurek, M., de Haller, A., Skoczylas, F. & Davy, C. (2010): Self-sealing of fractures in argillaceous formations in the context of geological disposal of radioactive waste – Review and synthesis. OECD/NEA 6184. OECD Nuclear Energy Agency, Paris, 310 pp.
- Boldini, D., Graziani, A. & Ribacchi, R. (2004): Raticosa Tunnel, Italy: Characterization of tectonized clay-shale and analysis of monitoring data and face stability. *Soils and Foundations* 44/1, 57-69. Japanese Geotechnical Society.
- Bolliger, T., Fejfar, O., Graf, H. & Kälin, D. (1996): Vorläufige Mitteilung über Funde von pliozänen Kleinsäugern aus den Höheren Deckenschottern des Irchels (Kt. Zürich). *Eclogae Geol. Helv.* 89, 1043-1048.

- Bollingerfehr, W., Herold, P., Dörr, S. & Filbert, W. (2014): Auswirkungen der Sicherheitsanforderung Rückholbarkeit auf existierende Einlagerungskonzepte und Anforderungen an neue Konzepte. Abschlussbericht der DBE Technology GmbH (DBETec), Peine (D), vom Februar 2014. Kommission Lagerung hoch radioaktiver Abfallstoffe K-MAT 24 c.
- Bosgiraud, J., Plas, F., Foin, R. & Armand, G. (2014): Demonstration of Plugs and Seals. The FSS Experiment (Full Scale Seal). DOPAS Deliverable D7.9 – Experiment poster of FSS with EC acknowledgements at the Saint Dizier (France).
- Bossart, P. & Thury, M. (eds.) (2008): Mont Terri Rock Laboratory – Project, Program 1996 to 2007 and Results. Reports of the Swiss Geological Survey No. 3. Swiss Geological Survey, Wabern.
- Bossart, P., Meier, P.M., Moeri, A., Trick, T. & Mayor, J.C. (2002): Geological and hydraulic characterization of the excavation disturbed zone in the Opalinus Clay of the Mont Terri Rock Laboratory. *Engineering Geology* 66, 19-38.
- Boyle, C. H. and S. A. Meguid. 2015. Mechanical performance of integrally bonded copper coatings for the long term disposal of used nuclear fuel. *Nucl. Eng. Des.*, 293, 403–412.
- Bradbury, M.H. & Baeyens, B. (1997a): Far-field sorption data bases for performance assessment of a L/ILW repository in an undisturbed Palfris marl host rock. PSI Report No. 97-15 and Nagra Tech. Rep. NTB 96-05.
- Bradbury, M.H. & Baeyens, B. (1997b): A mechanistic description of Ni and Zn sorption on Na-montmorillonite. Part II: Modelling. *J. Cont. Hydrol.* 27, 223-248.
- Bradbury, M.H. & Baeyens, B. (2003): Far-field sorption data bases for performance assessment of a HLW repository in an undisturbed Opalinus Clay host rock. PSI Report No. 03-08 and Nagra Tech. Rep. NTB 02-19.
- Bradbury, M.H. & Baeyens, B. (2006): A quasi-mechanistic non-electrostatic modelling approach to metal sorption on clay minerals. Chapter 19 in: Lützenkirchen, J. (ed.): Surface Complexation Modelling. Elsevier series, Interface Science and Technology 11, 518-538.
- Bradbury, M.H. & Baeyens, B. (2009a): Sorption modelling on illite. Part I: Titration measurements and the sorption of Ni, Co, Eu and Sn. *Geochim. Cosmochim. Acta* 73, 990-1003. doi:10.1016/j.gca.2008.11.017
- Bradbury, M.H. & Baeyens, B. (2009b): Sorption modelling on illite. Part II: Actinide sorption and linear free energy relationships. *Geochim. Cosmochim. Acta* 73, 1004-1013. doi:10.1016/j.gca.2008.11.016
- Bradbury, M.H. & Baeyens, B. (2011): Predictive sorption modelling of Ni(II), Co(II), Eu(III), Th(IV) and U(VI) on MX-80 bentonite and Opalinus Clay: A "bottom-up" approach. *Appl. Clay Sci.* 52, 27-33.
- Bradbury, M.H. & Sarott, F.A. (1994): Sorption databases for the cementitious near-field of a L/ILW repository for performance assessment. Nagra Tech. Rep. NTB 93-08.

- Bradbury, M.H. & Van Loon, L.R. (1997): Cementitious near-field sorption data bases for performance assessment of a L/ILW repository in a Palfris Marl host rock: CEM-94: Update 1, June 1996. Nagra Tech. Rep. NTB 96-04.
- Bradbury, M.H., Baeyens, B. & Thoenen, T. (2008): Sorption data bases for generic Swiss argillaceous, crystalline and calcareous rock systems. Nagra Working Report NAB 08-50.
- Bradbury, M.H., Baeyens, B. & Thoenen, T. (2010): Sorption data bases for generic Swiss argillaceous rock systems. Nagra Tech. Rep. NTB 09-03.
- Bradbury, M.H., Berner, U., Curti, E., Hummel, W., Kosakowski, G. & Thoene, T. (2014): The long term geochemical evolution of the nearfield of the HLW repository. Nagra Tech. Rep. NTB 12-01.
- Brandefelt, J., Näslund, J.-O., Zhang, Q. & Hartikainen, J. (2013): The potential for cold climate conditions and permafrost in Forsmark in the next 60'000 years. SKB Technical Report TR 13-04. Svensk Kärnbränslehantering AB, Stockholm.
- Breen, B.J., García-Siñeriz, J.L., Maurer, H., Mayer, S., Schröder, T.J., Verstricht, J. (2012): EC MoDeRn Project: In-situ Demonstration of Innovative Monitoring Technologies for Geological Disposal. Conference Proceedings of WM2012 Conference in Phoenix.
- Bucher, F. & Müller-Vonmoos, M. (1989): Bentonite as a containment barrier for the disposal of highly radioactive wastes. Applied Clay Science 4, 157-177.
- Bucher, F. & Spiegel, U. (1984): Quelldruck von hochverdichteten Bentoniten. Nagra Tech. Rep. NTB 84-18.
- Burrus, F., Bossart, P. & Nussbaum, C. (2010): Gallery 08: Documentation of the excavation and the convergence measurements. Unpubl. Mont Terri Technical Note. Mont Terri Project, Switzerland.
- Carbol, P., Fors, P., Gouder, T. & Spahiu, K. (2009): Hydrogen suppresses UO₂ corrosion. Geochim. Cosmochim. Acta 73, 4366-4375.
- Cartwright P.B. (1997): A review of recent in-situ stress measurements in United Kingdom Coal Measures strata.- Proceedings International Symposium on Rock Stress, Kumamoto, K. Sugawara and Y. Obara, editors, A. A. Balkema, Rotterdam, 469–474.
- Caruso, S. (2016): Estimation of the radionuclide inventories in LWR spent fuel assembly structural materials for long-term safety analysis. Top Fuel 2015, EPJ Nuclear Sci. Technol. 2, 4.
- Caruso, S. & Jatuff, F. (2014): Design, development and utilisation of a tomography station for γ -ray emission and transmission analyses of light water reactor spent fuel rods. Progress in Nuclear Energy 72, 49-54.
- Caruso, S. & Panadero, A.L. (2014): Development and validation of Ad Hoc ORIGEN-ARP libraries for very high burnup UO₂ PWR fuel with SCALE/TRITON. Physor 2014, October 3, 2014.

Caruso, S., Meleshyn, A. & Noseck, U. (2015): Estimation and comparison of the radionuclide inventories in vitrified high-level wastes from reprocessing plant. E-MRS 2015, Progress in Nuclear Energy <http://dx.doi.org/10.1016/j.pnucene.2015.11.003>

CAST (2016): www.projectcast.eu

CEBAMA (2016): Cement-based materials, properties, evolution, barrier functions. EC Horizon 2020 collaborative project, grant agreement No. 662147. <http://www.cebama.eu/>

Chang, C., Zoback, M.D. & Khaksar, A. (2006): Empirical relations between rock strength and physical properties in sedimentary rocks. Journal of Petroleum Science and Engineering 51, 223-237.

Churakov, S.V. & Daehn, R. (2012): Zinc adsorption on clays inferred from atomistic simulations and EXAFS spectroscopy. Environ. Sci. Technol. 46, 5713-5719.

Churakov, S.V., Gimmi, T., Unruh, T., Van Loon, L.R. & Juranyi, F. (2014): Resolving diffusion in clay minerals at different time scales: Combination of experimental and modeling approaches. Appl. Clay Sci. 96, 36-44.

Claude, A., Akçar, N., Ivy-Ochs, S., Schlunegger, F., Kubik, P., Rahn, M., Dehnert, A. & Schlüchter, C. (2014): Timing of Early and Middle Pleistocene glaciations in the Alps. Abstract Swiss Geoscience Meeting 2014, Fribourg. 232-233.

Cloet, V., Schwyn, B. & Wieland, E. (2014): Geochemische Nahfeld-Daten zu den SMA und ATA für die provisorischen Sicherheitsanalysen in SGT Etappe 2. Nagra Working Report NAB 14-52_Rev.1.

Cloet, V., Fries, T., Wetzig, V. (2016): SR-Experiment: Low pH shotcrete for rock support and synthesis report. Mont Terri Technical Report TR 2011-06. In Preparation

Cohen, D. (2015): Ice Flow Dynamics over Switzerland around the Last Glacial Maximum. Nagra Working Report NAB 15-22.

Croisé, J., Mayer, G., Marschall, P., Matray, J.-M., Tanaka, T. & Vogel, P. (2006): Gas Threshold Pressure Test Performed at the Mont Terri Rock Laboratory (Switzerland): Experimental Data and Data Analysis. Revue de l'Institut Français du Pétrole 61/5, 631-645.

Cuevas, J., Ruiz, A.L. & Fernandez, R. (2013): Comparison of alternative bentonites for potential use as buffer and sealing materials in the Swiss concept for radioactive waste disposal – Part 1: Methodology. Nagra Working Report NAB 13-69.

Cuevas, J., Fernandez, R., Ortega, A. & Ruiz, A.I. (2014): Comparison of alternative bentonites for potential use as buffer and sealing materials in the Swiss concept for radioactive waste disposal – Part 2: Results. Nagra Working Report NAB 14-65.

Cummings, A.D. Krywonos, J., Purcell, P., Rothwell, G., English, R. (2012): An experimental procedure for measuring accelerations and strains from a tie down system of a heavy nuclear transport package during a rail journey, Packaging, Transport, Storage & Security of Radioactive Material 23/ 3-4, 167-177.

- Curti, E. (2003): Glass dissolution parameters: Update for Entsorgungsnachweis. PSI-Report Nr. 03-18, Villigen and Nagra Tech. Rep. NTB 02-21.
- Curti, E. & Smith, P.A. (1991): Enhancement of borosilicate glass dissolution by silica sorption and diffusion in compacted bentonite: a model study". Scientific Basis for Nuclear Waste Management XIV, Mat. Res. Soc. Proc. 212, 31-39. Materials Research Society, Boston.
- Curti, E., Godon, N. & Vernaz, E.Y. (1993): Enhancement of the glass corrosion in the presence of clay minerals: testing experimental results with an integrated glass dissolution model. Scientific Basis for Nuclear Waste Management XVI, Mat. Res. Soc. Proc. 294, 163-170. Materials Research Society, Boston.
- Curti, E., Daehn, R., Farges, F. & Vespa, M. (2009): Na, Mg, Ni and Cs distribution and speciation after long-term alteration of a simulated nuclear waste glass: A micro-XAS/XRF/XRD and wet chemical study. Geochim. Cosmochim. Acta 73, 2283-2298.
- Curti, E., Fukiwara, K., Iijima, K., Tits, J., Cuesta, C., Kitamura, A., Glaus, M.A. & Mueller, W. (2010): Radium uptake during barite recrystallization as a function of solution composition at 23 ± 2 °C: An experimental ^{133}Ba and ^{226}Ra tracer study. Geochim. Cosmochim. Acta 74, 3553-3570.
- Curti, E., Froideval-Zumbiehl, A., Günther-Leopold, I., Martin, M., Bullemer, A., Linder, H., Borca, C.N. & Grolimund, D. (2014): Selenium redox speciation and coordination in high-burnup UO_2 fuel: Consequences for the release of ^{79}Se in a deep underground repository. J. Nucl. Mater. 453, 98-106.
- Cuss, R.J., Milodowski, A. & Harrington, J.F. (2011): Fracture transmissivity as a function of normal and shear stress: First results in Opalinus clay. Physics and Chemistry of the Earth. 36, 1960-1971.
- Daehn, R., Baeyens, B. & Bradbury, M.H. (2011): Investigation of the different binding edge sites for Zn on montmorillonite using P-EXAFS – the strong/weak site concept in the 2SPNE SC/CE sorption model. Geochim. Cosmochim. Acta 75, 5154-5168.
- Daehn, R., Arakcheeva, A., Schaub, Ph., Pattison, P., Chapuis, G., Grolimund, D., Wieland, E. & Leemann, A. (2016): Application of micro X-ray diffraction to investigate the reaction products formed by the alkali-silica reaction in concrete structures. Cement and Concrete Research 79, 49-56.
- Daneluzzi, R., Burrus, F., Küttel, T., Müller, H.R. & Köhler, S. (2014): Construction of the Emplacement Tunnel for the Full-scale Emplacement (FE) Experiment at Mont Terri Rock Laboratory. Nagra Working Report NAB 14-54.
- Daumas, S., Labat, M. & Lasne, E (2014): HT (Hydrogen Transfer) Experiment: Molecular study and classical microbiological analyses. Unpubl. Mont Terri Technical Note. Mont Terri Project, Switzerland.
- Dehnert, A., Lowick, S.E., Preusser, F., Anselmetti, F.S., Drescher-Schneider, R., Graf, H.R., Heller, F., Horstmeyer, H., Kemna, H.A., Nowaczyk, N.R., Züger, A. & Furrer, H. (2012): Evolution of an overdeepened trough in the northern Alpine Foreland at Niederweningen, Switzerland. Quaternary Science Reviews 34, 127-145.

- Delepine-Lesoille, S., Bertrand, J., Pilorget, G., Farhoud, R., Buschaert, S., Vogt, T. & Verstricht, J. (2015): Monitoring natural and engineered clay in geological repository with optical fiber sensors – Lessons learnt from large scale experiments. Paper in: Proceedings of the CLAY conference 'Clays in Natural and Engineered Barriers for Radioactive Waste Confinement', Brussels, 131-132.
- Deplazes, G., Bläsi, H.R., Schnellmann, M. & Traber, D. (2013): Sedimentologie und Stratigraphie der Effinger Schichten. Nagra Working Report NAB 13-16.
- Dilnesa, B.Z., Lothenbach, B., Le Saout, G., Renaudin, G., Mesbah, A., Filinchuk, Y., Wichser, A. & Wieland, E. (2011): Iron in carbonate containing AFm phases. Cement and Concrete Research 41, 311-323.
- Dilnesa, B.Z., Lothenbach, B., Renaudin, G., Wichser, A. & Kulik, D. (2014): Synthesis and characterization of hydrogarnet $\text{Ca}_3(\text{Al}_x\text{Fe}_{1-x})_2(\text{SiO}_4)_y(\text{OH})_{4(3-y)}$. Cement and Concrete Research 59, 96-111.
- Diomidis, N. (2014): Scientific basis for the production of gas due to corrosion in a deep geological repository. Nagra Working Report. NAB 14-21.
- Diomidis, N. & Johnson, L. (2014): Materials options and corrosion-related considerations in the design of spent fuel and high-level waste disposal canisters for a deep geological repository in Opalinus Clay. JOM, The Journal of The Minerals, Metals & Materials Society 66, 461-470.
- Diomidis, N., Johnson, L., Patel, R., Punshon, C. & King, F. (2012): Corrosion considerations in the design of a canister for the disposal of SF and HLW in deep geological repositories. In: Book of abstracts of the European Corrosion Congress (Eurocorr 2012), September 9 – 13, Istanbul, Turkey, 342.
- Diomidis, N., Cloet, V., Leupin, O.X., Marschall, P., Poller, A. & Stein, M (2016): Production, consumption and transport of gases in deep geological repositories according to the Swiss disposal concept. Nagra Tech. Rep. NTB 16-03.
- Dixon, D.A., Martino, J.B. & Onagi, D.P. (2009): Enhanced Sealing Project (ESP) Design, Construction and Instrumentation Plan – APM-REP-01601-0001. Nuclear Waste Management Organisation (NWMO), Canada.
- Dolder, F.D. (2015): Experimental characterization and quantification of cement-bentonite interaction using core infiltration techniques coupled with X-ray tomography. Dissertation, Institut für Geologie, Philosophisch-naturwissenschaftliche Fakultät Universität Bern.
- Dupray, F. & Laloui, L. (2016): Numerical analysis of canister movements in an engineered barrier system. Acta Geotechnica 11/1, 145-159.
- Ebert, A. (2014): Strukturgeologische Kernaufnahmen der Wirtgesteine aus Tiefbohrungen der Nordschweiz. Nagra Working Report NAB 13-89.
- Egli, D., Madritsch, H., Ibele, T., Mosar, J. & Vietor, T. (2014): Stress & strain around a multiply reactivated deep-seated fault zone and its impact on a potential geothermal reservoir – The Freiburg-Bonndorf-Bodensee fault zone. Geophysical Research Abstracts 16, EGU2014-10375, EGU General Assembly 2014.

Eisenlohr, T., Müller, P. & Laws, S. (2014): Geotechnische Beschreibung der oberflächennahen Zugangstunnelabschnitte basierend auf den Planungsstudien der Oberflächenanlagen. Nagra Working Report NAB 14-100.

ENSI (2009): Specific design principles for deep geological repositories and requirements for the safety case. Guideline for Swiss Nuclear Installations ENSI-G03/e. Swiss Federal Nuclear Safety Inspectorate (ENSI), Brugg.

ENSI (2010): Strahlenschutzziele für Kernanlagen. Richtlinie für die schweizerischen Kernanlagen ENSI-G15. Swiss Federal Nuclear Safety Inspectorate (ENSI), Brugg.

ENSI (2011): Sicherheitstechnische Klassierung für bestehende Kernkraftwerke – Richtlinie für die schweizerischen Kernanlagen. ENSI-G01, Januar 2011. Swiss Federal Nuclear Safety Inspectorate (ENSI), Brugg.

ENSI (2013): Arbeitstreffen KNS-ENSI zum Umgang mit Empfehlungen. Aktennotiz. ENSI 33/305 (Juli 2013). Swiss Federal Nuclear Safety Inspectorate (ENSI), Brugg.

ENSI (2015a): Auslegung und Betrieb von Lagern für radioaktive Abfälle und abgebrannte Brennelemente. Ausgabe September 2010, Revision 2 vom 30. Juni 2015. Richtlinie für die schweizerischen Kernanlagen ENSI-G04. Swiss Federal Nuclear Safety Inspectorate (ENSI), Brugg.

ENSI (2015b): Nachforderung zum Indikator "Tiefenlage im Hinblick auf bautechnische Machbarkeit" in Etappe 2 SGT. Aktennotiz 33/476. Eidgenössisches Nuklearsicherheitsinstitut ENSI, Brugg.

ENSI (2015c): Abfallbewirtschaftung im Vergleich. Forschungsprogramm "Radioaktive Abfälle" der Arbeitsgruppe des Bundes für die nukleare Entsorgung. Projektbericht. ENSI 33/188 (Februar 2015). Swiss Federal Nuclear Safety Inspectorate (ENSI), Brugg.

ENSI (2015d): Reaktorkern, Brennelemente und Steuerelemente: Auslegung und Betrieb. Richtlinie G20. Swiss Federal Nuclear Safety Inspectorate (ENSI), Brugg.

Eriksson, P. (2014): Basic Engineering of buffer production system, SKB Report P-14-11.

Favero, V. (*in prep.*): Multiphysical behaviour of shales. PhD EPFL.

Favero, V., Ferrari, A. & Laloui, L. (2013): Diagnostic analyses of the geomechanical database from cores of the Borehole Schlattingen SLA-1. Nagra Working Report NAB 13-45.

Favero, V., Ferrari, A. & Laloui, L. (2016): On the hydro-mechanical behaviour of reconstituted and natural Opalinus Clay Shale. *Engineering Geology* 208, 128-135.

Fälth, B., Hökmark, H. & Munier, R. (2010): Effects of large earthquakes on a KBS-3 repository. Evaluation of modelling results and their implications for layout design. SKB Technical Report TR-08-11, Stockholm,

Feist-Burkhardt, S. (2012): Palynostratigraphie des Mittleren Jura: Teil I – Bohrungen Benken, Schlattingen-1 und Weiach sowie einige Aufschlussproben der Lägern und deren Korrelation, Teil II – Bohrung Riniken, Aufschlussproben Bernhardholz, Dangstetten und Lägern. Nagra Working Report NAB 12-57.

- Feist-Burkhardt, S. & Pross, J. (2010): Dinoflagellate cyst biostratigraphy of the Opalinuston Formation (Middle Jurassic) in the Aalenian type area in southwest Germany and north Switzerland. *Lethaia* 43, 10-31.
- Feng, X., Bates, J.K., Buck, E.C., Bradley, Ch.R. & Gong, M. (1993): Long-term comparison of dissolution behavior between fully radioactive and simulated nuclear waste glasses. *Nucl. Technol.* 104, 193-206.
- Ferrari, A., Gruaz, G., Salager, S., Laloui, L. (2010): HA-Experiment – Analysis of the Opalinus Clay self sealing: experimental investigations (swelling tests). Mont Terri Technical Note TN 08-45rev..
- Ferrari, A. & Laloui, L. (2013) Advances in the testing of the hydro-mechanical behaviour of shales. In: *Multiphysical Testing of Soils and Shales*. Springer, pp. 57-68.
- Ferrari, A., Favero, V., Manca, D. & Laloui, L. (2012): Geotechnical characterization of core samples from the geothermal borehole Schlattingen SLA-1 by LMS/EPFL. Nagra Working Report NAB 12-50.
- Ferrari, A., Seiphoori, A., Rüedi, J. & Laloui, L. (2014a): Shot-clay MX-80 bentonite: An assessment of the hydro-mechanical behaviour. *Engineering Geology* 173, 10-18.
- Ferrari, A., Favero, V., Marschall, P. & Laloui, L. (2014b): Experimental analysis of the water retention behaviour of shales. *Inter. J. Rock. Mech. Min. Sci.* 72, 61-70.
- Ferrière, Ch. & Kluth, T. (2013): Projektstudie für eine Schmelzanlage zur Behandlung radioaktiv kontaminiert/ aktivierter metallischer Reststoffe. Nagra Working Report NAB 13-55.
- Ferry, C., Piron, J.-P., Poulesquen, A. & Poinsot, C. (2008): Radionuclides release from spent fuel under disposal conditions: Re-evaluation of the Instant Release Fraction. In: Lee, W.E., Roberts, J.W., Hyatt, N.C. & Grimes, R.W. (eds): *Scientific Basis for Nuclear Waste Management XXXI*. Warrendale, PA. Materials Research Society Symposium Proceedings 1107, 447-454.
- Fischer, K. & Henk, A. (2013): A workflow for building and calibrating 3-D geomechanical models – a case study for a gas reservoir in the North German Basin. *Solid Earth*, 4, 347-355.
- Fischer, U.H. & Haeberli, W. (2010): Glacial erosion modelling – results of a workshop held in Unterägeri, Switzerland, 29 April – 1 May 2010. Nagra Working Report NAB 10-34.
- Fischer, U.H. & Haeberli, W. (2012): Glacial overdeepening – results of a workshop held in Zürich, Switzerland, 20-21 April 2012. Nagra Working Report NAB 12-48.
- Fischer, U.H., Bebiolka, A., Brandefelt, J., Follin, S., Hirschorn, S., Jensen, M., Keller, S., Kennell, L., Näslund, J.-O., Normani, S., Selroos, J.-O. & Vidstrand, P. (2015): Radioactive waste under conditions of future ice ages. In: Haeberli, W. & Whiteman, C. (eds.): *Snow and Ice-Related Hazards, Risks and Disasters*. Elsevier, 345-395.
- Flowers, G.E. & Beaud, F. (2014): Sensitivity of modelled erosion rates to hydrologic transients and process representation in a hydraulicallycoupled ice-flow model. Nagra Working Report NAB 14-23.

- Fors, P., Carbol, P., Van Winckel, S. & Spahiu, K. (2009): Corrosion of high burn-up structured UO₂ fuel in presence of dissolved H₂. J. Nucl. Mater. 394, 1-8.
- Fraefel, M. (2008): Geomorphic response to neotectonic activity in the Jura Mountains and the southern Upper Rhine Graben. Diss. Univ. Basel.
- Fries, T., Weber, HP. & Wetzig, V. (2007): ESDRED: Low pH Shotcrete for rock support: Spraying tests at the Test Gallery Hagerbach. Nagra Working Report NAB 07-02.
- Fries, T., Cloet, V. & Wetzig, V. (2016): SR Experiment: Low-pH Shotcrete for Rock Support Synthesis Report. Nagra Working Report NAB 16-02.
- Fuhrmann, T. & Zippelt, K. (2013): Berechnung und Beurteilung rezenter vertikaler Ober-flächenbewegungen abgeleitet aus wiederholten Präzisionsnivelllements in den Regionen Nordschweiz und Südwestdeutschland. Nagra Working Report NAB 12-33.
- Gaar, D. (2013): Establishing chronologies of Late Pleistocene glacier advances in Northern Switzerland. PhD thesis. University of Berne.
- Gaboreau, S., Prêt, D., Tinseau, E., Claret, F., Pellegrini, D. & Stammose, D. (2011): 15 years of in situ cement-argillite interaction from Tournemire URL: Characterisation of the multi-scale spatial heterogeneities of pore space evolution. Appl. Geochem. 26, 2159-2171.
- Gaboreau, S., Lerouge, C., Dewonck, S., Linard, Y., Bourbon, X., Fialips, C.I., Mazurier, A., Prêt, D., Borschneck, D., Montouillout, V., Gaucher, E.C. & Claret, F. (2012): In-situ interaction of cement paste and shotcrete with claystones in a deep disposal context. American Journal of Science 312, 314-356.
- Galson, D.A. & Richardson, P.J. (2011): PAMINA: Performance Assessment Methodologies in Application to Guide the Development of the Safety Case. Project Summary Report Deliverable (D-N°: D5.1). European Commission.
- Ganopolski, A., Winkelmann, R. & Schellnhuber, H.J. (2016): Critical insolation – CO₂ relation for diagnosing past and future glacial inception. Nature 529, 202-203.
- García-Siñeriz, J.L., Abós, H., Martínez, V., De la Rosa, C., Mäder, U. & Kober, F. (2016): FEBEX DP: Dismantling of heater 2 at the FEBEX "in situ" test: Description of operations. Nagra Working Report NAB 16-11
- Garitte, B., Gens, A., Vaunat, J. & Armand, G. (2014): Thermal conductivity of argillaceous rocks: determination methodology using in situ heating tests. Rock Mechanics and Rock Engineering 47/1, 111-129.
- Garitte, B., Weber, H. & Müller, H.R. (2015a): FE/LUCOEX – Requirements, manufacturing and QC of the buffer components. Nagra Working Report NAB 15-24.
- Garitte, B., Weber, H. & Müller, H.R. (2015b): LUCOEX WP2 Report Deliverable D2.3 – Full-Scale Emplacement (FE) Experiment – Requirements, manufacturing and QC of the buffer components (with contributions from Köhler, S., Kaufhold, S., Plötze, M., Paysan, S., Ohms, F. & Holl, M.). EU report downloadable from www.lucoex.eu

- Gaus, I. (ed.) (2011): Long Term performance of Engineered Barrier Systems (PEBS). Mont Terri HE-E experiment: detailed design (with contributions from: Gaus, I., Köhler, S., Teodori, S., Weber, HP., Rösli, U., Steiner, P., Trick, T., García-Siñeriz, J.-L., Nussbaum, C., Czaikowski, O., Wieczorek, K., Schuster, K., Kuhlmann, U., Garitte, B., Gens, A. & Mayor, J.C. Nagra Working Report NAB 11-01.
- Gaus, I., Wieczorek, K., Schuster, K., Garitte, B., Senger, R., Vasconcelos, R. & Mayor, J.-C. (2014a): EBS behaviour immediately after repository closure in a clay host rock: HE-E experiment (Mont Terri URL). Clays in Natural and Engineered Barriers for Radioactive Waste Confinement, 5th international meeting, Montpellier, October 22 – 25, 2012, Geological Society, London, Special Publications 400, 71-91.
- Gaus, I., Garitte, B., Czaikowski, O., Senger, R., Gens, A., Vasconcelos, R., García-Siñeriz, J.L., Trick, T., Wieczorek, K., Schuster, K., Mayor, J.C., Velasco, M., Kuhlmann, U. & Villar, M.V. (2014b): The HE-E Experiment: Lay-out, interpretation and THM modelling. Nagra Working Report NAB 14-53.
- Gautschi, A. (2001): Hydrogeology of a fractured shale (Opalinus Clay): Implications for the deep disposal of radioactive wastes. *Hydrogeol. J.* 9, 97-107.
- Gens, A., Vaunat, J., Garitte, B. & Wileveau, Y. (2007): In situ behaviour of a stiff layered clay subject to thermal loading: observations and interpretation. *Géotechnique* 57/2, 207-228.
- Geomechanica (2013): Extent and shape of the EDZ around underground structures of a geological repository for radioactive waste – A sensitivity study for the candidate host rocks in the proposed siting regions in Northern Switzerland. Nagra Working Report NAB 13-78.
- Geomechanica (2014): HG-A experiment: Numerical simulation of the EDZ formation and mechanical re-compaction process using an FDEM approach. Unpubl. Mont Terri Technical Note. Mont Terri Project, Switzerland.
- Giger, S., Ewy, R.T. & Stankovich R. (2017, under review): Consolidated-undrained triaxial test results of Opalinus Clay and comparison with caprock shales. (Submitted to): Advances in Laboratory Testing and Modelling of Soils and Shales. International Workshop 18 – 20 January 2017, Villars/Switzerland.
- Giger, S. & Marschall, P. (2014): Geomechanical properties, rock models and in-situ stress conditions for Opalinus Clay in Northern Switzerland. Nagra Working Report NAB 14-01.
- Gillow, J.B. & Francis, A.J. (2006): Microbial gas generation under expected waste isolation pilot plant repository conditions: Final report. BNL-96148-2011-IR, Brookhaven National Laboratory.
- Gimmi, T. (2008): Modeling field diffusion experiments in clay rock: influence of numerical representation of borehole and rock interface. *Journal of Environmental Science for a Sustainable Society* 2, 63-70.
- Gimmi, T. & Kosakowski, G. (2011): How mobile are sorbed cations in clays and clay rocks? *Environ. Sci. Technol.* 45, 1443-1449.

- Gimmi, T. & Waber, H.N. (2004): Modelling of tracer profiles in pore water of argillaceous rocks in the Benken borehole: Stable water isotopes, chloride, and chlorine isotopes. Nagra Tech. Rep. NTB 04-05.
- Gimmi, T., Waber, H.N., Gautschi, A. & Rübel, A. (2007): Stable water isotopes in pore water of Jurassic argillaceous rocks as tracers for solute transport over large spatial and temporal scales. Water Resources Research 43, W04410.
- Gimmi, T., Leupin, O.X., Eikenberg, J., Glaus, M.A., Van Loon, L.R., Waber, H.N., Wersin, P., Wang, H.A.O., Grolimund, D., Borca, C.N., Dewonck, S. & Wittebroodt, Ch. (2014): Anisotropic diffusion at the field scale in a four-year multi-tracer diffusion and retention experiment – I: Insights from the experimental data. Geochim. Cosmochim. Acta 125, 373-393.
- Gin, S., Ribet, I. & Couillard, M. (2001): Role and properties of the gel formed during nuclear glass alteration: importance of gel formation conditions J. Nucl. Mater. 298, 1-10.
- Glaus, M., Frick, S., Rossé R. & Van Loon, L. (2011): Consistent interpretation of the results of through-, out-diffusion and tracer profile analysis for trace anion diffusion in compacted montmorillonite. J. Contam. Hydrol. 123, 1-10
- Glaus, M.A., Aertsens, M., Appelo, C.A.J., Kupcik, T., Maes, N., Van Laer, L. & Van Loon, L.R. (2015) Cation diffusion in the electrical double layer enhances the mass transfer rates for Sr^{2+} , Co^{2+} and Zn^{2+} in compacted illite. Geochim. Cosmochim. Acta 165, 376-388.
- Gmünder, C., Jordan, P. & Becker, J. (2013): Documentation of the Nagra 3D Geological Model 2012. Nagra Working Report NAB 13-28.
- Gmünder, C., Malaguerra, F., Nusch, S. & Traber, D. (2014): Regional Hydrogeological Model of Northern Switzerland. Nagra Working Report NAB 13-23.
- GNW (2000): Lager für schwach- und mittelaktive Abfälle am Wellenberg, Gemeinde Wolfenschiessen NW. Bericht zu Handen der Kantonalen Fachgruppe Wellenberg. GNW Tech. Ber. TB 00-01. Genossenschaft für nukleare Entsorgung Wellenberg GNW, Wolfenschiessen.
- Godon, N., Gin, S., Minet, Y., Grambow, B., Lemmens, K. & Aertsen, M. (2008): Reference report on the state of the art of glass properties and glass alteration during long term storage and under disposal conditions. NF-PRO Project, Deliverable 1.1.1 of RTD component 1 Part 1, European Commission (Contract F16W-CT-2003-02389), 144.
- González Sánchez, F., Van Loon, L.R., Gimmi, T., Jakob, A., Glaus, M.A. & Diamond, L.W. (2008a): Self-diffusion of water and its dependence on temperature and ionic strength in highly compacted montmorillonite, illite and kaolinite. Appl. Geochem. 23, 3840-3851.
- González Sánchez, F., Juranyi, F., Gimmi, T., Van Loon, L.R., Unruh, T. & Diamond, L. (2008b): Translational diffusion of water and its dependence on temperature in charged and uncharged clays: a neutron scattering study. J. Chem. Phys. 129, 174706/11. doi:10.1063/1.3000638.

- Gorski, C.A., Aeschbacher, M., Soltermann, D., Voegelin, A., Baeyens, B., Marques Fernandes, M., Hofstetter, T.B. & Sander, M. (2012): Redox properties of structural Fe in clay minerals: 1. Electrochemical quantification of electron-donating and -accepting capacities of smectites. *Environ. Sci. Technol.* 46, 9360-9368.
- Graf, H.R. (1993): Die Deckenschotter der zentralen Nordschweiz. Diss. ETH No. 10205, ETH Zürich.
- Graf, H.R. (2009a): Stratigraphie von Mittel- und Spätpleistozän in der Nordschweiz. Beiträge zur Geologischen Karte der Schweiz (N.F. 168). Bundesamt für Landestopografie swisstopo.
- Graf, H.R. (2009b): Stratigraphie und Morphogenese von frühpleistozänen Ablagerungen zwischen Bodensee und Klettgau. Eiszeitalter und Gegenwart/Quaternary Science Journal 58, 12-53.
- Graham, J. & Houlsby, G.T. (1983): Elastic anisotropy of a natural clay. *Géotechnique* 33/2, 165-180.
- Grambow, B. (1985): A general rate equation for nuclear waste glass corrosion. *Scientific Basis for Nuclear Waste Management VIII*, Mat.Res. Soc. Proc. 44, 15-27. Materials Research Society, Boston.
- Grambow, B. (1987): Nuclear Waste Glass Dissolution: Mechanisms, Model and Application – Report to JSS Project Phase IV. JSS Report 87-02. Svensk Kärnbränslehantering AB, Stockholm.
- Gras, J.M. (2014): State of the art of ^{14}C in Zircaloy and Zr alloys – ^{14}C release from zirconium alloy hulls. CAST project Document No: CAST-2014-D3.1.
- Gunzburger, Y. & Magnenet, V. (2014): Stress inversion and basement-cover stress transmission across weak layers in the Paris basin, France. *Tectonophys.* 617, 44-57, doi: 10.1016/j.tecto.2014.01.016.
- Haeberli, W., Linsbauer, A., Patton, H., Swift, D.A., Clark, C.D., Livingstone, S.J. & Cook, S.J. (2015): Morphological characteristics of glacial overdeepenings. Nagra Working Report NAB 15-32.
- Häner, A., Mayer, G., Schwyn, B. & Schweingruber, M. (2014): Chemische Risikobewertung – Beurteilung von Stoffen in einem geologischen Tiefenlager für radioaktive Abfälle aufgrund ihrer Chemotoxizität. Nagra Working Report NAB 14-35.
- Häuselmann, A.D., Fleitmann, D., Cheng, H., Tabersky, D., Günther, D. & Edwards, R.L. (2015): Timing and nature of the penultimate deglaciation in a high alpine stalagmite from Switzerland. *Quaternary Science Reviews* 126, 264-275.
- Haldimann, P. & Schatzmann, P. (2014): Charakterisierung der Lockergesteinsaquifere für die Modellierung der Biosphäre. Nagra Working Report NAB 13-75.
- Harrington, J.F. (ed.) (2013): FORGE Milestone D4.24-R Summary report: Experiments and modelling of excavation damage zone (EDZ) behaviour in argillaceous and crystalline rocks (Work Package 4) EC FORGE Project Report D4.24-R. Euratom 7th Framework Programme Project: FORGE (Fate of repository gases).

- Heidbach, O. & Reinecker, J. (2013): Analyse des rezenten Spannungsfeldes der Nordschweiz. Nagra Working Report NAB 12-05.
- Heidbach, O., Hergert, T., Reiter, K. & Giger, S.B. (2014): Local stress sensitivity analysis – case study Nördlich Lägern. Nagra Working Report NAB 13-88.
- Heiri, O., Koinig, K.A., Spötl, C., Barrett, S., Brauher, A., Drescher-Schneider, R., Gaar, D., Ivy-Ochs, S., Kerschner, H., Luetscher, M., Moran, A., Nicolussi, K., Preusser, F., Schmidt, R., Schoeneich, P., Schwörer, C., Sprafke, T., Terhorst, B. & Tinner, W. (2014): Palaeoclimate records 60 – 8 ka in the Austrian and Swiss Alps and their forelands. Quaternary Science Reviews 106, 186-205.
- Helmens, K.F. (2014): The Last Interglacial Glacial cycle (MIS 5-2) re-examined based on long proxy records from central and northern Europe. Quaternary Science Reviews 86, 115-143.
- Hergert, T., Heidbach, O., Reiter, K., Giger, S.B. & Marschall, P. (2015): Stress field sensitivity analysis in a sedimentary sequence of the Alpine foreland, Northern Switzerland. Solid Earth 6, 533-552.
- Herrero, J. (2015a): Review of international status on burnup credit implementation for long term spent nuclear fuel disposal. PSI Technical Report, SB-RND-ACT-014-13.008. TM-41-15-24 V.0.
- Herrero, J., Pecchia, M., Ferroukhi, H., Canepa, S., Vasiliev, A., Caruso S. (2015b): Computational scheme for burnup credit applied to long-term waste disposal. Proc. Int. Conf. on Nuclear Criticality Safety, ICNC2015, Charlotte, USA, September 13-17.
- Herrero, J., Vasiliev, A., Pecchia, M., Ferroukhi, H., Caruso, S. (2016): Review calculations for the OECD/NEA Burn-up Credit Criticality Safety Benchmark. Annals of Nuclear Energy 87, 48-57.
- Hofer, D., Raible, C.C., Dehnert, A. & Kuhlemann, J. (2012a): The impact of different glacial boundary conditions on atmospheric dynamics and precipitation in the North Atlantic region. Climate of the Past 8/3, 935-945. doi:10.5194/cp-8-935-2012.
- Hofer, D., Raible, C.C., Merz, N., Dehnert, A. & Kuhlemann, J. (2012b): Simulated winter circulation types in the North Atlantic and European region for preindustrial and glacial conditions. Geophysical Research Letters, 39, L15805. doi:10.1029/2012GL052296.
- Hofstetter, T.B., Sosedova, Y., Gorski, C., Vögelin, A. & Sander, M. (2014): Redox properties of iron-bearing clays and MX-80 bentonite – Electrochemical and spectroscopic characterization. Nagra Tech. Rep. NTB 13-03.
- Holdsworth, S.R. (2013): Ceramic material solutions for nuclear waste disposal canisters. Nagra Working Report NAB 12-45.
- Holdsworth, S.R., Graule, T. & Mazza, E. (2014): Feasibility evaluation study of candidate canister solutions for the disposal of spent nuclear fuel and high level waste. Nagra Working Report NAB 14-90.

- Holocher, J., Mayer, G., Namar, R., Siegel, P. & Hubschwerlen, N. (2008): VPAC – A numerical model for groundwater flow and radionuclide transport. Nagra Working Report NAB 08-05.
- Horsrud, P., Sonstebo, E.F., Boe, R. (1998): Mechanical and petrophysical Properties of the North Sea Shales. Int. Rock Mech. Min. Sci. 35/8, 1009-1020.
- Horsrud, P. (2001): Estimating mechanical properties of shale from empirical correlations. SPE Drilling & Completion 16/June, 68-73.
- HSK (1986): Gutachten zum Projekt Gewähr 1985 der Nationalen Genossenschaft für die Lagerung radioaktiver Abfälle (Nagra). HSK 23/28. Hauptabteilung für die Sicherheit der Kernanlagen (HSK), Villigen, Schweiz.
- HSK (1996): Gutachten zum Gesuch um Rahmenbewilligung für ein SMA-Endlager am Wellenberg. HSK 30/9, KSA 30/11. Hauptabteilung für die Sicherheit der Kernanlagen (HSK), Villigen, Schweiz.
- HSK (2001): Geologisches Tiefenlager für schwach- und mittelaktive Abfälle (SMA): Verfahren zur Auswahl eines Standortgebietes. HSK 30/17. Hauptabteilung für die Sicherheit der Kernanlagen (HSK), Villigen, Schweiz.
- HSK (2004): Stellungnahme zur Sicherheitsanalyse Kristallin-I der Nagra. HSK 23/73. Hauptabteilung für die Sicherheit der Kernanlagen (HSK), Villigen, Schweiz.
- HSK (2005): Gutachten zum Entsorgungsnachweis der Nagra für abgebrannte Brennelemente, verglaste hochaktive sowie langlebige mittelaktive Abfälle (Projekt Opalinuston). HSK 35/99. Hauptabteilung für die Sicherheit der Kernanlagen (HSK), Villigen.
- HSK (2007): Anforderungen an die Konditionierung radioaktiver Abfälle. Richtlinie für die schweizerischen Kernanlagen HSK-B05/d. Erläuterungsbericht zur Richtlinie. Hauptabteilung für die Sicherheit der Kernanlagen, Villigen.
- Huertas, F., Villar, M.V., García-Siñeriz, J.L., Sellin, P., Stührenberg, D. & Alheid, H.-J. (2008): Final Synthesis Report RTD Component 3: Thermo-hydro-mechanical (geochemical) processes in the engineered barrier system. Deliverable: D 3.6.2, NF-PRO Contract Number: FI6W-CT-2003-02389.
- IAEA (1996): Defence in depth in nuclear safety. INSAG-10. International Atomic Energy Agency IAEA, Vienna.
- IAEA (2006a): Geological disposal of radioactive waste. Safety requirements. IAEA Safety Standards Series No. WS-R-4. International Atomic Energy Agency, Vienna.
- IAEA (2006b): Fundamental safety principles. Safety Fundamentals No. SF-1. International Atomic Energy Agency, Vienna.
- IAEA (2012): Spent Fuel Performance Assessment and Research: Final Report of a Coordinated Research Project (SPAR-II). IAEA-TECDOC-1680. International Atomic Energy Agency, Vienna.
- IAEA (2016): Guidance for preparation of a safety case for a dual purpose cask containing spent fuel. IAEA Tecdoc Draft -TM-44985. International Atomic Energy Agency, Vienna.

- Ibele, T. (2015): Tectonics of the Hegau and Lake Constance region: A synthesis based on existing literature. Nagra Working Report NAB 12-23.
- ICRP (1998): Radiation protection recommendations as applied to the disposal of long-lived solid radioactive waste. ICRP publication 81. Annals of the ICRP. International Commission on Radiological Protection ICRP.
- ICRP (2006): Assessing dose of the representative person for the purpose of radiation protection of the public and the optimisation of radiological protection: Broadening the process. ICRP Publication 101. Annals of the ICRP, vol. 36 no. 3. International Commission on Radiological Protection ICRP.
- ICRP (2007): The 2007 recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Annals of the ICRP, vol. 37 no. 2-4. International Commission on Radiological Protection ICRP.
- ICRP (2013): Radiological protection in geological disposal of long-lived solid radioactive waste. ICRP Publication 122. Annals of the ICRP, vol. 42 no. 3. International Commission on Radiological Protection ICRP.
- IGD-TP (2016): <http://www.igdtp.eu/>
- I-NERI (2013): International Nuclear Energy Research Initiative, Fiscal Year 2013 Annual Report. DOE/NE-0145.
- Ingram, G.M. & Urai, J.L. (1999): Top-seal leakage through faults and fractures: the role of mudrock properties. In: Aplin, A.C., Fleet, A.J. & Macquaker, J.H.S. (eds): Muds and mudstones: Physical and fluid-flow properties. Geological Society Special Publication 158, 125-135.
- Intera Engineering Ltd. (2011): Descriptive Geosphere Site Model. NWMO DGR-TR-2011-24. Nuclear Waste Management Organisation NWMO, Toronto.
- Ivy-Ochs, S., Kerschner, H., Reuther, A., Preusser, F., Heine, K., Maisch, M., Kubik, P.W. & Schlüchter, C. (2008): Chronology of the last glacial cycle in the European Alps. Journal of Quaternary Science 23, 559-573.
- Jacobs, F., Mayer, G. & Wittmann, F.H. (1994): Hochpermeable, zementgebundene Verfüllmörtel für SMA Endlager. Nagra Tech. Rep. NTB 92-11.
- Jaeggi, K. & Frieg, B. (2010): OPA: Sondierbohrung Benken – Langzeitbeobachtung 2009. Dokumentation der Messdaten. Nagra Working Report NAB 10-28.
- Jenni, A., Mäder, U., Lerouge, C., Gaboreau, S. & Schwyn, B. (2014): In situ interaction between different concretes and Opalinus Clay. Physics and Chemistry of the Earth 70-71, 71-83.
- Johansson, J.A & Brinck, T. (2012): Mechanisms and energetics of surface reactions at the copper-water interface – A critical literature review with implications for the debate on corrosion of copper in anoxic water. SKB Technical Report TR-12-07. Svensk Kärnbränslehantering AB, Stockholm.

- Johnson, L. (2014): A model for radionuclide release from UO₂ and MOX fuel. Nagra Working Report NAB 13-37.
- Johnson, L.H. & King, F. (2003): Canister options for the disposal of spent fuel. Nagra Tech. Rep. NTB 02-11.
- Johnson, L.H. & Schneider, J. (2005): The impact of alternative spent fuel dissolution models on calculated releases from the EBS – some insights from the Opalinus Clay safety case. Integration of Engineered Barrier Systems in the Safety Case: the Role of Modelling, Workshop Proceedings, La Coruna, Aug. 24-26, 2005. NEA, Paris.
- Johnson, L., Günther-Leopold, I., Kobler Waldis, J., Linder, H.P., Low, J., Cui, D., Ekeroth, E., Spahiu, K. & Evins, L.Z. (2012): Rapid aqueous release of fission products from high burn-up LWR fuel: Experimental results and correlations with fission gas release. *J. Nucl. Mater.* 420, 55-62.
- Johnson, L., Gaus, I., Wieczorek, K., Mayor, J.C., Sellin, P., Villar, M.V., Samper, J., Cuevas, J., Gens, A., Velasco, M., Turrero, M.J., Montenegro, L., Martín, P.L. & Armand, G. (2014): Integration of the short-term evolution of the engineered barrier system (EBS) with the long-term safety perspective (Deliverable D4.1 of the PEBS project). Nagra Working Report NAB 14-79.
- Johnson, L.H. & Zuidema, P. (2013): Nagra strategy for development of canister for disposal of Spent Fuel and High-Level Waste. Nagra Working Report NAB 13-38.
- Jordan, P. (2010): Analysis of overdeepened valleys using the digital elevation model of the bedrock surface of Northern Switzerland. *Swiss Journal of Geosciences* 103/3, 375-384.
- Jordan, P., Malz, A., Heuberger, S., Pietsch, J., Kley, J. & Madritsch, H. (2015): Regionale geologische Profile durch die Nordschweiz und 2D-Bilanzierung der Fernschubdeformation im östlichen Faltenjura: Arbeitsbericht zu SGT Etappe 2. Nagra Working Report NAB 14-105.
- Karnland, O., Olsson, S. & Nilsson, U. (2006): Mineralogy and sealing properties of various bentonites and smectite-rich clay materials. SKB Technical Report TR-06-30. Svensk Kärnbränslehantering AB, Stockholm, 110 pp.
- Karnland, O., Nilsson, U., Weber, H. & Wersin, P. (2007): Sealing ability of Wyoming bentonite pellets foreseen as buffer material – Laboratory results. Nagra Working Report NAB 07-23.
- Karnland, O., Olsson, S., Dueck, A., Birgersson, M., Nilsson, U. & Hernan-Håkansson, T. (2009): Long term test of buffer material at the Äspö Hard Rock Laboratory, LOT Project. SKB Technical Report TR-09-29. Svensk Kärnbränslehantering AB, Stockholm.
- Keech, P. (2013): Using copper coatings for corrosion protection of a used fuel container during geological storage. International High Level Radioactive Waste Management Conference, Albuquerque, New Mexico, April 28 – May 3, 2013, 405-409.
- Keech, P., Vo, P., Ramamurthy, S., Chen, J., Jacklin, R. & Shoesmith, D. (2014): Design and development of copper coatings for long term storage of used nuclear fuel. *Corrosion Engineering Science and Technology* 49, 425-430.

KEG (2003): Kernenergiegesetz (KEG) vom 21. März 2003 [Nuclear Energy Act], Stand am 1. Juli 2016. Systematische Sammlung des Bundesrechts SR 732.1, Schweiz.

Keller, L.M., Schuetz, P., Erni, R., Rossell, M.D., Lucas, F., Gasser, P., Holzer, L. (2013a): Characterization of multi-scale microstructural features in Opalinus Clay. Microporous Mesoporous Mater. 170, 83-94.

Keller, L.M., Holzer, L., Schütz, Ph. & Gasser, Ph. (2013b): Pore space relevant for gas permeability in Opalinus clay: Statistical analysis of homogeneity, percolation, and representative volume element. Journal of Geophys. Res. Solid Earth 118, 2799-2812.

Keller, L. M., Seiphoori, A., Gasser, P., Lucas, F., Holzer, L. & Ferrari, A. (2014): The pore structure of compacted and partly saturated MX-80 bentonite at different dry densities. Clays and Clay Minerals 62/3, 174-187.

Keller, L.M., 2016. Pore geometry effects on elastic properties of Opalinus Clay. Geophysics, 81, 10.1190/GEO2015-0452.1.

Kennedy, K. (2004): Engineered Barrier Emplacement Experiment in Opalinus Clay (EB) – Granular Material Backfill QA Report with Emplacement Description. EC contract FIKW-CT-2000-00017. Project Deliverable D12. Unpubl. Mont Terri internal report.

Kennedy, K. & Plötze, M. (2004): Engineered Barrier Emplacement Experiment in Opalinus Clay (EB). Granular Material Backfill Emplacement Methods Evaluation. EC contract FIKW-CT-2000-00017. Project Deliverable D4. Unpubl. Mont Terri internal report.

KEV (2004): Kernenergieverordnung vom 10. Dezember 2004 (KEV) [Nuclear Energy Ordinance], Stand am 1. Juli 2016. Systematische Sammlung des Bundesrechts SR 732.11, Switzerland.

Kiefer, L., Deplazes, G. & Bläsi, H.R. (2015): Sedimentologie und Stratigraphie des Frühen Juras in der Nordschweiz: Staffelegg-Formation und sich nach Osten anschliessende Vorkommen. Nagra Working Report NAB 14-95.

Kienzler, B., Metz, V. & Valls, A. (eds.) (2014): Fast / Instant Release of Safety Relevant Radionuclides from Spent Nuclear Fuel (FIRST-Nuclides). Final scientific report. EC project, Contract Number: FP7-295722.

King, F. (2010): Critical review of the literature on the corrosion of copper by water. SKB Technical Report TR-10-69. Svensk Kärnbränslehantering AB, Stockholm.

King, F. & Lilja, C. (2013): Localised corrosion of copper canisters in bentonite pore water. SKB Technical Report TR-13-27. Svensk Kärnbränslehantering AB, Stockholm.

King, F., Lilja, C., Pedersen, K., Pitkänen, P. & Vähänen, M. (2010): An update of the state-of-the-art report on the corrosion of copper under expected conditions in a deep geologic repository. SKB Technical Report TR-10-67. Svensk Kärnbränslehantering AB, Stockholm.

Klos, R.A., Müller-Lemans, H., Van Dorp, F. & Gribi, P. (1996): TAME: The Terrestrial-Aquatic Model of the Environment : model definition. Nagra Tech. Rep. NTB 93-04.

- KNE (2005): Projekt Opalinuston Zürcher Weinland der Nagra: Beurteilung der erdwissenschaftlichen Datengrundlagen und der bautechnischen Machbarkeit. Expertenbericht der Kommission Nukleare Entsorgung (KNE) zuhanden der Hauptabteilung für die Sicherheit der Kernanlagen (HSK). HSK 35/98. Hauptabteilung für die Sicherheit der Kernanlagen (HSK), Villigen.
- KNS (2012): Stellungnahme zum Bericht zum Umgang mit den Empfehlungen in den Gutachten und Stellungnahmen zum Entsorgungsnachweis (NTB 08-02). KNS 23/270, März 2012. Eidgenössische Kommission für nukleare Sicherheit KNS, Schweiz.
- Kober, F. et al. (*in prep.*): FEBEX-DP Final Report. Nagra Tech. Rep. NTB 17-01.
- Kock, S. (2008): Pleistocene terraces in the Hochrhein area – formation, age constraints and neo-tectonic implications. PhD Thesis Univ. Basel.
- Köhler, S., Gariette, B., Weber, H. & Müller, H.R. (2015): FE/LUCOEX – Emplacement report. Nagra Working Report NAB 15-27.
- Kosakowski, G. & Berner, U. (2013): The evolution of clay rock/cement interfaces in a cementitious repository for low- and intermediate level radioactive waste. Physics and Chemistry of the Earth Parts A/B/C, 64, 65-86.
- KSA (2005): Stellungnahme zum Entsorgungsnachweis für abgebrannte Brennelemente, verglaste hochaktive sowie langlebige mittelaktive Abfälle (Projekt Opalinuston). KSA 23/170. Eidgenössische Kommission für die Sicherheit von Kernanlagen (KSA).
- Kudla, W., Schreiter, F., Gruner, M., Jobmann, M., Bollingerfehr, W., Müller-Hoeppe, N. & Herold, Ph. (2013): Schachtverschlüsse für Endlager für hochradioaktive Abfälle – ELSA Teil 1. Herausgegeben durch TU Bergakademie Freiberg und DBE Technology GmbH im Auftrag des Deutschen Bundesministeriums für Wirtschaft und Technologie, Förderkennzeichen 02E10921/02E10931.
- Kuhlemann, J. & Rahn, M. (2013): Plio-Pleistocene landscape evolution in Northern Switzerland. Swiss Journal of Geosciences 106, 451-467.
- Kwong, G.M. (2011): Status of corrosion studies for copper used fuel containers under low salinity conditions. NWMO Technical Report TR-2011-14. Nuclear Waste Management Organization, Toronto.
- Laine, H. & Karttunen, P. (2010): Long-term stability of bentonite. A literature review. Posiva Working Report 2010-53, 127 pp. Posiva, Helsinki.
- Landolt, D., Davenport, A., Payer, J. & Shoesmith D. (2009): A review of materials and corrosion issues regarding canisters for disposal of spent fuel and high-level waste in Opalinus Clay. Nagra Technical Report NTB 09-02.
- Lanyon, G.W. & Rüedi, J. (2008): SGT-ZE: Gas related properties of repository backfill materials (SF/HLW and L/ILW). Nagra Working Report NAB 08-34.
- Lanyon, G.W. & Gaus, I. (2013): Main outcomes and review of the FEBEX In Situ Test (GTS) and Mock-Up after 15 years of operation. Nagra Working Report NAB 13-96.

- Lanyon, G.W. & Madritsch, H. (2014): Simulation of layout determining fault networks based on 2D-seismic interpretations: Implications for subsurface space reserves in geological siting regions in northern Switzerland. Nagra Working Report NAB 14-88.
- Lanyon, G.W. & Senger, R. (2011): A structured approach to the derivation of effective properties for combined water and gas flow in the EDZ. *Transp. porous media* 90/1, 95-112.
- Lanyon, G.W., Martin, D., Giger, S. & Marschall, P. (2014a): Development and evolution of the Excavation Damaged Zone (EDZ) in the Opalinus Clay – A synopsis of the state of knowledge from Mont Terri. Nagra Working Report NAB 14-87.
- Lanyon, G.W., Marschall, P., Trick, T., de la Vaissiere, R., Shao, H. & Leung, H. (2014b): Self-sealing experiments and gas injection tests in a backfilled microtunnel of the Mont Terri URL. Geological Society, London, Special Publications 400/1, 93-106. doi:10.1144/SP400.8.
- Lemmens, K. (2001): The effect of clay on the dissolution of nuclear waste glass. *J. Nucl. Mat.* 298, 11-18.
- LES (2014): Annual Progress Report. <https://www.psi.ch/les/annual-reports>
- LES (2015). Annual Progress Report. <https://www.psi.ch/les/annual-reports>
- Leupin, O.X. & Johnson, L.H. (2013): Buffer requirements for a SF/HLW repository in Opalinus Clay. Nagra Working Report. NAB 13-46.
- Leupin, O.X. (ed.), Birgersson, M., Karnland, O., Korkeakoski, P., Sellin, P., Mäder, U. & Wersin P. (2014): Montmorillonite stability under near-field conditions. Nagra Tech. Rep. NTB 14-12.
- Leupin, O., Smith, P., Savage, D., Johnson, L., Marschall, P., Schneider, J. & Senger, R. (2016a): High-level waste repository-induced effects. Nagra Tech. Rep. NTB 14-13.
- Leupin, O., Smith, P., Savage, D., Johnson, L., Marschall, P., Schneider, J. & Senger, R. (2016b): Low- and intermediate-level waste repository-induced effects. Nagra Tech. Rep. NTB 14-14.
- Leupin, O.X., Bernier-Latmani, R., Bagnoud, A., Moors, H., Leys, N., Wouters, K. & Stroes-Gascoyne, S. (2017). Fifteen Years of Microbiological Investigation in Opalinus Clay: a Potential Host Rock for a Geologic Radioactive Waste Repository. *Swiss Journal of Geosciences* 110.
- Li X. (ed.) (2011): TIMODAZ – Thermal Impact on the Damaged Zone Around a Radioactive Waste Disposal in Clay Host Rocks / Final activity report. Sixth Framework Programme Euratom Research and Training Programme on Nuclear Energy (2002 – 2006). Number: FI6W-CT-2007-036449 (<http://www.timodaz.eu>).
- Li, X.L., Chen, G., Verstricht, J., Van Marcke, P. & Troullinos, I. (2013). The Large Scale In-Situ PRACTAY Heater and Seal Tests in URL HADES, Mol, Belgium. ASME 2013 15th International Conference on Environmental Remediation and Radioactive Waste Management. Paper No. ICEM2013-96294, doi:10.1115/ICEM2013-96294.

- Lisjak, A., Garitte, B., Grasselli, G., Müller, H. & Vietor, T. (2015): The excavation of a circular tunnel in a bedded argillaceous rock (Opalinus Clay): Short-term rock mass response and FDEM numerical analysis. *Tunnelling and Underground Space Technology* 45, 227-248.
- Lowick, S.E., Trauerstein, M. & Preusser, F. (2012): Testing the application of post IR-IRSL dating to fine grain waterlain sediments. *Quaternary Geochronology* 8, 33-40.
- Lowick, S.E., Buechi, M.W., Gaar, D., Graf, H.R. & Preusser, F. (2015): Luminescence dating of Middle Pleistocene proglacial deposits from northern Switzerland: methodological aspects and stratigraphical conclusions. *Boreas* 44/3, 459-482, 10.1111/bor.12114. ISSN 0300-9483.
- LUCOEX (2016): <http://www.lucox.eu/>
- Luo, J., Monningkoff, B. & Becker, J.K. (2013): Hydrogeological model Zürich Nordost and Südranden. Nagra Working Report NAB 13-24.
- Luo, J., Monningkoff, B. & Becker, J.K. (2014a): Hydrogeological model Nördlich. Nagra Working Report NAB 13-25.
- Luo, J., Monningkoff, B. & Becker, J.K. (2014b): Hydrogeological model Jura Ost. Nagra Working Report NAB 13-26.
- Luo, J., Seifert, S., Monningkoff, B. & Becker, J.K. (2014c): Hydrogeological model Jura-Südfuss. Nagra Working Report NAB 13-27.
- Macdonald, D.D., Sharifi-Asl, S. & Engelhardt, G.R. (2014): Issues in the corrosion of copper in a swedish high level nuclear waste repository – Phase III. Role of sulphide ion in anodic and cathodic processes. SMM Technical Note 2014-57. Strål Säkerhets Myndigheten, Sweden.
- Madigan, M., Martinko, J., Bender, K., Buckley, D. & Stahl, D. (2015): *Brock Biology of Microorganisms*. Pearson, London, 14th edition.
- Madritsch, H. (2015): Outcrop-scale fracture systems in the Alpine foreland of northern Switzerland: Kinematics and tectonic context. *Swiss Journal of Geosciences* 108/2, 155-181.
- Madritsch, H. & Hammer, P. (2012): Characterisation of Cenozoic brittle deformation of potential geological siting regions for radioactive waste repositories in Northern Switzerland based on structural geological analysis of field outcrops. Nagra Working Report NAB 12-41.
- Madritsch, H. & Vietor, T. (2010): Mine By (MB) Experiment: Excavation history of Niche 2 and results of structural geological tunnel mapping. Unpubl. Mont Terri Technical Note. Mont Terri Project, Switzerland.
- Madsen, F.T. (1998): Clay mineralogical investigations related to nuclear waste disposal. *Clay Minerals* 33/1, 109-129.

- Mäder, U. (2009): Reference pore water for the Opalinus Clay and 'Brown Dogger' for the provisional safety-analysis in the framework of sectoral plan – interim results (SGT-ZE). Nagra Working Report NAB 09-14.
- Maerten, L., Gillespie, P. & Pollard, D.D. (2002): Effects of local stress perturbation on secondary fault development. *Journal of Structural Geology* 24, 145-153.
- Malz, A. (2014): Inversionsstrukturen und abgescherte Überschiebungssysteme: Strukturinventar und strukturelle Analyse einender Deformation in Mitteleuropa am Beispiel der Thüringer Mulde und des Schweizer Faltenjura. Unpubl. PhD Thesis, Friedrich Schiller University Jena, 236 pp.
- Malz, A., Madritsch, H. & Kley, J. (2015): Improving 2D-seismic interpretation in challenging settings by intergration of restoration techniques: A case study from the Jura fold-and-thrust belt (Switzerland). *Interpretation* 3/4, 1-22. SAA37-SAA58, doi:10.1190/INT-2015-0012.1.
- Malz, A., Madritsch, H., Meier, B. & Kley, J. (2016): An unusual triangle zone in the external northern Alpine foreland (Switzerland): Structural inheritance, kinematics and implications for the development of the adjacent Jura fold-and-thrust belt. *Tectonophysics* 670, 127-143.
- Manca, D. (2015): Hydro-chemo-mechanical characterisation of sand/bentonite mixtures, with a focus on the water and gas transport properties. PhD dissertation, EPFL, Lausanne.
- Manca, D., Ferrari, A. & Laloui, L. (2016): Fabric evolution and the related swelling behaviour of a sand/bentonite mixture upon hydro-chemo-mechanical loadings. *Géotechnique* 66/1, 41-57.
- Marelli, S., Manukyan, E., Maurer, H.R., Greenhalgh, S.A. & Green, A.G. (2010): Appraisal of waveform repeatability for crosshole and hole-to-tunnel seismic monitoring of radioactive waste repositories. *Geophysics* 75, XQ21-Q34.
- Marelli S. (2011): Seismic imaging of temporal changes in underground radioactive waste repositories: Surveillance requirements and full waveform inversion issues. DISS. ETH NO. 20040. ETH, Zürich, 2011.
- Mari, J.L. & Yven, B. (2013): The application of high resolution 3D seismic data to model the distribution of mechanical and hydrogeological properties of a potential host rock for the deep storage of radioactive waste in France. *Marine and Petroleum Geology* 2013, DOI: 10.1016/j.marpetgeo.2013.10.014.
- Marques Fernandes, M., Stumpf, T., Baeyens, B., Walther, C. & Bradbury M.H. (2010): Spectroscopic identification of ternary Cm-carbonate surface complexes. *Environ. Sci. Technol.* 44, 921-927.
- Marques Fernandes, M.M., Ver, N. & Baeyens, B. (2015): Predicting the uptake of Cs, Co, Ni, Eu, Th and U on argillaceous rocks using sorption models for illite. *Appl. Geochem.* 59, 189-199.
- Marschall, P & Giger S. (2016): ENSI-Nachforderung zum Indikator "Tiefenlage im Hinblick auf bautechnische Machbarkeit" in SGT Etappe 2 – Geomechanische Unterlagen. Nagra Working Report NAB 16-43.

- Marschall, P. & Lunati, I. (eds.) (2006): Gas migration experiments in a heterogeneous shear zone of the Grimsel Test Site. Nagra Tech. Rep. NTB 03-11.
- Marschall, P., Horseman, S. & Gimmi, T. (2005): Characterisation of gas transport properties of the Opalinus Clay, a potential host rock formation for radioactive waste disposal. Revue de l'Institut Français du Pétrole, 60/1&2, 121-139.
- Marschall, P., Lanyon, B., Gaus, I. & Rüedi, J. (2013): FORGE D4-16: Gas transport processes at Mont Terri Test Site (EDZ and host rock) – Field results and conceptual understanding of self sealing processes. www.FORGEproject.org
- Martin, C.D. & Lanyon, G.W. (2004): Excavation Disturbed Zone (EDZ) in clay shale: Mont Terri. With contributions from P. Bossart and P. Blümling. Mont Terri Technical Report TR 2001-1. Mont Terri Project, Switzerland.
- Martin, C.D., Maciotta, R., Elwood, D., Lan, H. & Vietor, T. (2015): MB Experiment: Evaluation of the Mont Terri Mine-By response: Part 1: Interpretation of results and observations, Part 2: Summary of the instrumentation results. Mont Terri Technical Report TR 2009-02. Mont Terri Project, Switzerland.
- Martínez, V., Abós, H. & García-Siñeriz, J.L. (2016): FEBEXe: Final Sensor Data Report (FEBEX "in situ" Experiment). Nagra Working Rep. NAB 16-19.
- Martino, J.B., Dixon, D., Kozak, E.T., Gascoyne, M., Vignal, B., Sugita, Y., Fujita, T., Masumoto, K. (2007): The Tunnel Sealing Experiment: An international study of fullscale seals. Physics and Chemistry of the Earth, Parts A/B/C, Vol. 32, Issues 1-7, 93-107.
- Masurat, P., Eriksson, S. & Pedersen, K. (2010): Microbial sulfide production in compacted Wyoming bentonite MX-80 under in situ conditions relevant to a repository for high-level radioactive waste. Applied Clay Science 47, 58-64.
- Matter, A., Peters, Tj., Isenschmid, Ch., Bläsi, H.R. & Ziegler, H.J. (1987): Sondierbohrung Riniken, Geologie. Nagra Tech. Rep. NTB 86-02.
- Matter, A., Peters, Tj., Bläsi, H.R., Schenker, F. & Weiss, H.-P. (1988): Sondierbohrung Schafisheim, Geologie. Nagra Tech. Rep. NTB 86-03.
- Matzke, H. (1997): Alpha self-irradiation of waste glasses: state of the knowledge. Glass, Proceedings of the summer workshop held inMéjannes-Le-Clap, Aug. 31 – Sept. 7, 1997, Commissariat à l'Energie Atomique (CEA), France, 149-166.
- Mauclaire, L., McKenzie, J.A. & Schippers, A. (2008): MA-Experiment: Microbiological analysis of pore water samples from the PC and PC-C experiments in May 2006. Unpubl. Mont Terri Technical Note. Mont Terri Project, Switzerland.
- Maurer, H.R., Spillmann T. (2015): Gast Injection Phase Geophysical Monitoring and Maintenance. Nagra Arbeitsbericht NAB 14-062.
- Mayer, G. & Wittmann, F.H. (1996): Fliessfähiger, hochpermeabler Mörtel für die Verfüllung von kleinen Hohlräumen. Nagra Tech. Rep. NTB 95-03.

- Mayer, G., Moetsch, H.A. & Wittmann, F.H. (1998): Large-scale Experiment for Water and Gas Transport in Cementitious Backfill Materials (Phase 1) COLEX I. Nagra Tech. Rep. NTB 98-03.
- Mayor, J.C., García-Siñeriz, J.L., Alonso, E., Alheid, H.-J. & Blümling, P. (2007): Engineered barrier emplacement experiment in Opalinus Clay for the disposal of radioactive waste in underground repositories. In: Bossart, P. & Nussbaum, C. (eds.): Mont Terri Project – Heater Experiment, Engineered Barrier Emplacement and Ventilation Experiment. Rep. Swiss Geol. Surv. 1, 115-179.
- Mayor, J-C. & Velasco, M. (2014): EB Dismantling Synthesis Report. PEBS Deliverable D2.1-8.
- Mazurek, M. (2000): Geological and hydraulic properties of water-conducting features in crystalline rocks. In: Stober, I. & Bucher, K. (eds.): Hydrogeology of crystalline rocks. Kluwer Scientific Publishers, 3-26.
- Mazurek, M., Lanyon, G.W., Vomvoris, S. & Gautschi, A. (1998): Derivation and application of a geologic dataset for flow modelling by discrete fracture networks in low-permeability argillaceous rocks. Journal of Contaminant Hydrology 35, 1-17.
- Mazurek, M., Gautschi, A., Marschall, P., Vigneron, G., Lebon, P. & Delay, J. (2008): Transferability of geoscientific information from various sources (study sites, underground rock laboratories, natural analogues) to support safety cases for radioactive waste repositories in argillaceous formations. Physics and Chemistry of the Earth A/B/C 33 (2008), S95-S105. DOI: 10.1016/j.pce.2008.10.046
- Mazurek, M., Alt-Epping, P., Bath, A., Gimmi, T. & Waber, H.N. (2009): Natural tracer profiles across argillaceous formations: the CLAYTRAC project. OECD Nuclear Energy Agency, NEA No. 6253. OECD Nuclear Energy Agency, Paris, 358 pp.
- Mazurek, M., Alt-Epping, P., Bath, A., Gimmi, T., Waber, H.N., Buschaert, S., De Cannière, P., De Craen, M., Gautschi, A., Savoye, S., Vinsot, A., Wemaere, I. & Wouters, L. (2011): Natural tracer profiles across argillaceous formations. Applied Geochem. 26, 1035-1064.
- Mazurek, M., Waber, H.N., Mäder, U.K., Gimmi, T., De Haller, A. & Koroleva, M. (2012): Geochemical synthesis for the Effingen Member in boreholes at Oftringen, Gösgen and Küttigen. Nagra Tech. Rep. NTB 12-07.
- Mazurek, M., Oyama, T., Wersin, P. & Alt-Epping, P. (2015): Pore-water squeezing from indurated shales. Chemical Geology 400, 106-121.
- McGrail, B.P., Bacon, D.H., Icenhower, J.P., Mann, F.M., Puigh, R.J., Schaeff, H.T. & Mattigod, S.V. (2001): Near-Field Performance Assessment for a Low-Activity Waste Glass Disposal System: Laboratory Testing to Modeling Results. J. Nucl. Mater. 298, 95-111.
- Menaceur, H., Delage, P., Tang, A.-M. & Conil, N. (2015): The thermo-mechanical behaviour of the Callovo-Oxfordian claystone. International J. Rock Mech & Min. Sci. 78, 290-303.
- Messmer, S. & Berger, P. (2014): Sicherheitstechnische Betrachtungen zu Standseilbahnen für den Zugang zu einem zukünftigen geologischen Tiefenlager. Nagra Working Report NAB 14-77.

- Minardi, A., Crisci, E., Ferrari, A. & Laloui, L. (2016): Anisotropic volumetric behaviour of Opalinus clay shale upon suction variation. *Géotechnique Letters* 6, 144–148, <http://dx.doi.org/10.1680/jgele.16.00023>.
- MIND (2016): Microbiology In Nuclear waste Disposal. Euratom Research and Training Programme 2014 – 2018, grant agreement No. 661880. <http://www.mind15.eu/>
- MoDeRn (2013a): WP1 Report, Modern Monitoring Reference Framework report. Deliverable (D-Nº: 1.2).
- MoDeRn (2013b): WP2 Report, State of Art Report on Monitoring Technology. Deliverable (D-Nº: 2.2.2).
- Molnár, M., Palcsu, L., Futó, I., Svingor, É., Major, Z., Veres, M., Ormai, P. & Barnabás, I. (2010): Study of gas generation in real L/ILW containers. *J. Radioanal. Nucl. Chem.* 286, 745-750.
- Monfared, M., Delage, P., Sulem, J., Mohajerani, M., Tang, A.M. & De Laure, E. (2011): A new hollow cylinder triaxial cell to study the behaviour of geomaterials with low permeability. *International Journal of Rock Mechanics and Mining Sciences* 48/4, 637-649.
- Möri, A., Bossart, P., Matray, J.-M., Müller, H. & Frank, H. (2012): Mont Terri project, cyclic deformations in the Opalinus Clay. *Clays in Natural & Engineered Barriers for Radioactive Waste Confinement* (4th Internat. Meeting Clays 2010, Nantes, 29 March – 1st April 2010). ANDRA, Abstracts, 81-82.
- Moseley, G.E., Spötl, C., Svensson, A., Cheng, H., Brandstätter, S. & Edwards, R.L. (2014): Multi-speleothem record reveals tightly coupled climate between Central Europe and Greenland during Marine Isotope Stage 3. *Geology* 42, 1043-1046. doi: 10.1130/G36063.1
- Müller, P. & Jaeggi, D. (2012): Sedimentary structure in the sandy facies of the Opalinus Clay at Mont Terri rock laboratory, SO Experiment. Unpubl. Mont Terri Technical Note. Mont Terri Project, Switzerland.
- Müller, H.R., Garitte, B., Vogt, T., Köhler, S., Sakaki, T., Weber, H.-P., Spillmann, T., Hertrich, M., Becker, J.K., Giroud, N., Cloet, V., Diomidis, N. & Vietor, T. (2017): Implementation of the Full-Scale Emplacement (FE) Experiment at the Mont Terri rock laboratory. *Swiss Journal of Geosciences* (in press).
- Näslund, J.-O., Brandefelt, J. & Liljedahl, L.C. (2013): Climate considerations in longterm safety assessments for nuclear waste repositories. *Ambio* 42, 393-401.
- Nagra (1985a): Nukleare Entsorgung Schweiz: Konzept und Übersicht über das Projekt Gewähr 1985. Nagra Project Rep. NGB 85-01.
- Nagra (1985b): Projekt Gewähr 1985: Endlager für hochaktive Abfälle: Sicherheitsbericht. Nagra Project Rep. NGB 85-05.
- Nagra (1993a): Endlager für kurzlebige schwach- und mittelaktive Abfälle (Endlager SMA) – Vergleichende Beurteilung der Standorte Bois de la Glaive, Oberbauenstock, Piz Pian Grand und Wellenberg. Nagra Tech. Rep. NTB 93-02.

- Nagra (1993b): Endlager für kurzlebige schwach- und mittelaktive Abfälle (Endlager SMA) – Beurteilung der Langzeitsicherheit des Endlagers SMA am Standort Wellenberg (Gemeinde Wolfenschiessen). Nagra Tech. Rep. NTB 93-26.
- Nagra (1994a): Funktionen zur Ableitung von Personendosen aus Quelltermen im Rahmen der Sicherheitsanalyse Betrieb EL-SMA (Generelles Projekt EL-SMA Anlagen und Betrieb). Unpubl. Nagra Internal Rep.
- Nagra (1994b): Endlager für Kurzlebige Abfälle, Sicherheitsanalyse Betrieb, Technischer Bericht zum generellen Projekt SMA-AB, GRS. Unpubl. Nagra Internal Rep.
- Nagra (1996a): Sicherheitsanalyse Betrieb EL-SMA Wellenberg (Stufe: Vorprojekt Anlagen und Betrieb WLB) Ermittlung der Auslegungsstörfälle. Unpubl. Nagra Internal Rep.
- Nagra (1996b): Strahlenexposition der Bevölkerung infolge störfallbedingter Aktivitätsfreisetzung während der Betriebsphase. Unpubl. Nagra Internal Rep.
- Nagra (1997): Geosynthese Wellenberg 1996 – Ergebnisse der Untersuchungsphasen I und II. Nagra Tech. Rep. NTB 96-01.
- Nagra (2001): Sondierbohrung Benken: Untersuchungsbericht. Text- und Beilagenband. Nagra Tech. Rep. NTB 00-01.
- Nagra (2002a): Projekt Opalinuston – Konzept für die Anlage und den Betrieb eines geologischen Tiefenlagers. Entsorgungsnachweis für abgebrannte Brennelemente, verglaste hochaktive sowie langlebige mittelaktive Abfälle. Nagra Tech. Rep. NTB 02-02.
- Nagra (2002b): Projekt Opalinuston: Synthese der geowissenschaftlichen Untersuchungsergebnisse – Entsorgungsnachweis für abgebrannte Brennelemente, verglaste hochaktive sowie langlebige mittelaktive Abfälle. Nagra Tech. Rep. NTB 02-03.
- Nagra (2002c): Project Opalinus Clay: Safety Report: Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungsnachweis). Nagra Tech. Rep. NTB 02-05.
- Nagra (2004): Effects of post-disposal gas generation in a repository for spent fuel, high-level waste and long-lived intermediate level waste sited in Opalinus Clay. Nagra Tech. Rep. NTB 04-06.
- Nagra (2005): Entsorgungsprogramm 2005: Lagerkonzepte für ein geologisches SMA-Lager. Bautechnische und betriebliche Grundlagen zur Reevaluation potenzieller Lagerstandorte SMA. Nagra Working Report NAB 05-08.
- Nagra (2008a): Entsorgungsprogramm 2008 der Entsorgungspflichtigen. Nagra Tech. Rep. NTB 08-01.
- Nagra (2008b): Bericht zum Umgang mit den Empfehlungen in den Gutachten und Stellungnahmen zum Entsorgungsnachweis. Nagra Tech. Rep. NTB 08-02.
- Nagra (2008c): Vorschlag geologischer Standortgebiete für das SMA- und das HAA-Lager: Darlegung der Anforderungen, des Vorgehens und der Ergebnisse (Hauptbericht). Nagra Tech. Rep. NTB 08-03.

Nagra (2008d): Vorschlag geologischer Standortgebiete für das SMA- und das HAA-Lager – Geologische Grundlagen. Nagra Tech. Rep. NTB 08-04.

Nagra (2008e): Vorschlag geologischer Standortgebiete für ein SMA- und ein HAA-Lager: Begründung der Abfallzuteilung, der Barrierensysteme und der Anforderungen an die Geologie (Bericht zur Sicherheit und Machbarkeit). Nagra Tech. Rep. NTB 08-05.

Nagra (2008f): Modellhaftes Inventar für Radioaktive Materialien – MIRAM 08. Nagra Tech. Rep. NTB 08-06.

Nagra (2008g): Effects of post-disposal gas generation in a repository for low- and intermediate-level waste sited in the Opalinus Clay of Northern Switzerland. Nagra Tech. Rep. NTB 08-07.

Nagra (2009a): The Nagra Research, Development and Demonstration (RD&D) Plan for the disposal of radioactive waste in Switzerland. Nagra Tech. Rep. NTB 09-06.

Nagra (2009b): Standortunabhängige Grundlagen Anlagen und Betrieb SGT-ZE / SUG 2.3 – Alternatives Ausbaukonzept ("Liner Concept") für BE/HAA-Lagerstollen. Nagra Working Report NAB 09-07.

Nagra (2010a): Beurteilung der geologischen Unterlagen für die provisorischen Sicherheitsanalysen in SGT Etappe 2. Klärung der Notwendigkeit ergänzender geologischer Untersuchungen. Nagra Tech. Rep. NTB 10-01.

Nagra (2010b): PAMINA RTCD 2 Deliverable D2.2.E.1: Fully probabilistic safety assessment. Nagra Working Report NAB 10-37.

Nagra (2010c): Standortunabhängige Grundlagen Anlagen und Betrieb SGT Etappe 2 – Orientierende felsmechanische Berechnungen für BE/HAA-Lagerstollen in 400 m, 650 m und 900 m im intakten und gestörten Opalinuston. Nagra Working Report NAB 10-41.

Nagra (2011a): Sachplan geologische Tiefenlager Etappe 2 – Vorschläge zur Platzierung der Standortareale für die Oberflächenanlage der geologischen Tiefenlager sowie zu deren Erschliessung. Genereller Bericht. Nagra Tech. Rep. NTB 11-01.

Nagra (2011b): Stilllegungsstudie 2011: Radiologische Inventare der aktivierten Grundmaterien des KKL. Nagra Working Report NAB 11-11.

Nagra (2011c): Stilllegungsstudie 2011: Radiologische Inventare der aktivierten Grundmaterien des KKM. Nagra Working Report NAB 11-12.

Nagra (2011d): Stilllegungsstudie 2011: Radiologische Inventare der aktivierten Grundmaterien des KKB. Nagra Working Report NAB 11-13.

Nagra (2011e): Stilllegungsstudie 2011: Radiologische Inventare der aktivierten Grundmaterien des KKG. Nagra Working Report NAB 11-14.

Nagra (2013a): Standortunabhängige Betrachtungen zur Sicherheit und zum Schutz des Grundwassers – Grundlagen zur Beurteilung der grundsätzlichen Bewilligungsfähigkeit einer Oberflächenanlage für ein geologisches Tiefenlager. Nagra Tech. Rep. NTB 13-01.

Nagra (2013b): Sachplan geologische Tiefenlager Etappe 2, Standortareal JO-3+-SMA im Planungsperimeter Jura Ost für die Oberflächenanlage eines geologischen Tiefenlagers SMA, Planungsstudie. Nagra Working Report NAB 13-66.

Nagra (2013c): Sachplan geologische Tiefenlager Etappe 2, Standortareal JO-3+-HAA im Planungsperimeter Jura Ost für die Oberflächenanlage eines geologischen Tiefenlagers HAA, Planungsstudie. Nagra Working Report. NAB 13-67.

Nagra (2013d): Sachplan geologische Tiefenlager Etappe 2, Standortareal JO-3+-Kombi im Planungsperimeter Jura Ost für die Oberflächenanlage eines geologischen Tiefenlagers Kombi, Planungsstudie. Nagra Working Report NAB 13-68.

Nagra (2014a): SGT Etappe 2: Vorschlag weiter zu untersuchender geologischer Standortgebiete mit zugehörigen Standortarealen für die Oberflächenanlage: Sicherheitstechnischer Bericht zu SGT Etappe 2. Sicherheitstechnischer Vergleich und Vorschlag der in Etappe 3 weiter zu untersuchenden geologischen Standortgebiete. Nagra Tech. Rep. NTB 14-01.

Nagra (2014b): SGT Etappe 2: Vorschlag weiter zu untersuchender geologischer Standortgebiete mit zugehörigen Standortarealen für die Oberflächenanlage. Geologische Grundlagen. Dossiers I – VII. Nagra Tech. Rep. NTB 14-02.

Nagra (2014c): SGT Etappe 2: Vorschlag weiter zu untersuchender geologischer Standortgebiete mit zugehörigen Standortarealen für die Oberflächenanlage: Charakteristische Dosisintervalle und Unterlagen zur Bewertung der Barrierensysteme. Nagra Tech. Rep. NTB 14-03.

Nagra (2014d): Modellhaftes Inventar für Radioaktive Materialien – MIRAM 14. Nagra Tech. Rep. NTB 14-04.

Nagra (2014e): Provisional Safety Analyses for SGT Stage 2: Models, Codes and General Modelling Approach. Nagra Tech. Rep. NTB 14-09.

Nagra (2014f): Geochemical evolution of the L/ILW near-field. Nagra Tech. Rep. NTB 14-11.

Nagra (2014g): SGT Etappe 2: Biosphärenmodellierung für die provisorischen Sicherheitsanalysen. Nagra Working Report NAB 13-04.

Nagra (2014h): Long-term evolution of the Engineered Gas Transport System. Nagra Working Report NAB 14-16.

Nagra (2014i): Bautechnische Risikoanalyse zur Realisierung der Zugangsbauwerke. Nagra Working Report NAB 14-50.

Nagra (2014j): Ergänzende Sicherheitsbetrachtungen für die Untertageanlagen der geologischen Tiefenlager in der Betriebsphase: Vorgaben, Vorgehen und Dokumentation der Ergebnisse. Nagra Working Report NAB 14-51.

Nagra (2014k): Beurteilung der Tiefenlage in Bezug auf die geotechnischen Bedingungen: Grundlagen für die Abgrenzung und Bewertung der Lagerperimeter. Nagra Working Report NAB 14-81.

Nagra (2016a): Entsorgungsprogramm 2016 der Entsorgungspflichtigen. Nagra Tech. Rep. NTB 16-01.

Nagra (2016b): ENSI-Nachforderung zum Indikator "Tiefenlage im Hinblick auf bautechnische Machbarkeit" in SGT Etappe 2 – Zusammenfassende Darstellung der Zusatzdokumentation (Hauptbericht). Nagra Working Report NAB 16-41.

Nagra (2016c): ENSI-Nachforderung zum Indikator "Tiefenlage im Hinblick auf bautechnische Machbarkeit" in SGT Etappe 2 – Prüfung der Lager- und Barrierenkonzepte. Nagra Working Report NAB 16-42.

Nagra (2016d): ENSI-Nachforderung zum Indikator "Tiefenlage im Hinblick auf bautechnische Machbarkeit" in SGT Etappe 2 – Projektkonzepte für die Lagerkammern und Versiegelungsstrecken und deren Bewertung. Nagra Working Report NAB 16-45.

Nagra (2016e): ENSI-Nachforderung zum Indikator "Tiefenlage im Hinblick auf bautechnische Machbarkeit" in SGT Etappe 2 – Vortriebs- und Sicherungskonzepte für die Profile F, K09, K04, K04a und D (Ergänzende Unterlagen zu NAB 16-45). Nagra Working Report NAB 16-46.

Neuveiler, I., Sorensen, I. & Kinzelbach, W. (2004): Experimental and theoretical investigations of drainage in horizontal rough-walled fractures with different correlation structures. *Advances in Water Resources* 27, 1217-1231.

Newman, R.C. & Wang, S. (2010): Feasibility study of hydrogen monitoring during anaerobic corrosion of carbon steel in grouts. Nagra Working Report NAB 10-27.

Newman, R.C. & Wang, S. (2013): Understanding and quantifying the corrosion of carbon steel in grouts relevant to the Swiss L/ILW repository – Status reports 2011 and 2012. Nagra Working Report NAB 13-08.

Newman, R.C., Wang, S., Johnson, L. & Diomidis, N. (2013a): Carbon steel corrosion and hydrogen gas generation in cementitious grout. *Proceedings of the Gas Generation and Migration International Symposium and Workshop (FORGE)*, February 5-7, 2013, Luxembourg, 70-73.

Newman, R.C., Wang, S., Johnson, L. & Diomidis, N. (2013b): Carbon steel corrosion and hydrogen gas generation in cementitious grout under anoxic conditions. *Proceedings of the 5th International Workshop on Long-Term Prediction of Corrosion Damage in Nuclear Waste Systems*, October 6 – 10, 2013, Asahikawa, Japan.

Newman, R.C., Wang, S. & Senior, N. (2016): Understanding and quantifying the corrosion of carbon steel in grouts relevant to the Swiss L/ILW repository. Nagra Working Report NAB 15-17 Rev. 1.

Nilsson, U. (2014): Validation of retrieved sensors from he Prototype experiment at Äspö Hard Rock Laboratory. SKB Report P-13-31. Svensk Kärnbränslehantering AB, Stockholm.

Nussbaum, C., Girardin, C., Badertscher, N., Risse, V., Veuve, C., Mayoraz, J. & Bossart, P. (2010): Extension of the rock laboratory: Geological documentation of the Gallery 08 and adjacent niches (DR-A, MB, Niche 3 and TT). Unpubl. Mont Terri Technical Note. Mont Terri Project, Switzerland.

Ochs, M. & Talerico, C. (2004): SR-Can – Data and uncertainty assessment. Migration parameters for the bentonite buffer in the KBS-3 concept. SKB Technical Report TR-04-18. Svensk Kärnbränslehantering AB, Stockholm.

- Ochs, M., Vieille-Petit, L., Wang, L., Mallants, D. & Leterme, B. (2011): Additional sorption parameters for the cementitious barriers of a near-surface repository Project near-surface disposal of category A waste at Dessel DATA-LT(NF) Version 1. NIROND-TR 2010-06 E. ONDRAF/NIRAS, Bruxelles.
- Odom, J.M. & Peck, H.D. (1981): Hydrogen cycling as a general mechanism for energy coupling in the sulfate-reducing bacteria, *Desulfovibrio* sp.. FEMS Microbiology Letters 12, 47-50.
- OECD/NEA (2004): Die Sicherheit der geologischen Tiefenlagerung von BE, HAA und LMA in der Schweiz: Eine internationale Expertenprüfung der radiologischen Langzeitsicherheitsanalyse der Tiefenlagerung im Opalinuston des Zürcher Weinlands. OECD Nuclear Energy Agency, Issy-les-Moulineaux, France.
- OECD/NEA (2006): The NEA International FEP database, V. 2.1. OECD Nuclear Energy Agency, Paris.
- OECD/NEA (2012a): Methods for safety assessment of geological disposal facilities for radioactive waste: Outcomes of the NEA MeSA Initiative. OECD Nuclear Energy Agency, Paris.
- OECD/NEA (2012b): Burn-up credit criticality safety benchmark Phase VII. UO₂ Fuel: Study of Spent Fuel Compositions for Long-term Disposal. NEA (Paris).
- OECD/NEA (2013): The nature and purpose of the post-closure safety cases for geological repositories. NEA/RWM/R(2013)1. OECD Nuclear Energy Agency, Paris. www.oecd-nea.org.
- Oldberg, K. (2009): Distribution of fission gas release in 10 × 10 fuel. SKB Technical Report TR-09-25. Svensk Kärnbränslehantering AB, Stockholm.
- PAMINA (2011a): European handbook of the state-of-the-art of safety assessments of geological repositories. Part 1. Deliverable D1.1.4. European Commission, Brussels.
- PAMINA (2011b): PAMINA project summary report. Deliverable D5.1. European Commission, Brussels.
- Pantelias, M. (2013): Activation Neutronics for the Swiss Nuclear Power Plants. PhD Thesis, ETH Zurich.
- Pantelias, M. & Volmert, B. (2015): Activation Neutronics for a Swiss Pressurized Water Reactor. Nuclear Technology 192, 278-285, December 2015.
- Papafotiou, A. & Senger, R. (2014a): Thermo-hydraulic modelling of the temperature distribution in the siting region Nördlich Lägern. Nagra Working Report NAB 13-56.
- Papafotiou, A. & Senger, R. (2013): Thermo-hydraulic modelling of the temperature distribution in the siting region Zürich Nordost and Südrandten. Nagra Working Report NAB 13-97.
- Papafotiou, A. & Senger, R. (2014b): Thermo-hydraulic modelling of the temperature distribution in the siting region Jura Ost. Nagra Working Report NAB 14-39.

- Papafotiou, A. & Senger, R. (2014c): Sensitivity analyses of gas release from a L/ILW repository in the Opalinus Clay in the candidate siting regions of Northern Switzerland. Nagra Working Report NAB 13-92.
- Papafotiou, A. & Senger, R. (2014d): Sensitivity analyses of gas release from a SF/HLW repository in the Opalinus Clay in the candidate siting regions of Northern Switzerland. Nagra Working Report NAB 14-10.
- Papafotiou, A. & Senger, R. (2014e): Sensitivity study of gas release from a L/ILW repository – Comparison of the host rock formations in the different siting regions. Nagra Working Report NAB 14-98.
- Papafotiou, A. & Senger, R.K. (2016a): Sensitivity analyses of gas release from a L/ILW repository in the Opalinus Clay. Nagra Working Report NAB 16-07.
- Papafotiou, A. & Senger, R.K. (2016b): Sensitivity analyses of gas release from a SF/HLW repository in the Opalinus Clay. Nagra Working Report NAB 16-08.
- Partovi-Nia, R., Jacklin, R., Chen, J., Zagidulin, D., Ramamurthy, S., Keech, P.G. & Shoesmith, D.W. (2014): Surface analytical and electrochemical measurements on Cu-coated steel specimens. In: Book of abstracts of the European Corrosion Congress (Eurocorr 2014), September 8 – 12, Pisa, Italy.
- Patel, R., Punshon, C., Nicholas, J., Bastid, P., Zhou, R., Schneider, C., Bagshaw, N., Howse, D., Hutchinson, E., Asano, R. & King, F. (2012): Canister design concepts for disposal of spent nuclear fuel and high level waste. Nagra Tech. Rep. NTB 12-06.
- Patton, H., Swift, D.A., Clark, C.D., Livingstone, S.J., Cook, S.J. & Hubbard, A. (2015): Automated mapping of glacial overdeepenings beneath contemporary ice sheets: approaches and potential applications. Geomorphology 232, 209-223.
- Patton, H., Swift, D.A., Clark, C.D., Livingstone, S.J. & Cook, S.J. (2016): Distribution and characteristics of overdeepenings beneath the Greenland and Antarctic ice sheets: implications for overdeepening origin and evolution. Quaternary Science Reviews 148, 128-145.
- Payne, T.E., Brendler, V., Ochs, M., Baeyens, B., Brown, P.L., Davis, J.A., Ekberg, C., Kulik, D.A., Lutzenkirchen, J., Missana, T., Tachi, Y., Van Loon, L.R. & Altmann, S. (2013): Guidelines for thermodynamic sorption modelling in the context of radioactive waste disposal. Environmental Modelling & Software 42, 143-156.
- Pearson, F.J., Balderer, W., Loosli, H.H., Lehmann, B.E., Matter, A., Peters, T., Schmassmann, H. & Gautschi, A. (1991): Applied Isotope Hydrology – A Case Study in Northern Switzerland. Studies in Environmental Science 43, Elsevier, Amsterdam and Nagra Tech. Rep. NTB 88-01.
- Pearson, F.J., Arcos, D., Bath, A., Boisson, J.-Y., Fernández, A.M., Gaebler, H.E., Gaucher, E.C., Gautschi, A., Griffault, L., Hernan, P. & Waber, H.N. (2003): Geochemistry of water in the Opalinus Clay formation at the Mont Terri Rock Laboratory – Synthesis Report. Reports of the Federal Office of Water and Geology (FOWG), Geology Series No. 5.

- Pedersen, K., Bengsson, A., Edlund, J. & Eriksson, L. (2014): Sulphate-controlled diversity of subterranean microbial communities over depth in deep groundwater with opposing gradients of sulphate and methane, *Geomicrobiol. J.* 31, 617–631.
- Peehs, M., Garzarolli, F. & Goll, W. (1998): Assessment of dry storage performance of spent LWR fuel assemblies with increasing burn-up. IAEA International symposium on storage of spent fuel from power reactors, Vienna (Austria), 9-13 Nov. 1998. IAEA-SM-352/39.
- Petrini, K. & Simpson, G. (2008): Determination of stress (DS) experiment: 2D modelling of the stress distribution in the Mont Terri anticline. Unpubl. Mont Terri Technical Note. Mont Terri Project, Switzerland.
- Pettersson, S., Bodén, A. & Fries, T. (2007): Low-pH shotcrete for rock support: report on full scale demonstration. ESDRED Module 4 – Work Package 3.2, Deliverable 8.2.
- Peura, J., Sjöblom, V., Ritola, J., Holt, E. & Haapala, K. (2015): Manufacturing of buffer blocks, backfill blocks and pellets for Posiva's KBS-3V concept. LUCOEX Conference & Workshop, Oskarshamn, Sweden <http://www.lucoex.eu/conference/files/presentations/S4.3-Peura.pdf>
- Pietsch, J. & Jordan, P. (2014): Digitales Höhenmodell Basis Quartär der Nordschweiz – Version 2014 (SGT E2) und ausgewählte Auswertungen. Nagra Working Report NAB 14-02.
- Pike, S., Allen, C., Punshon, C., Threadgill , P., Gallegillo, M., Holmes, B. & Nicholas, J. (2010): Critical Review of Welding Technology for Canisters for Disposal of Spent Fuel and High Level Waste, Nagra Tech. Rep. NTB 09-05
- Pimenoff, N., Venäläinen, A. & Järvinen, H. (2012): Climate and sea level scenarios for Olkiluoto for the next 10'000 years. Posiva Report 2012-26. Posiva Oy, Helsinki.
- Pitty, A.F. & Alexander. W.R. (eds) (2011): A natural analogue study of cement buffered, hyperalkaline groundwaters and their interaction with a repository host rock IV: an examination of the Khushaym Matruk (central Jordan) and Maqrin (northern Jordan) sites. Bedrock Geosciences Technical Report 11-02.
- Plenkers, K. (2014): Das neue Schwachbebennetz in der Nordschweiz: Standortsuche, Standortauswahl, realisierte Stationen. Nagra Working Report NAB 14-56.
- Plötze, M. & Valter, M. (2011): Bentonite as barrier material – Thermal conductivity of compacted bentonite. Nagra Working Report NAB 11-16.
- Plötze, M. & Weber, H. (2007): ESDRED: Emplacement tests with granular bentonite MX-80 – Laboratory results from ETH Zürich. Nagra Working Report NAB 07-24.
- Poller, A., Smith, P., Mayer, G. & Hayek, M. (2014): Modelling of radionuclide transport along the underground access structures of deep geological repositories. Nagra Tech. Rep. NTB 14-10.
- Posiva (2012a): Safety Case for the disposal of spent nuclear fuel at Olkiluoto – Synthesis 2012. Posiva Report 2012-12. Posiva Oy, Helsinki.
- Posiva (2012b): Description of KBS-3H Design Variant. Posiva Report 2012-50. Posiva Oy, Helsinki. ISBN 978-951-652-232-9.

Posiva (2013): Safety Case for the Disposal of Spent Nuclear Fuel at Olkiluoto – Models and Data for the Repository System 2012. Parts 1 & 2. Posiva Report 2013-01. Posiva Oy, Helsinki.

Posiva (2014): Safety Case for the Disposal of Spent Nuclear Fuel at Olkiluoto: FEP Screening and Processing. Posiva Report 2014-03. Posiva Oy, Helsinki.

Preusser, F., Graf, H.R., Keller, O., Krayss, E. & Schlüchter, C. (2011): Quaternary glaciation history of northern Switzerland. *Eiszeitalter und Gegenwart/Quaternary Science Journal* 60, 282-305.

Raiko, H. (2012): Canister Design 2012. POSIVA 2012-13. Posiva Oy, Eurajoki.

Reisdorf, A.G., Wetzel, A., Schlatter, R. & Jordan, P. (2011): The Staffelegg Formation: a new stratigraphic scheme for the Early Jurassic of northern Switzerland. *Swiss Journal of Geosciences* 104/1, 97-146.

Reisdorf, A.G., Hostettler, B., Waltschew, A., Jaeggi, D. & Menkveld-Gfeller, U. (2014): Biostratigraphy of the basal part of the Opalinuston of the Mont Terri rock laboratory, Switzerland, SO Experiment. *Mont Terri Technical Report TR 2014-07*. Mont Terri Project, Switzerland.

Ricca, S. & Monti, G. (2014): Safety considerations for a trackless transport system (heavy load vehicle) for a future geological repository. Nagra Working Report NAB 14-78.

Robinson, P.C. (2013): STMAN: User Guide and Theoretical Background for Version 5.9. Nagra Working Report NAB 13-20.

Robinson, P.C. & Watson, C. (2013): PICNIC-TD: User Guide for Version 1.4. Nagra Working Report NAB 13-21.

Roche, V., Homberg, C. & Rocher, M. (2013): Fault nucleation, restriction, and aspect ratio in layered sections: Quantification of the strength and stiffness roles using numerical modeling. *Journal of Geophysical Research: Solid Earth* 118, 4446-4460.

Röllin, S., Spahiu, K. & Eklund, U-B. (2001): Determination of dissolution rates of spent fuel in carbonate solutions under different redox conditions with a flow-through experiment. *Journal of Nuclear Materials* 297, 231-243.

Rondinella, V.V., Wiss, T.A.G., Papaioannou, D., Nasyrow, R., Van Winckel, S., Serrano-Purroy, D. & Wegen, D.H. (2013): Nuclear fuel safety after discharge: property evolution and testing. Proc. Int. Conf. on LWR Fuel Performance (Topfuel 2013), Sept. 15-19, Charlotte, USA, ANS, paper 8539, 595-602.

Rondinella, V.V., Wiss, T.A.G., Papaioannou, D., Nasyrow, R., Cappia, F., Van Winckel, S., Serrano-Purroy, D. & Wegen, D.H. (2015): Spent nuclear fuel characterization in view of long-term storage. Proc. 15th International High-Level Radioactive Waste Management Conference (IHLRWMC), Charleston, April 12-16, ANS, Paper 12715, 479-485.

RPG (1979): Bundesgesetz über die Raumplanung (Raumplanungsgesetz, RPG) vom 22. Juni 1979, Stand am 1. Januar 2016. Systematische Sammlung des Bundesrechts SR 700, Schweiz.

- Rufer, D. & Waber, H.N. (2015): Noble and reactive gas data of porewaters and rocks from the Schlattingen borehole SLA-1. Nagra Working Report NAB 15-12.
- Rüedi, J., Teodori, S., Trick, T., Steiner, P., García-Siñeriz, J.L., Wetzig, V. & Reinhold, M. (2011): GAST (Gas-permeable seal test) Design Report. Nagra Working Report NAB 11-24.
- Rüedi, J., Teodori, S., Spillmann, T., Reinhold, M., Trick, T., Keller, M., Steiner, P., Isler, S., Gräfe, K., García-Siñeriz, J.L., Palacios Jimenez, B., Jacobs, F., Eiholzer, L., Maurer, H.R., Tisato, N. & Marelli, S. (2012): Gas-Permeable Seal Test at GTS. As-Built Report. Nagra Working Report NAB 12-59.
- Rüdebusch, A. (2008): Evaluation of methods for mineralisation of organic radioactive materials such as ion-exchange resins, translated in 2010. Nagra Working Report NAB 08-20E.
- Sasahara, A. & Matsumura, T. (2008): Post-irradiation examination focused on fuel integrity of spent BWR-MOX and PWR-UO₂ fuels stored for 20 years. Nucl. Eng. Design 238, 1250-1259.
- Sakaki, T., Köhler, S., Hertrich, M. & Müller, H.R. (2015): FE/LucoeX: Density measurement of granulated bentonite mixture in a full scale mockup test using dielectric tools. Lucoex Conference and Workshop, Oskarshamn, Sweden, 221.
- Savage, D. (2014): An assessment of the impact of the degradation of engineered structures on the safety-relevant functions of the bentonite buffer in a HLW repository. Nagra Tech. Rep. NTB 13-02.
- Schlatter, A. (2013): Rezente vertikale Oberflächenbewegungen in der Nordschweiz und in Südwesdeutschland – Kinematische Ausgleichung der Landesnivelllementlinien CH/D. Nagra Working Report NAB 12-34.
- Schwyn, B. (2008): Geochemische Nahfeld-Daten für die sicherheitstechnischen Betrachtungen zum Sachplan geologische Tiefenlager, Etappe 1. Nagra Working Report NAB 08-51.
- Scully, J.R. & Edwards, M. (2013): Review of the NWMO copper corrosion allowance. NWMO Technical Report TR-2013-04. Nuclear Waste Management Organization, Toronto, Canada.
- Seiphoori, A. (2014): Thermo-hydro-mechanical characterisation and modelling of MX-80 granular bentonite. Thèse EPFL, n° 6159. Ecole polytechnique fédérale de Lausanne.
- Seiphoori, A., Ferrari, A. & Laloui, L. (2014): Water retention behaviour and microstructural evolution of MX-80 bentonite during wetting and drying cycles. Géotechnique 64/9, 721-734, <http://dx.doi.org/10.1680/geot.14.P.017>.
- Sellin, P. (ed.) (2014): Experiments and modelling on the behaviour of EBS. FORGE Report D.3.38. Euratom 7th Framework Programme Project FORGE.
- Sellin, P. & Leupin, O. (2013): The use of clay as an engineered barrier in radioactive waste management – a review. Clays and Clay Minerals 61/6, 477-498.

- Senger, R.K. & Ewing, J.E. (2008): Evolution of temperature and water content in the bentonite buffer: Detailed modelling of two-phase flow processes associated with the early closure period – Complimentary simulations. Nagra Working Report NAB 08-53.
- Senger, R. & Ewing, J. (2009): Gas-L/ILW: Gas pressure buildup and transport in a deep geo-logic L/ILW repository in Opalinus Clay using large-scale and local-scale models. Nagra Working Report NAB 09-17.
- Senger, R. & Marschall, P. (2008): Task Force on EBS/Gas Transport in Buffer Material. Nagra Working Report NAB 08-24.
- Senger, R.K. & Papafotiou, A. (2014): Effects of salt enrichment in L/ILW caverns and SF/HLW tunnels due to water consumption by iron corrosion. Nagra Working Report NAB 13-72.
- Senger, R., Zuidema, P., Hugi, M., Mishra, S. & Jaquet, O. (1994): Investigating the effects of near-field characteristics on gas and water transport from UILW Repository. Proceedings of Post-Conference Seminar No. 10 of 12th International Conference on Structural Mechanics in Reactor Technology SMiRT-12, Stuttgart, August 15 – 20, 1993, 163-198.
- Senger, R., Papafotiou, A. & Marschall, P. (2013): Gas related property distributions in the proposed host rock formations of the candidate siting regions in Northern Switzerland and in the Helvetic Zone. Nagra Working Report NAB 13-83.
- Senger, R., Papafotiou, A. & Marschall, P. (2014a): Thermo-hydraulic simulations of the near-field of a SF/HLW repository during early- and late-time post-closure period. Nagra Working Report NAB 14-11.
- Senger, R.K., Lanyon, G.W. & Marschall, P. (2014b): Modeling the Hydraulic and Two-phase Flow Behaviour of the Heterogeneous, Fractured EDZ in the Opalinus Clay During the HG-A experiment at the Mont Terri URL. Extended Abstract We 10. Fourth EAGE Shale Workshop. Shales: What do they have in common? 6-9 April 2014, Porto, Portugal, S. 5.
- Senior, N.A, Newman, R.C., Abghari, B. & Keech, P.G. (2013): Influence of pH, temperature, and salinity upon anoxic copper corrosion. Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, Paper No. 3521. Asheville, NC, USA: NACE International, 1-9.
- SFOE (2000): EKRA, Disposal Concepts for Radioactive Waste – Final Report, 31 January 2000. Swiss Federal Office of Energy, www.bfe.admin.ch
- SFOE (2008): Sectoral plan for deep geological repositories. Conceptual part. Swiss Federal Office of Energy, Bern [German Version was revised in 2011].
- SFOE (2010): Forschungsprogramm Radioaktive Abfälle: Literaturstudie zum Stand der Markierung von geologischen Tiefenlagern. Swiss Federal Office of Energy, Bern.
- SFOE (2014a): Newsletter Tiefenlager, Nr. 12, April 2014. Swiss Federal Office of Energy, Bern.
- SFOE (2014b): Sachplan geologische Tiefenlager: Sozioökonomisch-ökologische Wirkungsstudie SÖW in Etappe 2. Schlussbericht. Swiss Federal Office of Energy, Bern.

- SFOE (2016): <http://www.bfe.admin.ch/radioaktiveabfaelle/01277/01308/index.html?lang=en>.
- Shafizadeh, A. (*in prep.*): Porosity and structural changes at cement/clay interfaces and their relations to transport properties. PhD LES/PSI. Paul Scherrer Institute, Würenlingen.
- Shafizadeh, A., Gimmi, T., Van Loon, L.R., Kaestner, A., Lehmann, E., Maeder, U.K. & Churakov, S.V. (2015): Quantification of water content across a cement-clay interface using high resolution neutron radiography. Physics Procedia 69, 516-523.
- SHARC Consortium (2010): SHARC – Annual Progress Report 2010. Commercial-in-Confidence. Unpublished Nagra Project Report.
- SHARC Consortium (2012a): The SHARC JIP Second Annual Report 2011. Commercial-in-Confidence. Unpublished Nagra Project Report.
- SHARC Consortium (2012b): The SHARC JIP Third Annual Report 2012. Commercial-in-Confidence. Unpublished Nagra Project Report.
- SHARC Consortium (2012c): The SHARC JIP Final Report – Highlights. Commercial-in-Confidence. Unpublished Nagra Project Report.
- Shaw, R.P. (2014): Principal outcomes of the FORGE (Fate of repository gases) Project. Euratom 7th Framework Programme Project, <http://www.bgs.ac.uk/forge/docs/reports/D0.8-R.pdf>
- Shoemaker, D.W. (2008): The role of dissolved hydrogen on corrosion/dissolution of spent nuclear fuel. NWMO TR-2008-19.
- Shoemaker D.W. (2013): Chemistry/Electrochemistry of Spent Nuclear Fuel as a Wasteform. Chapter 11: Uranium; Cradle to Grave. In: Burns, P. & Sigmon, G. (eds.): Mineralogical Association of Canada, Short Course 43, 337-368.
- Sindern, W. & Borowski, S. (2014): Sicherheitstechnische Betrachtungen zu Schachtförderanlagen für den Zugang zu einem zukünftigen geologischen Tiefenlager. Nagra Working Report NAB 14-75.
- Sitz, P. (2002): Verschlusskonzept Geologisches Tiefenlager Opalinuston. Unpubl. Nagra Internal Rep.
- SKB (2010a): Corrosion calculations report for the safety assessment SR-Site. SKB Technical Report TR-10-66. Svensk Kärnbränslehantering AB, Stockholm, Sweden.
- SKB (2010b): FEP report for the safety assessment SR-Site. SKB Technical Report TR 10-45. Svensk Kärnbränslehantering AB, Stockholm.
- SKB (2011): Long-term safety for the final repository for spent nuclear fuel at Forsmark: Main report of the SR-Site project. SKB Technical Report TR-11-01. Svensk Kärnbränslehantering AB, Stockholm.
- SKB (2014a): FEP report for the safety assessment SR-PSU. SKB Technical Report TR 14-07. Svensk Kärnbränslehantering AB, Stockholm.

SKB (2014b): Data report for the safety assessment SR-PSU. SKB Report Technical Report TR 14-10. Svensk Kärnbränslehantering AB, Stockholm.

Small, J., Nykyri, M., Helin, M., Hovi, U., Sarlin, T. & Itävaara, M. (2008): Experimental and modelling investigations of the biogeochemistry of gas production from low and intermediate level radioactive waste. *Appl. Geochem.* 23/6, 1383-1418.

Smart, N., Rance, A.P., Reddy, B. & Diomidis, N. (2014): The corrosion of carbon steel embedded in bentonite under anoxic conditions. In: Book of abstracts of the European Corrosion Congress (Eurocorr 2014), September 8-12, Pisa, Italy.

Smith, P.A. & Poller, A. (2012): The Nagra Resistor Network Code. Nagra Working Report NAB 12-36.

Smith, P., Gribi, P., Mayer, G. & Schneider, J. (2004): Project Opalinus Clay (Entsorgungsnachweis): Supplementary calculations to illustrate the influence of EDZ hydraulic conductivity on radionuclide transport. Nagra Working Report NAB 04-12.

Soltermann, D., Marques Fernandes, M., Baeyens, B., Daehn, R., Miehe-Brendle, J., Wehrli, B. & Bradbury, M.H. (2013): Fe(II) Sorption on a synthetic montmorillonite. A combined macroscopic and spectroscopic study. *Environ. Sci. Technol.* 47/13, 6978-6986.

Sorenson, K., Hanson, B. & Saltzstein, S. (2015): An integrated approach to closing the technical data gap for high burnup spent fuel performance during normal conditions of transport (NCT). IAEA International Conference on Management of Spent Fuel from Nuclear Power Reactors, Vienna, Austria, June 15-19.

Spillmann, T., Senger, R., Lanyon, G.W., Giroud, N. & Marschall, P. (2015): Preliminary analyses and numerical modeling of the gas permeable seal test (GAST) at the Grimsel Test Site, Switzerland. Proceedings TOUGH Symposium 2015, Berkeley, September 28-30, 2015, p. 8.

Stein, M. (*in prep.*): Möglichkeiten zur Vorbehandlung potenziell gasbildender schwach- und mittelaktiver Abfälle in der Schweiz. Nagra Working Report NAB 15-20.

Stroes-Gascoyne, S. (2011): Microbiological characteristics of compacted bentonite for a dry density of 1450 kg/m³: A literature review. Nagra Working Report NAB 11-05.

Stroes-Gascoyne, S., Schippers, A., Schwyn, B., Poulain, S., Sergeant, C., Simonoff, M., Le Marrec, C., Altmann, S., Nagaoka T., Mauclaire, L., McKemnzie, J., Daumas, S., Vinsot, A., Beaucaire, C. & Matray, J.-M. (2007): Microbial community analysis of Opalinus Clay drill core samples from the Mont Terri Underground Research Laboratory, Switzerland. *Geomicrobiology Journal* 24, 1-17.

Stroes-Gascoyne, A.S., Sergeant, C., Schippers, A., Hamon, C.J., Nèble, S., Vesvres, M.-H., Poulain, S. & Le Marrec, C. (2008): Microbial analyses of PC water and overcore samples: Synthesis of results. Unpubl. Mont Terri Technical Note. Mont Terri Project, Switzerland.

Stroes-Gascoyne, S., Frutschi, M., Hamon, C., Bagnoud, A., Leupin, O. & Bernier-Latmani, R. (2013): MA experiment: Role of moisture, bentonite density and water activity on the development of microorganisms in the bentonite after its dismantling from the EB experiment Unpubl. Mont Terri Technical Note. Mont Terri Project, Switzerland.

StSG (1991): Strahlenschutzgesetz (StSG) [Radiation Protection Act] vom 22. März 1991, Stand am 1. Januar 2007. Systematische Sammlung des Bundesrechts SR 814.50, Schweiz.

StSV (1994): Strahlenschutzverordnung (StSV) [Radiation Protection Ordinance] vom 22. Juni 1994, Stand am 1. Januar 2014. Systematische Sammlung des Bundesrechts SR 814.501, Schweiz.

Studer, M. & Zanini, M. (2013): Aufbau und Betrieb eines eigenständigen CORS-GNSS Netzes – Kurzbericht (für interessierte Dritte). Nagra Working Report NAB 10-14.

Svemar, C., Johannesson, L.-E., Grahm, P., Svensson, D., Kristensson, O., Lönnqvist, M. & Nilsson, U. (2016): Prototype Repository. Opening and retrieval of outer section of Prototype Repository at Äspö Hard Rock Laboratory. Summary report. SKB Technical Report TR-13-22. Svensk Kärnbränslehantering AB, Stockholm.

Svensson, D., Dueck, A., Nilsson, U., Olsson, S., Sandén, T., Lydmark, S., Jägerwall, S., Pedersen, K. & Hansen, S. (2011): Alternative buffer material. Status of the ongoing laboratory investigation of reference materials and test package 1. SKB Technical Report TR-11-06. Svensk Kärnbränslehantering AB, Stockholm, 146 pp.

Swanton, S.W., Baston, G.M.N. & Smart N.R. (2015): Rates of steel corrosion and carbon-14 release from irradiated steels – state of the art review. CAST project Document No: CAST-2015-D2.1.

swissnuclear (2013): Probabilistic Seismic Hazard Analysis for Swiss Nuclear Power Plant Sites – PEGASOS Refinement Project. Final Report, Vol. 1-5.

Szakálos, P. & Seetharaman, S. (2012): Corrosion of copper canister. SMM Technical Note 2012-17. Strål Säkerhets Myndigheten, Sweden.

Te Kamp, L. & Konietzky H. (2009): Numerical Modelling of the Thermo – Hydro – Mechanical Loading in a geological repository for HLW and SF. Nagra Working Report NAB 09-25.

Tevissen, E., Soler, J.M., Montarnal, P., Gautschi, A. & Van Loon, L.R. (2004): Comparison between in situ and laboratory diffusion studies of HTO and halides in Opalinus Clay from Mont Terri. Radiochim. Acta 92, 781-786.

Texier, D., Degnan, P., Loutre, M.F., Paillard, D. & Thorne, M. (2003): Modelling Sequential BIOsphere Systems under CLIMate Change for Radioactive Waste disposal. Project BIOCLIM. Proceedings of the international high-level waste management conference (30.3-2.4.2003, Las Vegas, U.S.A.).

Thien, B.M.J. (2010): Développement des bases théoriques nécessaires à la modélisation de la vitesse résiduelle d'altération en milieux aqueux des verres nucléaires AVM. Ph.D. Thesis, Univ. Montpellier II, France.

Thien, B.M.J., Godon, N., Hubert, F., Angeli, F., Gin, S. & Ayrat, A. (2010): Structural identification of a trioctahedral smectite formed by the aqueous alteration of a nuclear glass. Applied Clay Science 49, 135-141.

- Thien, B.M.J., Godon, N., Ballestrero, A., Gin, S. & Ayral, A. (2012): The dual effect of Mg on the long-term alteration rate of AVM nuclear waste glasses. *J. Nucl. Mat.* 427, 297-310.
- Thoenen, T., Hummel, W., Berner, U. & Curti, E. (2014): The PSI/Nagra Chemical Thermo-dynamic Database 12/07. Nagra Working Report NAB 14-49.
- Thöny, R. (2014): Geomechanical analysis for excavation-induced rock mass behavior of faulted Opalinus Clay at the Mont Terri Underground Rock Laboratory (Switzerland). Diss. ETH. No 21415. ETH, Zürich.
- Thury, M., Gautschi, A., Mazurek, M., Müller, W.H., Naef, H., Pearson, F.J., Vomvoris, S. & Wilson, W. (1994): Geology and hydrogeology of the crystalline basement of Northern Switzerland. Nagra Tech. Rep. NTB 93-01.
- USG (1983): Bundesgesetz über den Umweltschutz (Umweltschutzgesetz, USG) [Environmental Protection Act] vom 7. Oktober 1983, Stand am 1. August 2016. Systematische Sammlung des Bundesrechts SR 814.01, Schweiz.
- UVEK (2009): Verordnung des UVEK über die Gefährdungsannahmen und die Bewertung des Schutzes gegen Störfälle in Kernanlagen vom 17. Juni 2009, Stand am 1. August 2009. Systematische Sammlung des Bundesrechts SR 732.112.2, Schweiz.
- Valance, S. & Bertsch, J. (2015): Hydrides reorientation investigation of high burn-up PWR fuel cladding, *Journal of Nuclear Materials* 464, 371–381.
- Valcke, E. (2007): Integrated in situ corrosion test on α -active high-level waste (SF/HLW) glass – Phase 2 (CORALUS-2). European Commission, Contract No FIKW-CT-2000-0001. Final Report.
- Valter, M. (2015): Influence of physical factors on properties of clays in the radioactive waste disposal. Diss. ETH No. 22755, ETH Zürich.
- Valter, M. & Plötze, M. (2013): Bentonite – Behaviour at elevated temperature (interim report): Investigation of the behaviour of bentonite treated at different near-field relevant conditions (temperature, degree of saturation). Nagra Working Report NAB 13-42.
- Van Loon, L. (2014): Effective diffusion coefficients and porosity values for argillaceous rocks and bentonite: Measured and estimated values for the Provisional Safety Analyses for SGT-E2. Nagra Tech. Rep. NTB 12-03.
- Van Loon, L.R. & Mibus, J. (2015): A modified version of Archie's law to estimate effective diffusion coefficients of radionuclides in argillaceous rocks and its application in safety analyses. *Appl. Geochem.* 59, 85-94.
- Van Loon, L.R. & Soler, J.M. (2004): Diffusion of HTO, $^{36}\text{Cl}^-$, $^{125}\text{I}^-$ and $^{22}\text{Na}^+$ in Opalinus Clay: Effect of confining pressure, sample orientation, sample depth and temperature. PSI-Bericht 04-03 and Nagra Tech. Rep. NTB 03-07.
- Van Loon, L.R., Soler, J.M., Müller, W. & Bradbury, M.H. (2004a): Anisotropic diffusion in layered argillaceous rocks: a case study with Opalinus Clay. *Environ Sci. Technol.* 38, 5721-5728.

- Van Loon, L.R., Wersin, P., Soler, J.M., Eikenberg, J., Gimmi, Th., Hernán, P., Dewonck, S. & Savoye, S. (2004b): In-situ diffusion of HTO, $^{22}\text{Na}^+$, Cs^+ and I^- in Opalinus Clay at the Mont Terri underground rock laboratory. *Radiochim. Acta* 92, 757-763.
- Van Loon, L.R., Müller, W. & Iijima, K. (2005a): Activation energies of the self-diffusion of HTO, $^{22}\text{Na}^+$ and $^{36}\text{Cl}^-$ in a highly compacted argillaceous rock (Opalinus Clay). *Appl. Geochem.* 20, 961-972.
- Van Loon, L.R., Baeyens, B. & Bradbury, M.H. (2005b): Diffusion and retention of sodium and strontium in Opalinus Clay: Comparison of sorption data from diffusion and batch sorption measurements, and geochemical calculations. *Appl. Geochem.* 20, 2351-2363.
- Van Loon, L.R., Glaus, M.A. & Müller, W. (2007): Anion exclusion effects in compacted bentonites: towards a better understanding of anion diffusion. *Appl. Geochem.* 22, 2536-2552.
- Van Loon, L.R., Baeyens, B. & Bradbury, M.H. (2009): The sorption behaviour of caesium on Opalinus Clay: a comparison between intact and crushed material. *Appl. Geochem.* 24, 999-1004.
- Van Loon, L.R., Glaus, M.A., Ferry, C. & Latrille, C. (2012): Section 12: Studying radionuclide migration on different scales: the complementary roles of laboratory and in situ experiments. In: Poinsot, C. & Geckeis, H. (eds.): Radionuclide behaviour in the natural environment: Science, implications and lessons for the nuclear industry. Woodhead Publishing Limited, 446-483.
- Vernaz, E.Y. & Dussossoy, J.L. (1992): Current state of knowledge of nuclear waste glass corrosion mechanisms: the case of R7T7 glass. *Appl. Geochem., Suppl. Issue 1*, 13-22.
- Vietor, T., Armand, G., Nyonoza, S., Schuster, K. & Wieczorek, K. (2010): Excavation induced damage evolution during a mine-by experiment in Opalinus Clay. Clays in natural & engineered barriers for radioactive waste confinement: Abstracts. 4th international meeting, Nantes, March 29 – April 1st, 2010, ANDRA, Chatenay-Malabry, 2010, 207-208.
- Villar, M.V., Martín, P.L., Romero, F.J., Barcala, J.M. & Gutiérrez-Rodrigo, V. (2012): Gas transport through bentonite: influence of dry density, water content and boundary conditions. In: Skoczyłas, F., Davy, C.A., Agostini, F. & Burlion, N. (eds.): Propriétés de Transfert des Géomatériaux. Transfert 2012, Actes du Colloque, 379-389.
- Vinsot, A., Appelo, C. A.J., Lundy, M., Wechner, S., Lettry, Y., Lerouge, C., Fernández, A.M., Labat, M., Tournassat, C., De Cannière, P.D., Schwyn, B., McKelvie, J., Dewonck, S., Bossart, P. & Delay, J. (2014): In situ diffusion test of hydrogen gas in the Opalinus Clay. *Geol. Soc. Lond. Spec. Publ.* 400, 563-578. doi:10.1144/SP400.12
- Vlassopoulos, E. (2015): Development of an optimization code for the logistics of spent fuel assembly loading into final disposal canisters. MSc thesis, ETH Zurich.
- Vogt, T., Müller, H.R., Sakaki, T. & Vietor, T. (2013): Monitoring THM effects in a full scale EBS/host rock system – first experiences of the FE-Experiment in the Mont Terri URL during construction and ventilation phase. Proceedings of the MoDeRn International Repository Monitoring Conference and Workshop held on 19 – 21 March 2013 in Luxembourg, 326-334.

- Vogt, T., Müller, H.R., Sakaki, T., Hertrich, M., Spillmann, T., Garitte, B., Giroud, N. & Vietor, T. (2015): FE Experiment: The instrumentation and monitoring concept of a 1:1-scale heater experiment at the Mont Terri URL. CLAY conference – Clays in Natural and Engineered Barriers for Radioactive Waste Confinement, Brussels, 728-729.
- Vomvoris, S. & Kickmaier, W. (2007): Grimsel Test Site – Phase VI: Review of accomplishments and next steps. Proceedings 11th ICEM'07 Conference, Bruges/Belgium, Sept 2-6, 2007, 7.
- Waber, H.N., Heidinger, M., Lorenz, G. & Traber, D. (2014): Hydrochemie und Isotopenhydrogeologie von Tiefengrundwässern in der Nordschweiz und im angrenzenden Süddeutschland. Nagra Working Report NAB 13-63.
- Waber, H.N., Rufer, D., Kennnell, L. & Traber, D. (2015): Multi-tracer profile at high spatial resolution across the Opalinus Clay at the Mont Terri URL. Clays in Natural and Engineered Barriers for Radioactive Waste Confinement. 6th Internal Conference, Brussels, March 23-26, 2015, Abstracts, 350-351.
- Walke, R. & Keesmann, S. (2013): Nagra's Biosphere Assessment Code SwiBAC 1.2: Model Definition. Nagra Working Report NAB 12-27.
- Walke, R., Thorne, M. & Limer, L. (2013a): Nagra Biosphere Modelling: Review of Generic Data. Nagra Working Report NAB 13-49.
- Walke, R., van Dorp, F. & Keesmann, S. (2013b): Biosphere Modelling for C-14: Description of the Nagra Model. Nagra Working Report NAB 12-26.
- Wang, L., Martens, E., Jacques, D., De Cannière, P., Berry, J. & Mallants, D. (2009): Review of sorption values for the cementitious near field of a near surface radioactive waste disposal facility Project near surface disposal of category A waste at Dessel. NIRAS-MP5-03-03 Version 1. NIROND-TR-2008-23E, Bruxelles, Belgium.
- Wang, S., Newman, R.C., Johnson, L. & Diomidis, N. (2013): Anaerobic corrosion of carbon steel and gas generation in cementitious grout. In: Book of abstracts of the European Corrosion Congress (Eurocorr 2013), September 1 – 5, Estoril, Portugal.
- Warpinski, N.R. (1989): Determining the minimum in situ stress from hydraulic fracturing through perforations. International Journal of Rock Mechanics and Mining Sciences 26/6, 523-531.
- Warthmann, R., Mosberger, L. & Baier, U. (2013a): Langzeit-Degradation von organischen Polymeren unter SMA-Tiefenlagerbedingungen. Nagra Tech. Rep. NTB 13-04.
- Warthmann, R., Mosberger, L. & Baier, U. (2013b): Anaerober Abbau und Gasbildungskinetik für SMA in geologischen Tiefenlagern. Nagra Working Report NAB 13-52.
- Werme, L., Björner, I.K., Bart, G., Zwicky, H.U., Grambow, B., Lutze, W., Ewing, R.C. & Magrabi, C. (1990): Chemical corrosion of highly radioactive borosilicate nuclear waste glass under simulated repository conditions. J. Mater. Res. 5, 1130-1146.

- Wersin, P., Leupin, O.X.S., Mettler, S., Gaucher, E.C., Maeder, U., De Cannière, P., Vinsot, A., Gaebler, H.E., Kunimaro, T., Kiho, K. & Eichinger, L. (2011): Biogeochemical processes in a clay formation in situ experiment: Part A – Overview, experimental design and water data of an experiment in the Opalinus Clay at the Mont Terri Underground Research Laboratory, Switzerland. *Applied Geochemistry* 26, 931-953.
- Wersin, P., Mazurek, M., Waber, H.N., Mäder, U.K., Gimmi, T., Rufer, D. & de Haller, A. (2013): Rock and porewater characterisation on drillcores from the Schlattingen borehole. Nagra Working Report NAB 12-54.
- Wersin, P., Jenni, A. & Mäder, U. (2014): ABM Experiment (Test Package 1): A feasibility study on iron-bentonite interaction in block 3. Nagra Working Report NAB 14-24.
- Wersin, P., Mazurek, M., Waber, H.N., Mäder, U.K., Gimmi, T., Rufer, D., Lerouge, C., Oyama, T. & Traber, D. (2015a): Constraining porewater chemistry in a clay-rich rock sequence. *Clays in Natural and Engineered Barriers for Radioactive Waste Confinement*. 6th International Conference, Brussels, March 23-26, 2015, Abstracts, 332-333.
- Wersin, P., Traber, D. & Cloet, V. (eds.) (2015b): Workshop on porewater chemistry of clayrocks in repository environments. Basel/Switzerland, 27-29 October 2014. Nagra Working Report NAB 15-30.
- Wersin, P., Mazurek, M., Mäder, U.K., Gimmi, T., Rufer, D., Lerouge, C. & Traber, D. (2016): Constraining porewater chemistry in a 250 m thick argillaceous rock sequence. *Chemical Geology* 43/4, 43-61.
- Wettstein, S.J., Wittel, F.K., Araújo, N.A.M., Lanyon, B. & Herrmann, H.J. (2012): From invasion percolation to flow in rock fracture networks. *Physica A* 391, 264-277.
- Wetzig, V., Fries, T. & Iglesias, E. (2011): Low-pH shotcrete: Application as rock support for radioactive waste disposal. ITA-AITES World Tunnel Congress 2011, May 21-26, 2011, Helsinki Finland. ISBN 978-951-758-531-6.
- Wiborgh, M., Hoglund, L.O. & Pers, K. (1986): Gas formation in a L/ILW repository and gas transport in the host rock. Nagra Tech. Rep. NTB 85-17.
- Wieland, E. (2014): Sorption Database for the cementitious near field of L/ILW and ILW repositories for Provisional Safety Analyses for SGT-E2. Nagra Tech. Rep. NTB 14-08.
- Wieland, E. & Cvetkovic, B. (2016): Development of a Compound-specific Carbon-14 AMS Technique for the Detection of Carbon-14 Labelled Organic Compounds. CAST project Document No: CAST-2015-D2.3.
- Wieland, E. & Van Loon, L.R. (2002): Cementitious near field sorption database for performance assessment of ILW Repository in Opalinus Clay. Nagra Tech. Rep. NTB 02-20.
- Wieser, U., Burger, M. & Beyerle, P. (2014): Sicherheitstechnische Betrachtungen zu Zahnradbahnen für den Zugang zu einem zukünftigen geologischen Tiefenlager. Nagra Working Report NAB 14-76.
- Wigger, C., Van Loon, L. & Gimmi, T. (2015): Anion diffusion in low porosity argillaceous rocks. CLAY conference 'Clays in Natural and Engineered Barriers for Radioactive Waste Confinement', Brussels, 400-401.

- Wild, K.M., Wymann, L.P., Zimmer, S., Thoeny, R. & Amann, F. (2015): Water retention characteristics and state-dependent mechanical and petro-physical properties of a clay shale. *Rock Mechanics and Rock Engineering* 48/2, 427-439.
- Wileveau, Y. and Rothfuchs, T. (2007). THM behaviour of host rock (HE-D) Experiment: Study of Thermal effects on Opalinus Clay. Mont Terri Project, TR 2006-01.
- Wileveau, Y., Cornet, F.H., Desroches, J. & Blümling, P. (2007): Complete in situ stress determination in an argillite sedimentary formation. *J. Phys. Chem. Earth* 32, 866-878. doi:10.1016/j.pce.2006.03.018.
- Wilson, J., Savage, D., Bond, A., Watson, S., Pusch, R. & Bennett, D. (2011): Bentonite. A review of key properties, processes and issues for consideration in the UK context. QRS-1378ZG-1 Version 1.1, February 2011. 137 pp.
- Wimmers, K. & Koehrer, B. (2014): Integration of sedimentology, petrophysics and rock typing as key to understanding a tight gas reservoir. *Oil Gas European Magazine* 40/4, 196-200.
- Wiss, T., Hiernaut, J.P., Roudil, D., Colle, J.-Y., Maugeri, E., Talip, Z., Janssen, A., Rondinella, V., Konings, R.J.M., Matzke, H.-J. & Weber, W.J. (2014): Evolution of spent nuclear fuel in dry storage conditions for millennia and beyond. *Journal of Nuclear Materials* 451, 198-206.
- Yale, D.P. (2003): Fault and stress magnitude controls on variations in the orientation of in situ stress. *Geol. Soc., London, Spec. Publ.* 209/1, doi:10.1144/GSL.SP.2003.209.01.06, 55-64.
- Yamaguchi, T., Tanumas, S., Yasutomis, I., Nakayama, T., Tanabe, H., Katsurai, K., Kawamura, W., Maeda, K., Kitao, H. & Saigusa, M. (1999): A study on chemical forms and migration behavior of radionuclides in hull wastes. *Proceedings of ICEM 99*, September, Nagoya, Japan, ASME.
- Yamashita, Y., Tanabe, H., Sakuragi, T., Takahashi, R. & Sasoh, H. (2014): C-14 release behavior and chemical species from irradiated hull waste under geological disposal conditions. *Materials Research Symposium Proceedings* 1665, 187-194.
- Yang, Y.L. & Aplin, A.C. (2010): A permeability – porosity relationship for mudstones. *Marine and Petroleum Geology* 27/8, 1692-1697.
- Zang, A. & Stephansson, O. (2010): Stress field of the Earth's Crust. 1st ed., 323 pp. Springer, Heidelberg.
- Zoback, M.D. (2010): *Reservoir Geomechanics*, 449 pp. Cambridge.
- Zwicky, H.U., Grambow, B., Magrabi, C., Aerne, E.T., Bradley, R., Barnes, B., Gruber, Th., Mohos, M. & Werme, L.O. (1989): Corrosion behaviour of British Magnox Waste Glass in pure water. *Mat. Res. Soc. Proc.* 127, 129-136.

Appendix A

A.1 Decision of the Federal Council of August 2013 (translated)³⁶

Waste Management Programme and the report on the treatment of the recommendations made in the expert opinions and position statements on the "Entsorgungsnachweis" (demonstration of disposal feasibility): Public consultation on the decision of the Federal Council

of 28th August 2013

On 28th August 2013, the Federal Council approved the 2008 Waste Management Programme of the waste producers and took formal notice of the report on the treatment of the recommendations made in the expert opinions and position statements on the "Entsorgungsnachweis" (demonstration of disposal feasibility):

Decision on the 2008 Waste Management Programme of the waste producers and on the report of October 2008 on the recommendations made in the expert opinions and position statements on the "Entsorgungsnachweis" (demonstration of disposal feasibility)

The Federal Council of Switzerland finds:

1. With the submission of the Waste Management Programme of 2008 (Nagra 2008a), Nagra has fulfilled the legal obligation of the waste producers according to Article 32 of the Nuclear Energy Act and Article 52 of the Nuclear Energy Ordinance and paragraph 3 of the Resolution of the Federal Council of 2nd April 2008 on the Sectoral Plan for Deep Geological Repositories (conceptual part).
2. The Federal Council takes formal notice of the report on the treatment of the recommendations made in the expert opinions and position statements on the "Entsorgungsnachweis" (demonstration of disposal feasibility) (NTB 08-02). With submission of this report on behalf of the electricity utilities, Nagra has fulfilled paragraph 3 of the decision of the Federal Council of 28th June 2006 on the "Entsorgungsnachweis" (demonstration of disposal feasibility) for spent fuel assemblies, vitrified high-level waste and long-lived intermediate-level waste.
3. The next Waste Management Programme is to be submitted in 2016 together with the 2016 cost study.
4. Together with the application for construction of a deep geological repository, Nagra has to submit a report to the Federal Department of the Environment, Transport, Energy and Communications (DETEC) which provides estimates of the costs of retrieving the waste from a HLW, L/ILW or a combined repository during the monitoring phase, as well as the costs for retrieval after repository closure. In both cases, the costs of transporting the waste to an interim storage facility also have to be estimated.

³⁶ This translation is included to provide a broader context for non-German readers and is a free translation.

5. Conditions attached to the 2016 Waste Management Programme

5.1 *Application for construction of a deep geological repository:* In the update of the Waste Management Programme, Nagra has to explain how the results of investigations in a rock laboratory provide timely input for the nuclear construction application.

5.2 *L/ILW rock laboratory:* The planning of the underground rock laboratory for the L/ILW repository and the experiments to be conducted in the facility have to be specified and presented in more detail.

6. Conditions attached to the 2016 Waste Management Programme and the following:

6.1 *Research programme:* Nagra has to submit a Research, Development and Demonstration (RD&D) Plan together with the Waste Management Programme. The RD&D Plan has to document the purpose, scope, type and timing of future RD&D activities and the treatment of open questions. The report also has to document work being carried out on investigating the long-term stability of spent fuel assemblies during interim storage, the current status of science and technology regarding the long-term behaviour of spent fuel cladding tubes and the consequences arising from this. The 2016 RD&D Plan also has to include the understanding of the geotectonic evolution of the Hegau-Bodensee Graben and the role of cement minerals in the speciation and stabilisation of Fe(II) and Fe(III).

6.2 *Overall disposal system:* Future Waste Management Programmes have to show how the overall deep geological disposal system will be implemented technically and in terms of timing and how the individual research and development activities are linked with one another and with key milestones and decisions in the process of realising a deep geological repository. With regard to decision-making, Nagra has to show when and why which research projects will be undertaken and where and when the focus of activities will be. A range of alternatives have to be considered for safety-relevant decisions and a procedure selected that is suitable overall in terms of safety.

6.3 *Waste volumes:* In future Waste Management Programmes, the waste producers have to present the volumes of waste that are currently expected and show that these are upper estimates. Nagra also has to show what methods have been used for predicting waste volumes, what the differences are compared to earlier predictions and how these differences can be justified and interpreted.

6.4 *Implementation plan:* Future Waste Management Programmes have to show what preparations are being made for the long-term archiving of information on the deep geological repositories. For the application for a construction licence, the nuclear energy legislation and Guideline ENSI-G03 require a project to be submitted for the monitoring phase, a plan for repository closure and concepts for waste retrieval, marking and temporary closure in times of crisis. The preparations for these plans and projects have to be documented in future Waste Management Programmes.

6.5 *Taking into account experience and the current status of science and technology:* In the next Waste Management Programmes, Nagra has to show that it has taken into consideration all necessary measures in line with current experience and the state-of-the-art in science and technology to ensure that the legally defined protection objectives during construction and operation and after closure of a deep geological repository can be met. Appropriate optimisation measures that would bring additional benefits in terms of safety should also be documented and reviewed. In this connection, the appropriateness of such measures is to be interpreted in an overall context (i.e. also considering operational safety, long-term safety, safety during transport, personal doses, arisings of new wastes, etc.).

A.2 Summary of the documentation needed to meet the Swiss legal requirements related to the implementation of deep geological repositories for radioactive waste

| Authority decision | Documentation required | Source of requirement |
|--|--|--|
| Sectoral Plan – Stage 2 – Selection of at least two sites for the L/ILW and HLW repository | <p>Reports (document and support site selection). Include preliminary safety assessments and assessment of land use planning and environmental issues</p> <p>Submitted in December 2014</p> | Concept SGT |
| Licence for geological investigations at 2 sites selected in Stage 2 | <ul style="list-style-type: none"> a) Investigation programme b) Geological report c) Report on the potential impacts of the investigations on the geological conditions and the environment d) General maps and plans e) Indication of desired validity of the licence | KEV 58 |
| Sectoral Plan – Stage 3 – Site selection | <ul style="list-style-type: none"> a) Report supporting the selection of the respective sites for L/ILW and HLW b) Report on compliance with land use planning requirements <p>Both reports are also part of the general licence application</p> | Concept SGT |
| General licence | <ul style="list-style-type: none"> a) Safety analysis report and security report (incl. site characteristics, purpose and outline of project, anticipated exposure to radiation in the vicinity of the facility, details regarding staff and organisational structure, indication of long-term safety) b) Environmental impact report (EIA – Level 1) c) Report on compliance with land use planning requirements d) Concept for the monitoring period and closure of the facility e) Additional reports including: comparison of available options related to the safety of the deep geological repository, evaluation of the decisive properties for the selection of the site, cost estimate | <p>a – d: KEV 23 b: USG 10b, UVPV 9 and Appendix, 40.1/ 40.2 e: KEV 62</p> |
| Licence for underground geological investigations | <ul style="list-style-type: none"> a) Investigation programme b) Geological report c) Report on the potential impacts of the investigations on the geological conditions and the environment d) General maps and plans e) Indication of desired validity of the licence | KEV 58 |

(continued)

| Authority decision | Documentation required | Source of requirement |
|---|---|---|
| Construction licence | <ul style="list-style-type: none"> a) Facility concept/layout concept according to KEV 7 through 12 b) Environmental impact report (EIA – Level 2) c) Report on compliance with land use planning requirements d) Quality management programme for the project and construction phase e) Emergency protection concept f) Project for the monitoring period and plan for closure of the facility g) Report on compliance of the project with the general licence requirements | <p>a – g: KEV 24-2 and Appendix 4</p> <p>b: USG 10b, UVPV 9 and Appendix, 40.1/40.2</p> |
| Operating licence | <ul style="list-style-type: none"> a) Organisational and technical documentation, including safety report and security report b) Required documents for the operating licence c) Evidence of insurance cover d) Report on compliance of the facility with the requirements of the general licence and the construction licence | KEV 28-1, Appendices 3 and 4 |
| Preparation of monitoring phase | <p>Updated project for the monitoring phase:</p> <ul style="list-style-type: none"> a) Planned measures for monitoring the repository after emplacement of the waste has been completed b) Proposed duration of the monitoring period | KEV 68-1 |
| Licensing for closure of repository | <p>Closure project with reports addressing the following:</p> <ul style="list-style-type: none"> a) backfilling and sealing of the accesses to the disposal areas b) modifications needed to ensure long-term safety of the pilot facility c) backfilling and sealing the accesses to the repository d) assurance of long-term safety | KEV 69-2 |
| Release of the repository from the provisions of the nuclear energy legislation | Safety assessment report taking into account the effective implementation of the closure activities | ENSI-G03, 5.3.1 |
| Periodic updates | <ul style="list-style-type: none"> Updated Waste Disposal Programme Reports on cost estimates for decommissioning and waste disposal Research, Development and Demonstration Plan (RD&D Plan) Reports assessing the status and operation of the installation | <p>KEV 52 SEFV 4</p> <p>KEV 37 and Appendix 5</p> |

A.3 List of acronyms

| | |
|----------|---|
| ABM | Alternative Buffer Materials Project (Äspö experiment) |
| ABM-2 | Continuation of Alternative Buffer Materials Project (Äspö experiment) |
| AGNEB | Swiss Federal Workgroup for Nuclear Waste Disposal (<i>in german:</i> Arbeitsgruppe des Bundes für die nukleare Entsorgung) |
| Andra | National Radioactive Waste Management Agency, France (Agence nationale pour la gestion des déchets radioactifs) |
| ARE | Bundesamt für Raumförderung |
| Areva NC | French energy company (formerly COGEMA) |
| ASR | Alkali-silica reaction |
| BDG | Bois de la Glaive (former potential site for L/ILW) |
| BFE | Swiss Federal Office of Energy (<i>in german:</i> Bundesamt für Energie) |
| BGS | British Geological Survey |
| BIOPROTA | International Forum for Biosphere Modelling |
| BUC | Burnup Credit |
| BWR | Boiling Water Reactor |
| BZL | Storage facility operated by PSI for wastes from medicine, industry and research (<i>in german:</i> Bundeszwischenlager) |
| C-FRS | CRIEPI's Fractured Rock Studies |
| Ca | Calcium |
| CAST | CArbon-14 Source Term (EU project) |
| CATCLAY | Processes of Cation Migration in Clayrocks (EU project) |
| CD | Cyclic Deformations (Mont Terri experiment) |
| CEBAMA | Cement-based materials, properties, evolution, barrier functions (an EC Horizon 2020 collaborative project) |
| CERN | European Organization for Nuclear Research |
| CFM | Colloid Formation and Migration (Grimsel Test Site experiment) |
| CI | Cement Clay Interaction (Mont Terri experiment) |
| CLAYTRAC | Natural Tracer Profiles across Argillaceous Formations: The CLAYTRAC Project (OECD / NEA Clay Club Project) |
| COGEMA | <i>In french:</i> Compagnie générale des matières nucléaires; reprocessing of spent power reactor fuel at COGEMA La Hague site, merged together with Framatome and CEA Industrie to form Areva NC in 2001 |
| CRIEPI | Central Research Institute of Electric Power Industry of Japan |
| Cs | Cesium |
| CS | CO ₂ -Sealing integrity (Mont Terri experiment) |
| CSIRO | Commonwealth Scientific and Industrial Research Organisation |
| DBETec | DBE TECHNOLOGY GmbH ein Unternehmen der Deutschen Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe mbH (DBE) |

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|---------------------|---|
| DEM | Digital Elevation Model |
| DENSFILL | Subproject of FE Experiment in the Mont Terri URL for density emplacement of bentonite by a single screw conveyer |
| DETEC | Federal Department of the Environment, Transport, Energy and Communications |
| DFN | Discrete Fracture Network |
| DM-B | Long-term Deformation Measurement II (Mont Terri experiment) |
| DoE USA | U.S. Department of Energy |
| DR-A | Long-term Diffusion (Mont Terri experiment) |
| DR-B | Hydrogeochemistry and Transport Mechanisms (Mont Terri experiments) |
| DOPAS | Full-Scale Demonstration of Plugs and Seals (EU project) |
| DR | Radionuclide Diffusion and Retention (Mont Terri experiment) |
| EB | Engineered Barriers (Mont Terri experiment and EU project) |
| EBS | Engineered Barrier System |
| EBS Task Force | International Working Group for Modelling of Coupled THM Processes in Engineered Barriers (Äspö) |
| EC | European Community |
| EDZ | Excavation-Damaged Zone |
| EG | EDZ gas diffusion by carbon isotopes (Mont Terri Experiment) |
| EGT | Expert Group on Nuclear Waste Disposal (<i>in German:</i> Expertengruppe Geologische Tiefenlagerung), former |
| EGTS | Engineered Gas Transport System |
| EKRA | An expert group established by the Federal Department of the Environment, Transport, Energy and Communication (DETEC) to develop radioactive waste disposal concepts (Expertengruppe Entsorgungskonzepte für radioaktive Abfälle) |
| EIA – Level 1 and 2 | Environmental impact report |
| EMPA | Swiss Federal Laboratories for Materials Science and Technology, Dübendorf, Switzerland |
| ENSI | Swiss Federal Nuclear Safety Inspectorate (<i>in German:</i> Eidgenössisches Nuklearsicherheitsinspektorat), before 1.1.2009: Nuclear Safety Inspectorate (HSK) |
| EML | Environmental Biology Laboratory at EPFL, Lausanne |
| EPFL | Swiss Federal Institute of Technology, Lausanne (<i>in French:</i> Ecole polytechnique fédérale de Lausanne) |
| Erkat ER 600 | Hydraulic drum cutter |
| ESDRED | Engineering Studies and Demonstration of Repository Designs (EU project) |
| ESP | Enhanced Sealing Project (Atomic Energy of Canada Limited's Underground Research Laboratory, Canada) |
| ETHZ | Swiss Federal Institute of Technology, Zürich (<i>in German:</i> Eidgenössische Technische Hochschule Zürich) |
| EU | European Union |

| | |
|----------------|---|
| Euratom | European Atomic Energy Community, founded 1957 |
| EZ-B | Fracture generation (Mont Terri experiments) |
| FA | Fuel assembly |
| FE | Full-scale Emplacement experiment at Mont Terri |
| FEBEX | Full-scale Engineered Barriers Experiment for a Deep Geological Repository for High-level Waste in Crystalline Rock (Grimsel Test Site experiment) |
| FEBEX-DP | Full-scale Engineered Barrier Experiment – Dismantling Project (Grimsel Test Site experiment) |
| FEP | Features, Events and Processes |
| FGR | Fission gas release |
| First-Nuclides | Fast / Instant Release of Safety Relevant Radionuclides from Spent Nuclear Fuel (EU project) |
| FORGE | Fate of Repository Gases (EU project, Euratom 7 th Framework Programme Project) |
| FSS | Full Scale Seal Project at St. Dizier) |
| FUNMIG | FUNDamental processes in radionuclide MIGration (EU project) |
| GA08 | Gallery 08 in the Mont Terri URL |
| GAST | Full-scale GAs-permeable Seal Test (Grimsel Test Site experiment) |
| GLASTAB | Long-term behaviour of glass: Improving the glass source term and substantiating the basic hypotheses (EU project) |
| GMT | Gas MigraTion in EBS and geosphere (Grimsel Test Site experiment) |
| GNSS | Global Navigation Satellite System |
| GNW | Cooperative for Radioactive Waste Disposal, Wellenberg (<i>in German:</i> Genossenschaft für nukleare Entsorgung Wellenberg), Wolfenschiessen, dissolved in 2003 |
| GPZ-1 | Large-scale gas injection test GPZ-1 (Meuse/Haute Marne project) |
| GS/HG-D | Gasfrac self-sealing/Reactive gas transport in argillaceous formations (Mont Terri experiment) |
| GTS | Grimsel Test Site |
| HADES | Underground Research Facility in Mol, Belgium, operated by ONDRAF/NIRAS |
| HE-E | In-situ heater test (PEBS) (Mont Terri experiment and EU project) |
| HG-A | Gas paths through host rock and along seals (Mont Terri experiment) |
| HG-D | Reactive gas transport in argillaceous formations (Mont Terri experiment) |
| HLW | High-level waste |
| HM | Hydromechanical processes |
| HM-B | Mechanical suction in borecores (Mont Terri experiment) |
| HORIZON 2020 | EU Framework Programme for Research and Innovation with nearly €80 billion of funding available over 7 years (2014 to 2020) |
| HPF | Hyperalkaline Plume in Fractured rock (Grimsel Test Site experiment) |
| HSK | Nuclear Safety Inspectorate (Hauptabteilung für die Sicherheit der Kernanlagen), since 1.1.2009: Swiss Federal Nuclear Safety Inspectorate (ENSI) |

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|-------------------|---|
| HT | Hydrogen Transfer (Mont Terri experiment) |
| IAEA | International Atomic Energy Agency |
| IC-A | Corrosion of iron in bentonite (Mont Terri experiment) |
| ICRP | International Commission on Radiation/Radiological (in text) Protection |
| IGD-TP | Implementing Geological Disposal of Radioactive Waste Technology Platform |
| IGSC | OECD/NEA's Integration Group for the Safety Case |
| I/HLW | Intermediate and high level waste |
| ILW | Long-lived intermediate level waste |
| INTESC | International Experiences in Safety Cases for Geological Repositories |
| IRF | Instant Release Fraction |
| IRRC | Integrated Radionuclide Release Code |
| IRT | International Review Team of the OECD Nuclear Energy Agency |
| ISC | In-Situ Stimulation and Circulation Project |
| ISRAM | Information System for Radioactive Materials |
| JGB | Japanese Grouting Project (including experiments at Grimsel Test Site) |
| ITU / JRC-ITU | Institute for Transuranium Elements / Joint Research Centre – Institute for Transuranium Elements in Eggenstein-Leopoldshafen near Karlsruhe (Germany) |
| KBS-3V, KBS-3H | Posiva's emplacement concepts: KBS-3V (borehole emplacement), KBS-3H (in-tunnel emplacement) |
| KEG | Nuclear Energy Act (NEA) |
| KEV | Nuclear Energy Ordinance (NEO) |
| KIT | Karlsruher Institute of Technology |
| KKB | Beznau nuclear power plant |
| KKG | Gösgen nuclear power plant |
| KKL | Leibstadt nuclear power plant |
| KKM | Mühleberg nuclear power plant |
| KNE | Commission for Nuclear Waste Disposal (<i>in German:</i> Kommission Nukleare Entsorgung), replaced by Expert Group on Nuclear Waste Disposal (EGT) in 2012 |
| KNS | Federal Nuclear Safety Commission (<i>in German:</i> Eidgenössische Kommission für Nukleare Sicherheit), former Federal Commission for Nuclear Safety (KSA) |
| KSA | Federal Commission for Nuclear Safety (<i>in German:</i> Kommission für die Sicherheit von Kernanlagen), replaced by Federal Nuclear Safety Commission (KNS) in 2007 |
| KWO | Kraftwerke Oberhasli AG |
| LASMO | Large Scale Monitoring (Grimsel Test Site experiment) |
| LC-xy | Different types of L/ILW disposal containers |
| LCS | Long-term Cement Studies (Grimsel Test Site experiment) |
| LES | Laboratory for Waste Management at the Paul Scherrer Institute |
| LGM | Last Glacial Maximum |

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|------------------------|--|
| L/ILW | Low and intermediate-level waste |
| LiDAR | Light detection and ranging, is a surveying technology that measures distance by illuminating a target with a laser light |
| LLW | Low-level waste |
| LMS | Laboratory of Soil Mechanics at EPFL, Lausanne |
| LOT | Long Term Test of Buffer Material (Äspö experiment) |
| LP | Long-term monitoring of pore pressures (Mont Terri experiment) |
| LTD | Long Term Diffusion (Grimsel Test Site experiment) |
| LUCOEX | Large Underground Concept Experiments (EU project) |
| LWR | Light-Water Reactor |
| MA | Minimal requirements (Mindestanforderungen) |
| MA | Microbial activity (Mont Terri experiment) |
| MA-A | Platform microbial studies (Mont Terri experiment) |
| MaCoTe | Material Corrosion Test (Grimsel Test Site experiment) |
| MADUK | Messnetz zur automatischen Dosisleistungsüberwachung in der Umgebung der Kernkraftwerke (MADUK complements NADAM around NPPs; see NADAM) |
| MB | Mine-By test (Mont Terri experiment) |
| MCDA | Multi-Criteria-Decision-Analysis |
| MeSA | Methods for Safety Assessment for Geological Disposal Systems for Radioactive Waste |
| MICADO | Model Uncertainty for the Mechanism of Dissolution of Spent Fuel in Nuclear waste repository (EU project) |
| MIND | Microbiology in Nuclear waste Disposal, a Horizon 2020 project from Euratom Research and Training Programme 2014 – 2018 |
| MIR | Medicine, Industry and Research |
| MIRAM | Model Inventory for Radioactive Materials |
| MIS | Marine Isotope Stage |
| MO | Monitoring (Mont Terri experiment) |
| MODARIA | Modelling and Data for Radiological Impact Assessments (EU project) |
| MoDeRn | Monitoring Developments for safe Repository operation and staged closure (EU project) |
| MODERN2020, Modern2020 | Development and demonstration of monitoring strategies and technologies for geological disposal |
| MOX | Mixed Oxide fuel, blend of UO ₂ and PuO ₂ |
| MT | Mont Terri URL (<i>in German:</i> Felslabor Mont Terri, FMT) |
| MX-80 | Sodium bentonite from Wyoming (USA) |
| Na | Sodium |
| NADAM | Netz für die automatische Dosisleistungsalarmierung und -messung (refers to the Swiss network for monitoring of radioactivity) |

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|------------------|---|
| NEA | Nuclear Energy Agency of the OECD |
| NF-PRO | Understanding and physical and numerical modelling of the key processes in the near-field and their coupling for different host rocks and repository strategies (Euratom 6 th Framework Programme) |
| NPPs | Nuclear Power Plant |
| NWMO | The Nuclear Waste Management Organization, Toronto, Canada |
| OBS | Oberbauensteinstock (former potential site for L/ILW repository in Switzerland) |
| OECD/NEA | Organisation for Economic Co-operation and Development/Nuclear Energy Agency |
| ONDRAF/ NIRAS | Organisme national des déchets radioactifs et des matières fissiles, Belgium |
| OPC | Ordinary Portland Cement |
| ORNL | Oak Ridge National Laboratory, Tennessee (US Department of Energy science and energy laboratory) |
| PAMINA | Performance Assessment Methodologies to Guide the Development of the Safety Case (EU project) |
| PC | Porewater Chemistry Experiment (Mont Terri experiment) |
| PC-C | Gas porewater equilibrium (Mont Terri experiment) |
| PEBS | Long-term performance of Engineered Barrier Systems (EU project proposal) |
| PEGASOS | Probabilistic Seismic Hazard Analysis for Swiss Nuclear Power Plant Sites (<i>in german: Probabilistische Erdbeben-Gefährdungs-Analyse für KKW-Standorte in der Schweiz</i>) |
| Phase | 2D code from Rockscience |
| PICNIC-TD | Successor code od PICNIC for modelling transport of dissolved radionuclides along a porous, water-saturated 1D linear transport path (PICNIC) with additional capability of handling time-varying groundwater flow and radionuclides transport in the matrix parallel to a water-conducting feature |
| Posiva | Posiva Oy, Finland |
| PPG | Piz Pian Grand (former potential site for L/ILW repository in Switzerland) |
| PRACLAY test | The Large Scale In-Situ PRACLAY Heater and Seal Tests in URL HADES, Mol, Belgium |
| PSG | Pore Space Geometry (Grimsel Test Site experiment) |
| PSI | Paul Scherrer Institute |
| PWR | Pressurised Water Reactor |
| QA | Quality Assurance |
| QC | Quality Control |
| QMS | Quality Management System |
| RBG | Rahmenbewilligung (eliminate RGB in text...) |
| RECOSY | Investigations of Redox Controlling Systems (EU project) |
| RK&M | "Preservation of Records, Knowledge and Memory across Generations" initiative |
| RPG | Space Planning Act (<i>in german: Raumplanungsgesetz</i>) |

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| RWMC | Radioactive Waste Management Funding and Research Center, Japan |
| SA | Safety analysis |
| SB | Self-sealing barriers of clay-sand mixtures (Mont Terri experiment) |
| SELFrac | Fractures and self-healing within the excavation-disturbed zone in clays (Mont Terri experiment and EU project) |
| SF | Spent fuel |
| SFA | Spent fuel assembly |
| SFOE | Swiss Federal Office of Energy, Bern |
| SFR | L/ILW repository in Sweden |
| SFS | Spent Fuel Stability (EU project) |
| SGT | Sectoral Plan "Deep geological repositories" (<i>in German:</i> Sachplan geologische Tiefenlager) |
| SHARC SHARC-II | Shale Research Centre of CSIRO, the SHARC Consortium is a joint industry project |
| SIMAN, SIMAN II | SIMulated Annealing, disposal canister fuel loading optimisation programme |
| SINQ | Neutron source at PSI |
| SKB | Swedish Nuclear Fuel and Waste Management Company (Svensk Kärnbränslehantering AB, Sweden) |
| SLS | Synchrotron Facility at PSI |
| SNF | Spent nuclear fuel |
| SO | Sedimentology of Opalinus Clay (Mont Terri experiment) |
| SOURCE-TERM | Source term (EU project) |
| Sr | Strontium |
| SR | Low-pH Shotcrete for Rock support (Mont Terri experiment) |
| SRB | Sulphate-reducing bacteria |
| SSM | Swedish Radiation Safety Authority |
| STMAN | Family of three computer codes that model release of radionuclides from different waste forms and subsequent 1D radial transport the engineered barriers (SPENT, STRENG and STALLION) |
| StSG | Radiation Protection Act (<i>in German:</i> Strahlenschutzgesetz) |
| Studsvik | Supplier of nuclear analysis software and specialised services to the international nuclear industry (former AB Atomenergi), headquartered in Nyköping, Sweden |
| SwiBAC | Swiss Biosphere Assessment Code which evaluates the distribution of radionuclides in a terrestrial fresh-water ecosystem used for agriculture with a dynamic compartment modelling approach |
| TAME | Terrestrial-Aquatic Model of the Environment (Nagra's earlier biosphere modelling code, successor code: SwiBAC) |
| TBM | Tunnel Boring Machine |
| TEM | Test and Evaluation of Monitoring Systems (Grimsel Test Site experiment) |

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|-------------|--|
| TH | Coupled Thermo-Hydraulic processes |
| THM | Thermo-Hydro-Mechanical processes |
| THMC | Coupled Thermo-Hydro-Mechanical and Chemical processes |
| TIMODAZ | Thermal impact on the damaged zone around a radioactive waste disposal in clay host rocks (EU project) |
| TOUGH | Computer code for 3D modelling of THM processes including unsaturated conditions and gas generation |
| TSC | Transport Storage Cask |
| TSX | Tunnel Sealing Experiment (Atomic Energy of Canada Limited's Underground Research Laboratory) |
| TURVA-2012 | Posiva's safety case |
| UPC | Universitat Politècnica de Catalunya, Spain |
| URL | Underground Research Laboratory |
| USM | Lower Freshwater Molasse (Untere Süßwassermolasse) |
| USG | Environmental Protection Act (Umweltschutzgesetz) |
| UVPV | Environmental Impact Assessment Ordinance (<i>in German:</i> Verordnung über die Umweltverträglichkeitsprüfung) |
| VA | More stringent requirements (Verschärfte Anforderungen) |
| VE | Ventilation Test (Mont Terri experiment) |
| VPAC | Versatile Performance Assessment Code (for modelling groundwater flow, radionuclide release and transport in a saturated 2D or 3D porous medium) |
| WAC | Waste Acceptance Criteria |
| WIPP | Waste Isolation Pilot Plant, Carlsbad, New Mexico |
| WLB | Wellenberg (potential site for L/ILW repository in Switzerland) |
| WPNCS | NEA/OECD Working Group on Nuclear Criticality Safety |
| WPRS | NEA/OECD Working Party on Scientific Issues in Reactors Systems |
| XAS | X-ray Absorption Spectroscopy could be included in text |
| XRF | X-ray Fluorescence Spectroscopy could be included in text |
| XRD | X-ray Diffraction |
| ZHAW | Zurich University of Applied Sciences (<i>in German:</i> Zürcher Hochschule für Angewandte Wissenschaften), Winterthur |
| ZWIBEZ | Waste storage facility located at Beznau nuclear power plant |
| ZWILAG | Centralised storage facility located in Würenlingen, operational since 2002 |
| 2SPNE SC/CE | 2 Site Protolysis Non Electrostatic Surface Complexation and Cation Exchange |