

Technical Report 21-02

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

November 2021

National Cooperative
for the Disposal of
Radioactive Waste

Hardstrasse 73
5430 Wettingen
Switzerland
Tel. +41 56 437 11 11

www.nagra.ch

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The report reflects contributions of >30 Nagra staff that deliver the RD&D programme. The coordination is with the Head of Research and Development (I. Gaus).

An earlier version of the report has been reviewed by representatives of waste management organisations in France (Andra, F. Plas), Belgium (ONDRAF/NIRAS, M. Van Geet), Sweden (SKB, J. Andersson (JABIA AB)) and the Nagra Technical Advisory Committee (TA).

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Abstract

Nagra's mission is to develop and implement safe and sustainable long-term solutions for all radioactive waste arising in Switzerland from the use of nuclear energy and from medicine, industry and research in a timely manner 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 (NEA 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. Article 36 of the Swiss Nuclear Energy Ordinance (NEO 2004) specifies the research activities. Art. 36 par. 2 NEO 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 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 (RD&D Plan) together with the Waste Management Programme every five years. The present RD&D Plan is in line with the Federal Council's decision and with the regulatory framework in Switzerland. The RD&D Plan documents the objectives, scope, nature and timing of future RD&D activities and describes how existing open questions have been addressed. It outlines both a strategic plan for Nagra's RD&D activities contributing to the implementation of a combined repository or two separate repositories for high-level waste (HLW) and low- and intermediate-level waste (L/ILW) as well as a technical work programme consistent with the strategic objectives.

Part 1 – Chapters 1 – 5

The first part of this report focuses on providing the programme context, i.e. the roadmap for the stepwise implementation of the combined or separate HLW and L/ILW repositories and the planning assumptions consistent with these requirements (Chapters 1 – 4). The Nagra Disposal Programme Roadmap (Nagra Roadmap) supports programme planning, coordination and visualisation of the expected future programme, based on the current boundary conditions. It is a tool for specifying, planning and communicating the entire, integrated programme.

The Roadmap is arranged over three integrated tiers, each with a different focus:

- Tier 1: Programme, captures a high-level description of the Nagra disposal programme all the way up to the return of the site(s) to a greenfield state around 2126. Tier 1 covers the iterative repository design and safety assessment process and the legally binding licensing process. It sets out the overarching framework against which programme activities are mapped at Tier 2 and Tier 3.
- Tier 2: Optimisation, captures the activities at the core of the programme, up to the return to a greenfield state. Specifically, Tier 2 covers the development and optimisation of the repository design from the perspective of safety during construction, operation and post-closure and from the perspective of implementation, to ensure technical feasibility and practicability.
- Tier 3: RD&D, captures the underpinning RD&D activities necessary to optimise and realise a Swiss repository up until first L/ILW emplacement around 2050 and HLW emplacement around 2060. Tier 3 covers RD&D activities required to support specific optimisation work at Tier 2, communicating the necessity and sufficiency of the Nagra RD&D programme.

The specification, planning and implementation of RD&D is a needs-driven process, where the general drivers are the optimisation processes which must be carried out from the perspective of safety (recurring safety cases at each milestone) and implementation (confidence underpinning the feasibility of the design at each milestone). The ongoing development of the repository concept, design and components currently represents an important component of the RD&D activities.

Tier 3 of the Roadmap covers all RD&D activities which will be managed by Nagra, but the current focus is on ten specific programme aspects with a significant RD&D component. For these aspects, the Roadmap illustrates how the Nagra RD&D Plan meets the evolving needs of the programme, as the licensing process necessitates an increasing level of refinement in the various elements of the disposal programme.

The current status of work is also described in Chapter 5 of Part 1 of this report and includes the progress of the Sectoral Plan process and the preparations for the submission of the general licence applications, currently foreseen for 2024. This also includes the structure of the safety case that will be submitted with the licence applications, and the changes to the Nagra repository project since 2016. The current international status of HLW (and L/ILW) disposal is documented and defines the starting point for the RD&D activities over the remainder of the Nagra disposal programme. Finally, the key principles regarding RD&D resources and competence management are highlighted.

Part 2 – Chapters 6 – 8

In the second part of this report, the focus is 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 optimising the concepts and 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 *sensu stricto* as RD&D. As part of this optimisation process (safety, feasibility, implementation and thus also cost), this also includes the development of alternatives at all levels to ensure flexibility in terms of including future developments in the concepts.

Given the very broad nature of the activities involved and the need to keep the document sufficiently succinct, the initial focus is on the planning of the RD&D programme for the remainder of the implementation period up to repository closure and the return to a greenfield state. This is described in Chapter 6 and includes the main objectives of the planned activities in the facilities for underground geological investigations as well as their approximate timing.

Chapter 7 describes how Nagra plans to address programme aspects with a significant RD&D component (Tier 3 of the Nagra Roadmap). Much of the RD&D is necessary to contribute towards and underpin future decision-making. While feasibility will be demonstrated at a conceptual level for the general licence applications, there are many areas of the programme where maintaining flexibility is highly beneficial. Such flexibility is particularly valuable in areas where considerable progress is expected in the intermediate term, e.g. specific technological developments and advances in materials science. From a safety or other perspective it could be beneficial to optimise specific solutions initially chosen in the near term once the time for implementation arrives.

The individual Tier 3 roadmaps cover RD&D contributions to decision-making and providing confidence in the selection of specific technologies and approaches within the appropriate time-frames. They communicate the need to maintain options and alternatives until the programme approaches a specific milestone, with optimisation as the key driver in each case. These programme aspects with a significant RD&D component that are developed as separate Tier 3 roadmaps are: (1) spent fuel, (2) monitoring, (3) thermal output, (4) gas, (5) geological evolution, (6) hydrochemistry and barriers, (7) L/ILW container, (8) HLW canister, (9) backfilling, sealing and closure, and (10) emplacement and retrievability.

Chapter 8 first provides a detailed overview of the progress since the previous RD&D Plan (Nagra 2016b), highlighting and summarising the achievements realised in the various domains described below. It continues with a description of the technical work programme over the next five to ten years.

Geological information – The main drivers for the work are (1) the site selection process, (2) the safety case to be developed for the selected site(s), including provision of the basis for assessing repository-induced effects, and (3) the engineering of the subsurface infrastructure.

- The bulk of the RD&D activities foreseen supports the geosphere characterisation in the siting regions and the development of the site-specific models. These are strongly supported by the results of the 3D seismic campaigns and the deep borehole campaign in the siting regions.
 - Characterisation methods for the sedimentary facies have made significant progress, while the tectonic picture for the three siting regions has become clear. Based on the seismic interpretation, the advanced characterisation of sedimentological and tectonic features will continue to refine this.
 - Major progress was achieved through benchmarking of geomechanical properties, while novel techniques for characterising the stress field in the siting regions are being applied and interpreted.
 - The hydrogeological and hydrogeochemical characterisation techniques, already fairly mature, have been further refined, providing increased insight into the expected long-term evolution of the porewater and groundwater systems.
 - The activities providing an understanding of the long-term geological and climate evolution have made a major leap forward and are also supported by an extensive Quaternary sediment characterisation programme. The novel assessment methodology developed is based on the evaluation of fluvial processes, the evolution of local topography and glacial erosion dynamics. It will provide strong support for site selection and for the subsequent description of the long-term evolution of the selected site(s).
- Process understanding of the key safety-relevant phenomena in the containment-providing rock zone was further refined to provide the basis for the description of repository-induced effects and for the safety assessment.
 - In the area of radionuclide transport, where understanding was already highly advanced, concluding syntheses of various aspects (e.g. competitive sorption) are being compiled to underpin the safety assessment.
 - Gas transport characterisation receives considerable attention, also internationally, and has focused most recently on the characterisation of gas-induced fractures. To accommodate remaining uncertainties, a framework was developed to assess gas-related impacts in the siting regions.

- A more robust geomechanical understanding provides strong support for repository design and is now based on more advanced constitutive models. The impact of material heterogeneity is being further assessed.
- Understanding of thermal properties and behaviour is key for the thermal dimensioning of the repository and efforts are focused on extensive characterisation, benchmarking of experiments in underground rock laboratories (URLs) and development of probabilistic workflows to support site selection and thermal optimisation.
- While the state of the art regarding understanding of self-sealing processes in the host rock is mature, novel small-scale visualisation experiments convincingly demonstrate the rapid self-sealing of artificial fractures.

Radioactive waste and materials – Comprehensive knowledge of the radiological and material properties of all waste streams destined for disposal is key to the design and safety analysis of the planned repositories.

- A refined description of the inventory will be prepared for the general licence applications, leading to an update of the respective databases. The state of the art regarding waste conditioning is being followed closely in order to identify waste treatment options for optimisation in future programme stages.
- Further progress was made in reducing uncertainties in the safety analysis related to the waste characteristics:
 - The focus is mainly on the radionuclide release from spent fuel and the release rate of ^{14}C from L/ILW, since reducing these can contribute to optimising safety. International efforts play a major role in targeting specific aspects of the spent fuel release, and long-term experiments focus on ^{14}C release from metallic and organic wastes.
 - While uncertainties with respect to glass dissolution remain and are being further investigated, they do not have consequences for post-closure safety.
 - Uncertainties regarding the gas produced by the waste have been further reduced by increasing confidence that corrosion rates of metals, which are the main source of repository gases, will be very low.
 - To ensure criticality safety, the methodology based on burnup credit was further developed and loading curves were obtained for nominal canisters. To ensure criticality safety in the later stages of repository evolution, the method will be further improved.
- Assessing the state and integrity of spent fuel after dry storage is mainly an issue related to handling and to the design of the waste encapsulation plant. Along with multiple international initiatives, Nagra also contributed significantly to investigations on spent fuel rods and structural materials.
- In the context of the thermal optimisation of the repository, logistics optimisation software has been enhanced to allow for more comprehensive analysis of canister loading options.

Design and technology development – The general feasibility of a repository and its safe operation, backfilling and closure must be demonstrated at the conceptual level for the general licence applications.

Multiple aspects of the subsurface infrastructure lie in the domain of engineering and infrastructure development. This applies specifically to the development of generic design concepts and operating schemes and their adaptation first to the specific sites in the three siting regions and ultimately to the selected site(s).

- Based on a deepened analysis of the anticipated behaviour of the rock mass, a shield tunnel boring machine (TBM) with segmental lining support has been chosen as the reference for construction of the emplacement drifts for spent fuel (SF) and HLW. Different tunnel support systems have been successfully tested.
- The buffer emplacement technology for meeting the post-closure safety requirements was already demonstrated at a 1:1 scale in the FE experiment in the Mont Terri Rock Laboratory, and further experience is being gained in large-scale emplacement experiments at the Grimsel Test Site (GTS). Evaluation of alternative, more widely available bentonites that fulfil the requirements continues in the context of the optimisation process.
- The design of the HLW carbon steel disposal canister has progressed. In anticipation of the general licence applications, a larger-scale feasibility demonstration will be pursued. The development of alternative canisters continues, with a major focus on copper-coated canisters that have reached a high level of maturity as a result of international developments.
- The design and prototype production of the L/ILW disposal containers has been completed. Their sizes are now also optimised for interim storage. Options for infilling the containers have been further elaborated.
- The cement-based backfill for the L/ILW emplacement caverns has to be designed to meet the requirements for post-closure safety (radionuclide retention and gas storage capacity). The focus of the work is on selection of the aggregates and the engineering properties of the selected compositions.
- For sealing and closure of the repository, variants that are optimised for post-closure requirements and implementation are being investigated. This is supported by international plug and seal demonstrations and the 1:1 Gas-permeable Seal Test (GAST) at the GTS and its supporting laboratory experiments.

The conceptual design and preparation of the surface facilities is based on standard engineering practice and, in this phase, does not require specific RD&D activities. One exception is the waste encapsulation plant, which still has the potential to be significantly optimised based on the canister loading concepts that will be used in the context of thermal optimisation of the repository design and operation.

Evolution of safety-relevant properties and processes in the near-field – The RD&D needs in this domain are driven by the component-specific functions that have to be fulfilled with respect to the post-closure safety assessment. This requires a detailed understanding of repository evolution, both for HLW and L/ILW, which is challenging as the processes are highly coupled and the environments are complex.

HLW near-field:

- Understanding of the thermo-hydro-mechanical (THM) evolution has deepened through continuation of a series of large-scale URL experiments and benchmarking of their respective models. A repository-scale THM assessment workflow has been developed to support site selection and repository optimisation.
- Progress in the estimation of corrosion rates under repository-relevant conditions means that reference corrosion rates can now be estimated realistically, resulting in lower gas generation rates in the early stage of the HLW repository evolution.
- The widespread application of bentonite in the designs of advanced international waste management programmes means that understanding of the evolution of the bentonite barrier has reached a high level of maturity, allowing the remaining issues specific to the Swiss concept to be addressed. Higher temperature performance of bentonite is being investigated in the context of the thermal optimisation of the HLW repository.
- The characterisation of the excavation damaged zone (EDZ) based on investigations in the Mont Terri Rock Laboratory has now been summarised and integrated, while upscaling methods of the EDZ have been developed. The role of the EDZ as a preferential flow path for radionuclides was shown to be minimal in a dead-end HLW emplacement drift concept.

L/ILW near-field:

- The thermo-hydro-mechanical workflow mentioned above also extends to the L/ILW near-field to assess the impact of gas generation and the interactions between the HLW and L/ILW sections of a combined repository. The performance confirmation of gas-permeable seals was further developed and will be finalised in anticipation of the general licence applications.
- The cementitious near-field of the L/ILW repository is characterised by strongly coupled hydro-chemical processes. From a post-closure safety point of view, ensuring a high-pH environment and favourable gas-related properties is key. A broad spectrum of experiments, from the molecular to the URL scale, along with their respective modelling, generally leads to converging outcomes in terms of safety-relevant impacts. While certain interactions can now be shown to be self-limiting (e.g. cement-clay interactions), some significant uncertainties remain for other issues, which will be difficult to reduce (e.g. related to the heterogeneity of the waste). These will be integrated into the safety analysis by defining bounding assumptions.
- Microbial investigations suggest that selected backfill materials (and possibly the EDZ) are likely to host microbial activity which, if it can be shown to have beneficial impacts with respect to gas mitigation, can potentially be optimised.

Knowledge of radionuclide transport in clay- and cement-based backfills has reached a high level of maturity, and the synthesis will be integrated into the sorption and diffusion databases for the safety case for the general licence applications.

Monitoring – Monitoring studies conducted since 2016 have focused on concepts for underground and surface-based monitoring, strategic aspects of monitoring parameter selection and the link to safety analysis, as well as practical work on the development and testing of monitoring techniques and sensors.

With the current status of the RD&D programme described in this report, Nagra is well placed to submit the documents for the general licence applications as planned in 2024 and to move forward with its repository programme.

Zusammenfassung

Die Nagra hat den Auftrag, zeitgerecht und mit vertretbarem Aufwand ein sicheres geologisches Tiefenlager für alle radioaktiven Abfälle der Schweiz, die aus der Kernenergienutzung und aus Medizin, Industrie und Forschung anfallen, zu realisieren. Die erforderlichen Rahmenbewilligungsgesuche für die Tiefenlager werden im Rahmen des Sachplans geologische Tiefenlager vorbereitet und eingereicht. Gemäss Art. 31 Abs. 1 des Kernenergiegesetzes (KEG, NEA 2003) sind die Betreiber von Kernanlagen verpflichtet, alle von ihnen verursachten radioaktiven Abfälle sicher zu entsorgen. Dies beinhaltet auch die notwendigen Vorarbeiten wie Forschung und geologische Untersuchungen. Art. 36 der Kernenergieverordnung (KEV, NEO 2004) erläutert die Forschungstätigkeiten. Art. 36 Abs. 2 der KEV besagt, dass die Bewilligungsinhaber die Entwicklung der Technik, auch in organisatorischer und personeller Hinsicht, verfolgen und prüfen müssen, inwieweit daraus Erkenntnisse für die Sicherheit und die Sicherung ihrer Anlagen abgeleitet werden können. Im Falle der Nagra betrifft diese Verordnung die geologischen Tiefenlager. In seinem Entscheid vom August 2013 hat der Bundesrat festgelegt, dass die Nagra alle fünf Jahre zusammen mit dem Entsorgungsprogramm einen Forschungs- und Entwicklungsplan (RD&D-Plan) einreichen muss. Der vorliegende RD&D-Plan steht im Einklang mit diesem Entscheid des Bundesrats und mit den gesetzlichen Rahmenbedingungen in der Schweiz. Der RD&D-Plan dokumentiert Ziele, Umfang, Art und Zeitplan der zukünftigen RD&D-Aktivitäten und beschreibt, wie bestehende offene Fragen angegangen werden. Er enthält einen strategischen Plan für die RD&D-Aktivitäten der Nagra, die zur Umsetzung des Vorhabens für ein Kombilager bzw. der Vorhaben für zwei getrennte Einzellager (ein Tiefenlager für hochaktive Abfälle (HAA) und eines für schwach- und mittelaktive Abfälle (SMA)) beitragen, sowie ein technisches Arbeitsprogramm, das mit den strategischen Zielen im Einklang steht.

1. Teil – Kapitel 1 – 5

Der erste Teil des Berichts fokussiert auf die Darstellung des Programmkontexts, d.h. im Rahmen der Gesamtplanung (der sog. Roadmap) wird aufgezeigt, wie die schrittweise Umsetzung des Vorhabens für ein Kombilager bzw. der Vorhaben für zwei Einzellager erfolgt und wie die Planungsannahmen mit den bestehenden Anforderungen abgestimmt werden (Kapitel 1 – 4). Die «Nagra-Roadmap Entsorgungsprogramm» (nachfolgend Nagra-Roadmap genannt) unterstützt die Programmplanung, Koordinierung und Visualisierung des zu erwartenden Programms, welches auf den aktuellen Randbedingungen beruht. Die Nagra-Roadmap dient als Instrument zur Konkretisierung, Planung und Kommunikation des gesamten, integrierten Programms.

Die Roadmap ist in drei Ebenen mit unterschiedlichem Fokus unterteilt:

- Ebene 1 (Programm-Ebene) umfasst eine übergeordnete Beschreibung des Nagra-Entsorgungsprogramms bis hin zur Wiederherstellung des Zustands 'grüne Wiese' um das Jahr 2126. Ebene 1 deckt den iterativen Prozess der Lagerauslegung und Sicherheitsbeurteilung sowie das gesetzlich verbindliche Bewilligungsverfahren für das Tiefenlager ab. Sie bildet den übergeordneten Rahmen für die Programmaktivitäten auf Ebene 2 und Ebene 3.
- Ebene 2 (Optimierungs-Ebene) umfasst die Kernaktivitäten des Programms bis hin zur Wiederherstellung des Zustands 'grüne Wiese'. Insbesondere deckt Ebene 2 die Entwicklung und Optimierung der Lagerauslegung aus Sicht Sicherheit während des Baus, Betriebs und nach dem Verschluss ab, sowie aus Sicht der Umsetzung zur Gewährleistung der technischen Machbarkeit und Durchführbarkeit.

- Ebene 3 (RD&D-Ebene) umfasst die grundlegenden RD&D-Aktivitäten, die für die Optimierung und Realisierung eines Schweizer Tiefenlagers bis hin zur ersten Einlagerung von SMA um 2050 und von HAA um 2060 notwendig sind. Ebene 3 deckt RD&D-Aktivitäten ab, die erforderlich sind, um spezifische Optimierungsarbeiten auf Ebene 2 zu unterstützen. Ebene 3 hebt die Notwendigkeit und Angemessenheit des RD&D-Plans der Nagra hervor.

Die Festlegung, Planung und Umsetzung der RD&D-Aktivitäten ist ein bedarfsorientierter Prozess, bei dem die wichtigsten Treiber die Optimierungsprozesse sind, die aus der Perspektive der Sicherheit (mit Sicherheitsnachweisen an jedem Meilenstein) und der Umsetzung (mit Nachweis der zuverlässigen Machbarkeit der Lagerauslegung an jedem Meilenstein durchgeführt werden müssen. Die stetige Entwicklung des Lagerkonzepts, der Lagerauslegung und der Systemkomponenten ist gegenwärtig ein wichtiger Bestandteil der RD&D-Aktivitäten.

Ebene 3 der Roadmap umfasst alle RD&D-Aktivitäten im Verantwortungsbereich der Nagra. Indes liegt der gegenwärtige Fokus auf zehn spezifischen Programmaspekten, die alle einen signifikanten RD&D-Anteil aufweisen. Für diese Aspekte illustriert die Roadmap, wie der RD&D-Plan der Nagra den sich entwickelnden Bedürfnissen des Programms gerecht wird, für welches das Bewilligungsverfahren eine zunehmende Verfeinerung der verschiedenen Elemente des Entsorgungsprogramms erfordert.

Der aktuelle Stand der Arbeiten wird auch im ersten Teil beschrieben (Kapitel 5), inklusive des Fortschritts im Sachplanverfahren und der Vorbereitungen für die Einreichung der Rahmenbewilligungsgesuche, die gegenwärtig für 2024 vorgesehen ist. Dazu gehören auch die Struktur des Sicherheitsnachweises, der mit den Bewilligungsgesuchen eingereicht wird, und die Änderungen der Lagerprojekte der Nagra seit 2016. Auch der aktuelle internationale Stand der Entsorgung von HAA (und SMA) wird dokumentiert. Dieser definiert den Ausgangspunkt für die RD&D-Aktivitäten während der verbleibenden Phasen des Nagra-Entsorgungsprogramms. Schliesslich werden die wichtigsten Prinzipien bezüglich RD&D-Ressourcen- und Kompetenzmanagement hervorgehoben.

2. Teil – Kapitel 6 – 8

Im zweiten Teil des Berichts liegt der Fokus auf der Prüfung und Beschreibung der Arbeiten, die notwendig sind, um die wissenschaftlichen und technischen Grundlagen der Nagra weiterzuentwickeln und sicherzustellen, dass die Technologien, Daten und Expertisen zur Optimierung der Konzepte erlangt und zukünftige Meilensteine in der Planung und Entwicklung des Tiefenlagers, einschliesslich der späteren Umsetzung, rechtzeitig und kosteneffizient erreicht werden. Der Bericht umfasst daher mehr als die Beschreibung von Aktivitäten, die im engeren Sinn als RD&D definiert sind. Im Rahmen dieses Optimierungsprozesses (Sicherheit, Machbarkeit, Umsetzung und somit auch Kosten) schliesst dies auch die Entwicklung von Alternativen auf allen Ebenen ein, um Flexibilität hinsichtlich der Berücksichtigung zukünftiger Entwicklungen der Konzepte zu gewährleisten.

Angesichts des sehr breiten Spektrums der Aktivitäten und der Notwendigkeit, das Dokument ausreichend kurz zu fassen, liegt der Fokus zu Beginn vor allem auf der Planung des RD&D-Programms für die verbleibenden Realisierungsphasen bis hin zum Verschluss des Tiefenlagers und zur Wiederherstellung des Zustands 'grüne Wiese'. Dies wird in Kapitel 6 beschrieben und beinhaltet die wichtigsten Ziele der geplanten Aktivitäten in den Bauten für erdwissenschaftliche Untersuchungen untertag (BEUU) sowie deren ungefähren Zeitplan.

Kapitel 7 beschreibt, wie die Nagra Programmaspekte mit einer bedeutenden RD&D-Komponente anzugehen gedenkt (Ebene 3 der Nagra-Roadmap). Ein Grossteil der RD&D-Aktivitäten wird benötigt, um zu künftigen Entscheidungsprozessen beizutragen und diese zu untermauern. Während die Machbarkeit in den Rahmenbewilligungsgesuchen auf einer konzeptuellen Ebene nachgewiesen wird, gibt es viele Bereiche des Programms, in denen die Erhaltung von Flexibilität sehr vorteilhaft ist. Flexibilität ist in denjenigen Bereichen besonders wertvoll, in denen mittelfristig erhebliche Fortschritte erwartet werden, z. B. bei spezifischen technologischen Entwicklungen und Fortschritten in der Materialwissenschaft. In solchen Fällen ist es vorteilhaft, dass eine zu Beginn gewählte Lösung zum Zeitpunkt der Umsetzung aus einer Sicherheits- oder sonstigen Perspektive optimiert wird.

Die Roadmaps der Ebene 3 zeigen auf, wie RD&D-Aktivitäten innerhalb eines angemessenen Zeitrahmens zur Entscheidungsfindung beitragen und Vertrauen in die Auswahl spezifischer Technologien und Herangehensweisen schaffen. Sie zeigen die Notwendigkeit auf, Optionen und Alternativen aufrechtzuerhalten, bis das Programm einen bestimmten Meilenstein erreicht, wobei die Optimierung jeweils den Haupttreiber darstellt. Programmaspekte mit einer erheblichen RD&D-Komponente, die in separaten Roadmaps der Ebene 3 entwickelt wurden, sind: (1) abgebrannte Brennelemente, (2) Überwachung, (3) Wärmeleistung, (4) Gas, (5) geologische Entwicklung, (6) Hydrochemie und Barrieren, (7) SMA-Endlagerbehälter, (8) HAA-Endlagerbehälter, (9) Verfüllung, Versiegelung und Verschluss sowie (10) Einlagerung und Rückholbarkeit.

Kapitel 8 vermittelt einen detaillierten Überblick über die seit dem letzten RD&D-Plan (Nagra 2016b) erzielten Fortschritte, indem es das Erreichen in den nachfolgend beschriebenen Bereichen hervorhebt und zusammenfasst. Danach folgt eine Beschreibung des technischen Arbeitsprogramms für die nächsten 5 bis 10 Jahre.

Geologische Informationen – Die wichtigsten Treiber für diese Arbeiten sind (1) das Standortwahlverfahren, (2) der für den oder die gewählten Standort(e) zu entwickelnde Langzeitsicherheitsnachweis, einschliesslich der Bereitstellung von Grundlagen für die Prüfung der lagerbedingten Einflüsse und (3) die technische Entwicklung der Infrastruktur untertage.

- Der Grossteil der vorgesehenen RD&D-Aktivitäten dient der geologischen Charakterisierung der Standortgebiete und der Entwicklung von standortbezogenen Modellen, basierend auf den Ergebnissen der 3D-Seismik-Kampagnen und der Tiefbohrkampagne in den Standortgebieten.
 - Die Charakterisierungsmethoden für die Sedimentfazies haben erhebliche Fortschritte gemacht, und das tektonische Bild der drei Standortgebiete ist klarer geworden. Basierend auf der seismischen Interpretation wird dieses Bild durch die detaillierte Charakterisierung der sedimentologischen und tektonischen Verhältnisse laufend verfeinert.
 - Wichtige Fortschritte wurden durch das Benchmarking der geomechanischen Eigenschaften erzielt, und es wurden neuartige Techniken zur Charakterisierung des Spannungsfelds in den Standortgebieten angewandt und interpretiert.
 - Die bereits ziemlich ausgereiften hydrogeologischen und hydrogeochemischen Charakterisierungstechniken wurden weiter verfeinert und bieten nun einen verbesserten Einblick in die erwartete Langzeitentwicklung der Porenwässer und der Grundwassersysteme.
 - Die Aktivitäten zum Verständnis der geologischen und klimatischen Langzeitentwicklung haben einen grossen Sprung nach vorne gemacht, was auch durch ein umfangreiches Programm zur Charakterisierung der Quartärsedimente unterstützt wird. Die neu entwickelte Bewertungsmethodik beruht auf der Untersuchung und Bewertung fluviatiler Prozesse, der Entwicklung der lokalen Topografie und der glazialen Erosionsdynamik. Sie wird die Standortwahl sowie die anschliessende Beschreibung der Langzeitentwicklung des oder der ausgewählten Standorte(s) massgeblich unterstützen.

- Das Prozessverständnis für die wichtigsten sicherheitsrelevanten Phänomene im einschluss-wirksamen Gebirgsbereich wurde weiter verfeinert, um die Grundlage für die Bewertung lagerbedingter Einflüsse sowie für den Sicherheitsnachweis zu schaffen.
 - Im Bereich des Radionuklidtransports, wo das Prozessverständnis bereits weit fort-geschritten ist, werden abschliessende Synthesen zu verschiedenen Aspekten (z. B. kom-petitive Sorption) erstellt, um die Sicherheitsanalysen zu untermauern.
 - Der Charakterisierung des Gastransports wird – auch international – grosse Aufmerk-samkeit gewidmet, wobei der Schwerpunkt in jüngster Zeit auf der Charakterisierung gasinduzierter Klüfte liegt. Zur Einordnung der verbleibenden Ungewissheiten wurde ein Verfahren für die Beurteilung gasbezogener Einflüsse in den Standortgebieten entwickelt.
 - Ein robusteres geomechanisches Prozessverständnis, welches nun auf weiter verfeinerten Stoffgesetzen basiert, bietet eine solide Grundlage für die Lagerauslegung. Die Auswir-kungen der Gesteinsheterogenität werden weiter überprüft.
 - Das Verständnis von thermischen Eigenschaften und der thermischen Entwicklung ist ausschlaggebend für die entsprechende Dimensionierung des Tiefenlagers. Die Aktivi-täten konzentrieren sich auf eine ausführliche Charakterisierung, das Benchmarking von Felslabor-Experimenten und die Entwicklung probabilistischer Methoden zur Unterstüt-zung der Standortwahl und der thermischen Optimierung.
 - Während der Stand der Technik in Bezug auf das Verständnis der Selbstabdichtungs-prozesse im Wirtgestein ausgereift ist, haben neuartige, kleinskalige Visualisierungs-experimente die schnelle Selbstabdichtung künstlicher Klüfte überzeugend nachgewiesen.

Radioaktive Abfälle und Materialien – Umfassende Kenntnisse der radiologischen und materiel-len Eigenschaften und Materialeigenschaften aller für die Tiefenlagerung bestimmten Abfall-ströme sind entscheidend für die Auslegung und Sicherheitsanalyse der geplanten Tiefenlager.

- Für die Rahmenbewilligungsgesuche werden eine verfeinerte Beschreibung des Inventars und eine Aktualisierung der jeweiligen Datenbanken vorbereitet. Neueste Erkenntnisse im Bereich der Abfallbehandlung werden aufmerksam verfolgt, um Optionen zur Optimierung der Abfallbehandlung in zukünftigen Realisierungsetappen zu identifizieren.
- Weitere Fortschritte wurden bei der Verringerung von Ungewissheiten bzgl. Abfallcharakteri-sierung in den Sicherheitsanalysen verzeichnet:
 - Der Fokus liegt vor allem auf der Freisetzung von Radionukliden aus abgebrannten Brennelementen und der Freisetzungsrates von ^{14}C aus SMA, da deren Verringerung zur Sicherheitsoptimierung beitragen kann. Internationale Bemühungen spielen eine wich-tige Rolle bei der Betrachtung spezifischer Aspekte zur Freisetzung von Radionukliden aus abgebrannten Brennelementen sowie bei Langzeitexperimenten zur Freisetzung von ^{14}C aus metallischen und organischen Abfällen.
 - Ungewissheiten bzgl. der Glasauflösung bleiben zwar bestehen und werden weiter unter-sucht, haben aber keine Auswirkungen auf die Langzeitsicherheit.
 - Ungewissheiten in Bezug auf die von den Abfällen erzeugten Gase wurden weiter reduziert, da das verbesserte Prozessverständnis das Vertrauen in die sehr niedrigen Korrosionsraten von Metallen, der Hauptquelle für die Gasbildung, erhöhte.
 - Um die Sicherheit bzgl. Kritikalität zu gewährleisten, wurde eine Methodik weiterent-wickelt, die auf dem sogenannten *burnup credit* beruht, und es wurden Beladungskurven für Standard-Endlagerbehälter erstellt. Die Methodik wird weiter verbessert, um die Sicherheit bzgl. Kritikalität auch in den späteren Phasen der Tiefenlagerentwicklung zu gewährleisten.

- Die Beurteilung des Zustands und der Integrität der abgebrannten Brennelemente nach der Trockenlagerung ist vor allem für die Handhabung und die Auslegung der Verpackungsanlage relevant. Im Kontext mit zahlreichen internationalen Initiativen leistete die Nagra auch einen wichtigen Beitrag zu Untersuchungen an abgebrannten Brennstäben und Strukturmaterialien.
- In Zusammenhang mit der thermischen Optimierung des Tiefenlagers wurde die Software zur Optimierung der Logistik verbessert, um Beladungsoptionen für die Endlagerbehälter umfassender analysieren zu können.

Auslegung und Technologieentwicklung – Die generelle Machbarkeit eines Tiefenlagers sowie dessen sicherer Betrieb, Verfüllung und Verschluss müssen in den Rahmenbewilligungsgesuchen auf konzeptioneller Ebene nachgewiesen werden.

Zahlreiche Aspekte der Infrastruktur untertage fallen in den Bereich der Technik- und Infrastruktur-entwicklung. Dies gilt insbesondere für die Entwicklung generischer Auslegungskonzepte und Betriebsabläufe sowie für deren standortspezifische Anpassung, zunächst an die spezifischen Standorte in den drei Standortgebieten und schliesslich am oder an den gewählten Standort(en).

- Basierend auf einer vertieften Analyse des zu erwartenden Gebirgsverhaltens wurde eine Tunnelbohrmaschine mit Schildvortrieb und Tübbingausbau als Referenzverfahren für den Bau der BE/HAA-Lagerstollen gewählt. Verschiedene Tunnelausbauten wurden erfolgreich getestet.
- Dass die Einlagerungstechnologie für die Verfüllung die Anforderungen aus Sicht Langzeitsicherheit erfüllt, wurde bereits in einem Grossversuch im Massstab 1:1 im Felslabor Mont Terri demonstriert. Weitere Erfahrungen werden in Grossversuchen zur Einlagerungstechnologie im Felslabor Grimsel gesammelt. Die Untersuchungen an alternativen, leichter verfügbaren Bentoniten, welche die Anforderungen erfüllen, werden im Zusammenhang mit dem Optimierungsprozess weiterverfolgt.
- Die Entwicklung des HAA-Endlagerbehälters aus Karbonstahl wurde vorangetrieben. Mit Blick auf die Rahmenbewilligungsgesuche wird an einem Grossversuch zum Nachweis der Machbarkeit gearbeitet. Die Entwicklung alternativer Endlagerbehälter wurde fortgesetzt, wobei der Schwerpunkt auf kupferbeschichteten Endlagerbehältern liegt, die infolge internationaler Entwicklungen bereits einen hohen Reifegrad erreicht haben.
- Die Entwicklung und Produktion von Prototypen der SMA-Endlagerbehälter wurde abgeschlossen. Deren Abmessungen sind nun auch für die Zwischenlagerung optimiert. Optionen für die Verfüllung der Endlagerbehälter wurden weiterentwickelt.
- Die zementbasierte Verfüllung der SMA-Lagerkavernen muss so ausgestaltet werden, dass sie die Anforderungen an die Langzeitsicherheit erfüllt (Rückhaltung der Radionuklide und Gasspeicherkapazität). Der Schwerpunkt der Arbeiten liegt auf der Auswahl der Zuschlagstoffe und der bautechnischen Eigenschaften der gewählten Zementrezepturen.
- Für die Versiegelung und den Verschluss des Tiefenlagers werden Varianten untersucht, die hinsichtlich der Anforderungen aus Sicht Langzeitsicherheit und aus Sicht Umsetzung optimiert sind. Unterstützt wird dies durch internationale Verschluss- und Versiegelungsdemonstrationen sowie durch den Grossversuch im Massstab 1:1 zur Demonstration der gasdurchlässigen Stollenversiegelung im Felslabor Grimsel und die dazugehörigen Labor-experimente.

Die Auslegung und Vorbereitung der Oberflächenanlagen basiert auf der üblichen Ingenieurpraxis und erfordert in dieser Phase keine spezifischen RD&D-Aktivitäten. Eine Ausnahme bildet jedoch die Verpackungsanlage, die auf Basis der Behälterbeladungskonzepte, welche im Rahmen der thermischen Optimierung der Lagerauslegung und der Betriebsabläufe zum Einsatz kommen, noch erhebliches Optimierungspotenzial aufweist.

Entwicklung sicherheitsrelevanter Eigenschaften und Prozesse im Nahfeld – Der RD&D-Bedarf auf diesem Gebiet wird durch komponentenspezifische Funktionen bestimmt, die im Hinblick auf die Langzeitsicherheit zu erfüllen sind. Dies erfordert ein detailliertes Verständnis der Entwicklung der HAA- und SMA-Tiefenlager, was eine Herausforderung darstellt, da die Prozesse stark gekoppelt sind und das Umfeld komplex ist.

HAA-Nahfeld:

- Das Verständnis der thermo-hydro-mechanischen (THM) Entwicklung wurde durch die Fortsetzung einer Reihe grossmassstäblicher Felslabor-Experimente und durch Benchmarking der entsprechenden Modelle vertieft. Es wurde eine THM-Bewertungsmethodik im Massstab 1:1 entwickelt, um die Standortwahl und die Lageroptimierung zu unterstützen.
- Fortschritte bei der Abschätzung von Korrosionsraten unter lagerrelevanten Bedingungen zeigen, dass Referenzwerte für die Korrosionsraten nun realistisch abgeschätzt werden können, was zu niedrigeren Gasbildungsraten in der frühen Phase der Entwicklung des HAA-Tiefenlagers führt.
- Die breite Verwendung von Bentonit in der Lagerauslegung in fortgeschrittenen internationalen Entsorgungsprogrammen hat dazu geführt, dass das Verständnis der Entwicklung der Bentonitbarriere einen hohen Reifegrad erreicht hat. Dadurch können die im Schweizer Konzept verbleibenden Fragen angegangen werden. Das Verhalten von Bentonit bei höheren Temperaturen wird im Rahmen der thermischen Optimierung des HAA-Tiefenlagers untersucht.
- Die Charakterisierung der Auflockerungszone, die auf Untersuchungen im Felslabor Mont Terri basiert, wurde nun zusammengefasst und integriert, und Upscaling-Methoden zur Auflockerungszone wurden entwickelt. Der Einfluss der Auflockerungszone als bevorzugter Fliesspfad für Radionuklide erwies sich im verwendeten Blindstollenkonzept für die HAA-Lagerstollen als minimal.

SMA-Nahfeld:

- Die zuvor erwähnte thermo-hydro-mechanische Bewertungsmethodik umfasst auch das SMA-Nahfeld. Hier werden die Auswirkungen der Gasbildung und die Wechselwirkungen zwischen den HAA- und SMA-Lagerteilen eines Kombilagers bewertet. Der Nachweis der Funktionstüchtigkeit der gasdurchlässigen Versiegelung wurde weiterentwickelt und wird im Hinblick auf die Rahmenbewilligungsgesuche fertiggestellt.
- Das Zement-Nahfeld des SMA-Lagers wird durch stark gekoppelte hydro-chemische Prozesse geprägt. Aus Sicht der Langzeitsicherheit ist es entscheidend, ein Hoch-pH-Milieu sowie günstige gasbezogene Eigenschaften zu gewährleisten. Ein breites Spektrum von Experimenten – vom molekularen bis zum Felslabor-Massstab – führt zusammen mit entsprechenden Modellierungen zu konvergierenden Ergebnissen in Bezug auf sicherheitsrelevante Auswirkungen. Während bestimmte Wechselwirkungen inzwischen als selbstbegrenzend

nachgewiesen werden können (z.B. die Wechselwirkungen zwischen Zement und Ton), bleiben bei anderen Fragen noch erhebliche Ungewissheiten bestehen (z.B. im Zusammenhang mit der Heterogenität der Abfälle), die sich nur schwer verringern lassen. Diese Ungewissheiten werden in der Sicherheitsanalyse berücksichtigt, indem abdeckende Annahmen definiert werden.

- Mikrobiologische Untersuchungen in den ausgewählten Verfüllmaterialien (und möglicherweise auch in der Auflockerungszone) deuten auf eine mikrobielle Aktivität hin. Diese kann, wenn sie nachweislich zur Verringerung der Gasbildung beiträgt, möglicherweise optimiert werden.

Die Kenntnisse über den Radionuklidtransport in ton- und zementbasierten Verfüllungen sind inzwischen sehr ausgereift. Die Synthese dieser Kenntnisse wird in die Sorptions- und Diffusionsdatenbanken für den Langzeitsicherheitsnachweis für die Rahmenbewilligungsgesuche integriert.

Überwachung – Die seit 2016 durchgeführten Überwachungsstudien konzentrierten sich auf Konzepte für die untertägige und oberirdische Überwachung, auf strategische Aspekte bei der Auswahl von Überwachungsparametern und auf die Verknüpfung mit der Sicherheitsanalyse sowie auf praktische Arbeiten zur Entwicklung und Prüfung von Überwachungstechniken und -sensoren.

Mit dem in diesem Bericht beschriebenen aktuellen Stand des RD&D-Plans hat die Nagra gute Voraussetzungen, um die Unterlagen für die Rahmenbewilligungsgesuche wie geplant im Jahr 2024 einzureichen und um ihr Tiefenlagerprogramm voranzutreiben.

Résumé

La Nagra a pour mission de construire, dans des délais et à des coûts raisonnables, des dépôts en couches géologiques profondes qui permettront de confiner de manière sûre l'ensemble des déchets radioactifs issus de l'utilisation de l'énergie nucléaire et des applications de la médecine, de l'industrie et de la recherche en Suisse. Les demandes d'autorisation générale requises pour les dépôts seront préparées et déposées dans le cadre du plan sectoriel « Dépôts en couches géologiques profondes ». Selon l'art. 31 al. 1 de la loi suisse sur l'énergie nucléaire (LENu, NEA 2003), la gestion sûre des déchets nucléaires incombe à leurs producteurs. Cette obligation inclut les activités préliminaires au stockage géologique proprement dit, telles que la recherche et les investigations géologiques. Les activités de recherche font l'objet de l'art. 36 de l'ordonnance sur l'énergie nucléaire (OENu, NEO 2004). L'art. 36 al. 2 de l'OENu précise que les titulaires d'une autorisation générale devront suivre les développements technologiques, y compris ceux qui concernent l'organisation et le personnel, et examiner dans quelle mesure on peut en tirer des conclusions concernant la sécurité et la sûreté de l'installation (ici : les dépôts géologiques). Le Conseil fédéral, dans une décision datée d'août 2013, stipule que la Nagra devra présenter tous les 5 ans un plan de recherche, de développement et de démonstration (RD&D) en même temps que le programme de gestion des déchets. Le présent plan de RD&D a été rédigé en réponse à la demande du Conseil fédéral et en conformité avec le cadre réglementaire en vigueur en Suisse. Le plan de RD&D documente les objectifs, la portée, la nature et le calendrier des futures activités de RD&D et décrit la démarche suivie pour résoudre les questions encore ouvertes. Il comprend, d'une part, un plan stratégique pour les activités de RD&D de la Nagra contribuant à la mise en œuvre d'un dépôt combiné ou de deux dépôts distincts pour les déchets de haute activité (DHA) et les déchets de faible et de moyenne activité (DFMA) et, d'autre part, un programme de travail technique correspondant aux objectifs stratégiques.

1^{ère} partie

La première partie du rapport s'attache à présenter le contexte du programme, c'est-à-dire la marche à suivre pour la mise en œuvre progressive des dépôts combinés ou séparés pour les DHA et les DFMA, ainsi que les hypothèses de planification correspondantes (chapitres 1 – 4). La « feuille de route » de la Nagra pour le programme de gestion des déchets, ci-après désignée par le terme de « roadmap », est un outil de planification, de coordination et de visualisation du programme prévisionnel. Sur la base des conditions cadres actuelles, la roadmap permet de définir, de planifier et de communiquer l'ensemble du programme intégré.

La roadmap comprend trois niveaux intégrés, dont chacun sert un objectif différent :

- Niveau 1 – Programme : décrit de manière générale le programme de gestion des déchets de la Nagra sur l'ensemble de sa durée, c'est-à-dire jusqu'à ce que le ou les sites aient été remis à l'état d'origine en ~ 2126. Le niveau 1 couvre le processus itératif de conception et d'évaluation de la sûreté du dépôt, ainsi que le processus d'autorisation du dépôt défini par la loi. Il pose le cadre général dans lequel s'inscrivent les activités des niveaux 2 et 3.
- Niveau 2 – Optimisation : concerne les activités centrales du programme, jusqu'au retour du site à l'état d'origine. Plus précisément, le niveau 2 couvre d'une part le développement et l'optimisation de la conception du dépôt du point de vue de la sûreté, pendant les phases de construction, d'exploitation et post-fermeture, et d'autre part la mise en œuvre du dépôt, en mettant l'accent sur la faisabilité technique et la praticabilité.

- Niveau 3 – RD&D : présente les activités de RD&D nécessaires à l'optimisation et à la réalisation d'un dépôt final en Suisse jusqu'à la mise en place des premiers conteneurs de DHA en 2060 environ. Le niveau 3 décrit les activités de RD&D qui sont nécessaires à certaines tâches d'optimisation du niveau 2, en soulignant l'adéquation de ces activités aux besoins.

La spécification, la planification et la mise en œuvre des activités de RD&D est un processus axé sur les besoins, dont les moteurs généraux sont les processus d'optimisation nécessaires du point de vue de la sûreté (analyses de sûreté récurrentes à chaque étape de la procédure) et de la mise en œuvre (s'assurer à chaque étape que la conception technique est réalisable). Le développement de variantes de dépôt représente une part importante des activités de RD&D actuelles.

Le niveau 3 de la roadmap couvre l'ensemble des activités de RD&D qui seront gérées par la Nagra, mais l'accent est actuellement mis sur dix aspects spécifiques du programme où les activités de RD&D jouent un rôle important. Pour ces points précis, la roadmap illustre la manière dont le plan de RD&D de la Nagra répond à l'évolution des besoins du programme au fur et à mesure de son développement, lorsqu'un traitement plus détaillé de certains de ses éléments est requis par le processus d'autorisation.

La première partie fait enfin le point de la situation actuelle (chapitre 5) et présente notamment l'état d'avancement de la procédure du plan sectoriel ainsi que les préparatifs en vue des demandes d'autorisation générale, actuellement prévues pour 2024. Ce chapitre évoque en outre la structure du dossier de sûreté qui sera joint aux demandes d'autorisation, de même que les modifications apportées au projet de dépôt de la Nagra depuis 2016. Il documente l'état actuel du stockage des déchets de haute activité (et des déchets de faible et de moyenne activité) au niveau international. L'état actuel des travaux constitue le point de départ des activités de RD&D prévues pour le reste du programme de stockage géologique. Le chapitre 5 détaille également les principes clés concernant la gestion des ressources et des compétences en matière de RD&D.

2^e partie

Dans la seconde partie du rapport, l'accent est mis sur l'évaluation et la description des travaux nécessaires pour, d'une part, continuer d'enrichir la base de connaissances scientifiques et techniques de la Nagra et, d'autre part, assurer l'acquisition, en temps utile et à un coût raisonnable, de la technologie, des données et de l'expertise nécessaires à l'optimisation des concepts et à la réalisation des futures étapes de la planification et du développement du dépôt, y compris sa mise en œuvre. Le rapport ne se limite par conséquent pas à la description des activités de RD&D proprement dites. Dans le cadre du processus d'optimisation décrit ici (sûreté, faisabilité, mise en œuvre et donc aussi coûts), il s'agit également de mettre au point des alternatives à tous les niveaux, afin de maintenir une certaine flexibilité en intégrant aux concepts une dimension évolutive.

Etant donné le large éventail d'activités concernées et la nécessité de rédiger un document de taille raisonnable, l'accent est tout d'abord mis sur la planification des activités de RD&D durant le reste de la période de mise en œuvre du programme, jusqu'à la fermeture du dépôt et au retour du site à l'état original. Ceci fait l'objet du chapitre 6, qui aborde les objectifs principaux des activités prévues dans les installations pour les investigations géologiques souterraines ainsi que leur calendrier approximatif.

Le chapitre 7 décrit comment la Nagra prévoit d'aborder les aspects du programme qui se caractérisent par un besoin important en RD&D (niveau 3 de la roadmap de la Nagra), c'est-à-dire où les activités de RD&D jouent un rôle dans la prise de décision. La faisabilité sera démontrée au

niveau conceptuel à l'occasion des demandes d'autorisation générale, mais le maintien d'une certaine flexibilité peut s'avérer très bénéfique à de nombreux égards. Cette flexibilité est particulièrement précieuse pour des domaines où l'on peut s'attendre à des progrès considérables à moyen terme, par exemple des développements technologiques spécifiques ou des avancées en science des matériaux. Ici, sélectionner à court terme une solution spécifique peut, à l'heure de la mise en œuvre, se révéler moins bénéfiques pour la sûreté, ou tout autre aspect, du dépôt.

Les roadmaps de niveau 3 énumèrent les activités de RD&D nécessaires à la prise de décision et à la sélection de technologies et d'approches spécifiques dans les délais requis. Dans une perspective d'optimisation, elles soulignent la nécessité de préserver différentes variantes et alternatives jusqu'à une étape donnée. Les aspects du programme caractérisés par un besoin important en RD&D et faisant l'objet de roadmaps distinctes de niveau 3 sont les suivants : (1) combustible usé, (2) surveillance, (3) dégagement thermique, (4) gaz, (5) évolution géologique, (6) hydrochimie et barrières, (7) conteneur de déchets de faible et de moyenne activité, (8) conteneur de déchets de haute activité, (9) scellement, fermeture et remblayage et (10) mise en place et récupérabilité.

Le chapitre 8 donne un aperçu détaillé des progrès réalisés au cours des cinq dernières années et des résultats obtenus dans les différents domaines. Il se poursuit par une description du programme de travail technique pour les 5 à 10 prochaines années. Les progrès réalisés depuis le précédent plan RD&D (Nagra 2016b) sont mis en évidence.

- *Informations géologiques* – Les principaux moteurs du travail sont (1) la procédure de sélection du ou des site(s), (2) le dossier de sûreté à élaborer pour le(s) site(s) sélectionné(s), y compris les connaissances nécessaires à l'évaluation des effets induits par le dépôt et (3) l'ingénierie de l'infrastructure souterraine.
- L'essentiel des activités de RD&D prévues concerne la caractérisation de la géosphère dans les régions d'implantation et le développement de modèles spécifiques aux sites. Ces activités reposent largement sur les résultats des campagnes de sismique-3D et des forages profonds dans les régions d'implantation.
 - Les méthodes de caractérisation des faciès sédimentaires ont fait des progrès significatifs. En parallèle, les connaissances sur la tectonique des trois régions d'implantation se sont beaucoup étoffées. Cette amélioration va se poursuivre grâce à l'interprétation des résultats de la campagne sismique, qui va permettre la caractérisation avancée des éléments sédimentologiques et tectoniques.
 - Des progrès importants ont été réalisés grâce à l'analyse comparative des propriétés géomécaniques, tandis que de nouvelles techniques de caractérisation du champ de contraintes dans les régions d'implantation sont en cours de réalisation et d'interprétation.
 - Les techniques de caractérisation hydrogéologique et hydrogéochimique, déjà bien avancées, ont été affinées, ce qui a permis de mieux appréhender l'évolution attendue à long terme du système des eaux interstitielles et souterraines.
 - Les activités permettant de comprendre l'évolution géologique et climatique à long terme ont fait un grand bond en avant, avec la mise en œuvre supplémentaire d'un vaste programme de caractérisation des sédiments quaternaires. La méthodologie d'évaluation qui a été élaborée sur la base de l'évaluation des processus fluviaux, de l'évolution de la topographie locale et de la dynamique de l'érosion glaciaire, est unique en son genre. Elle sera d'une grande utilité pour la sélection des sites et la description ultérieure de l'évolution à long terme du ou des site(s) sélectionné(s).

- La compréhension des processus pour les principaux phénomènes importants pour la sûreté dans la zone de confinement géologique a été affinée, ce qui viendra étayer l'évaluation des effets induits par le dépôt et l'évaluation de la sûreté.
 - Dans le domaine du transport des radionucléides, où l'on disposait déjà de connaissances solides, des synthèses finales sont en cours de compilation dans divers domaines (par exemple la sorption compétitive) et viendront étayer l'analyse de sûreté.
 - La caractérisation du transport des gaz fait, également au niveau international, l'objet d'une attention considérable. Les recherches récentes concernent plus particulièrement la caractérisation des fractures induites par les gaz. Pour réduire les incertitudes qui subsistent, un cadre méthodologique a été élaboré pour évaluer les incidences liées au gaz dans les régions d'implantation.
 - L'amélioration des connaissances en matière de géomécanique, qui reposent désormais sur des modèles constitutifs plus avancés, est très utile dans le cadre de la conception du dépôt. L'impact de l'hétérogénéité des matériaux est en cours d'évaluation.
 - La compréhension des propriétés et du comportement thermiques est essentielle pour le dimensionnement thermique du dépôt. En vue de la sélection du site et de l'optimisation thermique, les efforts se concentrent sur une caractérisation approfondie, l'évaluation comparative des expériences en laboratoire souterrain et le développement de processus basés sur des méthodes probabilistes.
 - Alors que les processus d'auto-colmatage dans la roche d'accueil étaient déjà bien connus, des expériences de visualisation novatrices, à petite échelle, ont démontré de manière convaincante l'auto-colmatage rapide des fractures artificielles.

Déchets et matériaux radioactifs – Pour la conception du système de dépôt et les analyses de sûreté, il est indispensable de connaître en détail les propriétés radiologiques et physiques de tous les flux de déchets destinés au stockage géologique.

- L'inventaire des déchets sera affiné pour les demandes d'autorisation générale, ce qui entraînera une mise à jour des bases de données respectives. Les avancées en matière de conditionnement des déchets font l'objet d'un suivi attentif, afin d'identifier les différentes possibilités de traitement qui pourront conduire à une optimisation au cours des futures étapes du programme.
- Les incertitudes liées aux caractéristiques des déchets dans l'analyse de sûreté ont également pu être réduites à plusieurs niveaux :
 - Les recherches sont axées principalement sur le relâchement de radionucléides par le combustible usé et sur le taux de relâchement du ^{14}C par les déchets de faible et de moyenne activité, car dans les deux cas, une réduction peut contribuer à optimiser la sûreté. Les projets menés au niveau international jouent ici un rôle décisif, qu'il s'agisse du combustible usé et de l'étude de certains phénomènes de relâchement, ou encore des expériences à long terme sur le relâchement de ^{14}C par les déchets métalliques et organiques.
 - Bien que des incertitudes concernant la dissolution du verre subsistent et fassent l'objet d'études plus approfondies, elles n'ont pas de conséquences sur la sûreté après fermeture.
 - Les incertitudes concernant les gaz produits par les déchets ont encore été réduites par l'étude des taux de corrosion des métaux, qui sont la principale source de gaz dans le dépôt et dont on a acquis la conviction qu'ils seront très faibles.
 - Dans le domaine de la sûreté liée à la criticité, la méthodologie prenant en compte le crédit de combustion a été affinée et des courbes de charge ont été obtenues pour des conteneurs nominaux. La méthode sera encore améliorée afin que les risques de criticité n'affectent pas la sûreté du dépôt au cours des phases tardives de son évolution.

- Pour planifier les opérations de manipulation des conteneurs et la conception de l'installation de conditionnement, il faut pouvoir évaluer l'état et l'intégrité du combustible usé après l'entreposage à sec. Parallèlement à de multiples initiatives internationales, la Nagra a contribué de manière significative aux recherches sur les barres de combustible usé et les matériaux structurels.
- Dans le cadre de l'optimisation thermique du dépôt, les systèmes informatiques d'optimisation logistique ont été améliorés pour permettre une analyse plus complète des différentes possibilités à disposition pour le chargement des conteneurs.

Conception et développement technologique – Dans le cadre des demandes d'autorisation générale, il doit être démontré au niveau conceptuel qu'un dépôt géologique peut être construit, exploité, remblayé et fermé de manière sûre.

- Bon nombre d'aspects de l'infrastructure souterraine relèvent du domaine de l'ingénierie et du développement des infrastructures. C'est notamment le cas du développement de concepts génériques et de schémas d'exploitation, et de leur adaptation, d'abord aux sites identifiés dans trois régions d'implantation, puis au(x) site(s) sélectionné(s).
 - Pour les tunnels destinés aux éléments combustibles usés et aux déchets de haute activité, la méthode de construction de référence prévoit l'usage d'un tunnelier à bouclier, suivi de l'installation d'un revêtement segmentaire. Cette méthode a été sélectionnée sur la base d'une analyse approfondie du comportement attendu de la masse rocheuse. Différents systèmes de soutènement ont été testés avec succès.
 - La technologie de mise en place des remblais répondant aux exigences de sûreté post-fermeture a déjà été démontrée à l'échelle 1 dans le cadre de l'expérience FE au laboratoire souterrain du Mont Terri. Les connaissances acquises sont complétées par des expériences de mise en place à grande échelle en cours au laboratoire souterrain du Grimsel. L'évaluation d'autres types de bentonite, répondant aux exigences de sûreté mais plus largement disponibles, se poursuit dans le cadre du processus d'optimisation.
 - La conception du conteneur de référence en acier au carbone pour le stockage des DHA a progressé. Dans la perspective des demandes d'autorisation générale, la démonstration de faisabilité à plus grande échelle va se poursuivre. La recherche d'alternatives pour les matériaux a continué, avec une attention spéciale accordée aux conteneurs à revêtement en cuivre qui ont, grâce aux développements internationaux, atteint un niveau de maturité élevé.
 - La conception et la production de prototypes de conteneurs de stockage pour déchets de faible et de moyenne activité ont été achevées. Leurs dimensions ont été également optimisées pour le stockage intermédiaire. Les options de remplissage ont été élaborées plus avant.
 - Le comblement à base de ciment des cavernes de stockage pour DFMA doit être conçu de manière à satisfaire aux exigences de sûreté après fermeture (rétention des radionucléides et stockage des gaz). Les travaux se concentrent sur la sélection des agrégats et les propriétés techniques des compositions choisies.
 - Pour le scellement et la fermeture du dépôt, des variantes optimisées au regard des exigences post-fermeture et de la mise en œuvre sont en cours d'étude et un concept générique a été sélectionné. Ces travaux sont appuyés par des expériences internationales portant sur les bouchons et scellements, et par la démonstration à l'échelle 1 intitulée «Gas permeable Seal Test» (GAST) au laboratoire souterrain du Grimsel, accompagnée de diverses expériences de laboratoire.

- La conception et les travaux préparatoires pour les installations de surface reposent sur des pratiques d'ingénierie standard et ne nécessitent pas d'activités de RD&D spécifiques au cours de la présente phase, à l'exception de l'installation de conditionnement. Celle-ci présente un potentiel d'optimisation important au niveau des concepts de chargement des conteneurs, utilisés dans le cadre de l'optimisation thermique de la conception et de l'exploitation du dépôt.

Évolution des propriétés et des processus pertinents pour la sûreté dans le champ proche – Les besoins de RD&D dans ce domaine sont déterminés, pour chaque composant, par les fonctions spécifiques qui doivent être remplies dans le cadre de l'évaluation de la sûreté après fermeture. Il est ici nécessaire de bien comprendre comme le dépôt, tant de DHA que de DFMA, va évoluer, ce qui constitue un défi particulier, car les processus sont fortement couplés et les environnements complexes.

Champ proche des DHR :

- Nous disposons d'une meilleure compréhension de l'évolution thermo-hydro-mécanique (THM) grâce à la poursuite d'une série d'expériences à grande échelle qui se sont déroulées dans les laboratoires souterrains et à l'étude comparative de leurs modèles respectifs. Un processus d'évaluation THM à l'échelle du dépôt a été élaboré en vue de la sélection du site et de l'optimisation du dépôt.
- Grâce aux progrès réalisés dans l'estimation des taux de corrosion dans les conditions de dépôt, il est désormais possible de formuler des taux de référence réalistes, avec comme corollaire une baisse des taux de génération des gaz au cours de la phase initiale de l'évolution du dépôt de DHA.
- Du fait de l'utilisation généralisée de la bentonite dans le cadre des programmes avancés de gestion des déchets au niveau international, la compréhension de l'évolution de la barrière de bentonite a atteint un niveau de maturité élevé, ce qui permet de se concentrer sur des questions encore ouvertes spécifiques au concept suisse. Les performances de la bentonite à des températures plus élevées sont étudiées dans le cadre de l'optimisation thermique du dépôt de DHA.
- La caractérisation de la zone endommagée (ou « EDZ »), basée sur des investigations au laboratoire souterrain du Mont Terri, a été résumée et intégrée. Par ailleurs, des méthodes de transposition à plus grande échelle pour l'évaluation de la performance de l'EDZ ont été élaborées. Il a été démontré que le rôle de l'EDZ en tant que cheminement préférentiel pour les radionucléides était minime dans un concept prévoyant le stockage des DHA dans un tunnel en cul-de-sac.

Champ proche des déchets de faible et de moyenne activité :

- Le processus d'évaluation thermo-hydro-mécanique mentionné plus haut est également applicable au champ proche des DFMA et permet d'évaluer l'impact de la génération de gaz et les interactions entre les zones pour DHA et DFMA d'un dépôt combiné. Les travaux sur la performance des joints perméables au gaz se sont poursuivis et seront finalisés en prévision des demandes d'autorisation générale.
- Le champ proche des DFMA, riche en ciment, est caractérisé par des processus hydro-chimiques fortement couplés. Du point de vue de la sûreté après fermeture, il est essentiel de garantir un environnement à pH élevé et des propriétés favorables au regard de la production de gaz. Une large palette d'expériences, de l'échelle moléculaire à celle des laboratoires souterrains, ainsi que les modélisations correspondantes, aboutissent généralement à des résultats similaires en termes d'impacts pertinents pour la sûreté. S'il est désormais possible de démontrer que certaines interactions sont autolimitatives (ainsi par exemple les interactions ciment-argile), il reste des incertitudes importantes, et difficiles à réduire, dans d'autres domaines (dues par exemple à l'hétérogénéité des déchets). Ces incertitudes seront intégrées dans l'analyse de sûreté sous la forme d'hypothèses limitatives.
- Les études microbiennes suggèrent que l'EDZ (et les matériaux de remblayage sélectionnés) sont susceptibles d'héberger une activité microbienne qui, s'il peut être démontré qu'elle a des impacts bénéfiques sur la réduction des gaz, peut potentiellement être optimisée.

Les connaissances relatives au transport des radionucléides dans les remblais à base d'argile et de ciment ont atteint un haut niveau de maturité. La synthèse de ces connaissances sera intégrée dans les bases de données de sorption et de diffusion figurant dans le dossier de sûreté des demandes d'autorisation générale.

Surveillance – Les études de surveillance menées depuis 2016 ont porté sur les concepts de surveillance souterraine et en surface, les aspects stratégiques de la sélection des paramètres de surveillance et les rapports avec l'analyse de sûreté, ainsi que, concrètement, sur des travaux de développement et de test des techniques de surveillance et des capteurs.

Considérant l'état actuel du programme de RD&D décrit dans le présent rapport, la Nagra est bien positionnée pour soumettre les documents requis dans le cadre des demandes d'autorisation générale comme prévu en 2024 et poursuivre à l'avenir son programme de stockage géologique.

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Acronyms

Abbreviation	Explanation
ABM	Alternative Buffer Materials Project (Äspö experiment)
AC	Non-fissile actinides
ACED	Assessment of Chemical Evolution of ILW and HLW Disposal Cells (EURAD)
AMAC	Advanced Methodology for Activation Characterisation (Nagra)
Andra	National Radioactive Waste Management Agency, France (<i>Agence nationale pour la gestion des déchets radioactifs</i>)
ASR	Site selection in preparation for general licences (<i>Auswahl der Standorte für die Vorbereitung der Rahmenbewilligungsgesuche</i>)
ATW	Alpha-toxic waste
B-Shaft	Shaft for operations (<i>Betriebszugang</i>)
BA	Operational waste from the NPPs (<i>Betriebsabfälle</i>)
BEACON	Bentonite Mechanical Evolution (Euratom project)
BEUU	Facilities for underground geological investigations (<i>Bauten für erdwissenschaftliche Untersuchungen untertag</i>)
BEVA	SF/HLW encapsulation plant (<i>BE/HAA-Verpackungsanlage</i>)
BIOPROTA	International Forum for Biosphere Modelling
BN	Bitumen Nitrate (Mont Terri Rock Laboratory experiment)
BNFL	British Nuclear Fuels Ltd.
BUC	Burnup credit
BZL	Swiss Federal Interim Storage Facility (<i>Bundeszwischenlager</i>)
CAST	Carbon-14 Source Term (Euratom project)
CEBAMA	CEment-BASed MAterials, Properties, Evolution, Barrier Functions (an EC Horizon 2020 collaborative project)
CEC	Cation exchange capacity
CERN	European Organization for Nuclear Research
CI-D	Cement Clay Interaction (Mont Terri Rock Laboratory experiment)
CIM	Carbon-14 and Iodine-129 Migration in Cement
CLAYWAT	Binding State of Pore Water in Clay-rich Media (project lead by the University of Berne)
COGEMA	Reprocessing of spent power reactor fuel at COGEMA La Hague site, merged together with the French nuclear companies, Framatome and CEA Industrie, to form Areva NC in 2001 (<i>Compagnie générale des matières nucléaires</i>)
CONCORD	Container Corrosion under Disposal Conditions (EURAD work package)
CORI	Cement-Organic-Radiouclide Interactions (EURAD work package)
COVRA	Central Organisation for Radioactive Waste in the Netherlands (<i>Centrale Organisatie Voor Radioactief Afval</i>)
CRZ	Containment-providing rock zone

Abbreviation	Explanation
C-S-H	Calcium silicate hydrate
DECOVALEX	DEvelopment of COupled Models and their VALidation against Experiments (international project)
DETEC	Swiss Federal Department of the Environment, Transport, Energy and Communications (<i>Eidgenössisches Departement für Umwelt, Verkehr, Energie und Kommunikation UVEK</i>)
DISCO	Modern Spent Fuel Dissolution in Spent Container Conditions
EB	Engineered Barriers (Mont Terri Rock Laboratory experiment and EU project)
EBS	Engineered barrier system
EBS Task Force	International Working Group for Modelling of Coupled THM Processes in Engineered Barriers (Äspö)
EDZ	Excavation damaged zone
EGOS	Expert Group on Operational Safety
EGT	Expert Group on Nuclear Waste Disposal (<i>Expertengruppe Geologische Tiefenlagerung</i>)
EGTS	Engineered Gas Transport System
EKRA	Swiss Expert Group on Disposal Concepts for Radioactive Waste established by the Federal Department of the Environment, Transport, Energy and Communications (DETEC) (<i>Expertengruppe Entsorgungskonzepte für radioaktive Abfälle</i>)
EIA	Environmental Impact Assessment
EMPA	Swiss Federal Laboratories for Materials Science and Technology, Dübendorf, Switzerland (<i>Eidgenössische Materialprüfungs- und Forschungsanstalt</i>)
ENSI	Swiss Federal Nuclear Safety Inspectorate (<i>Eidgenössisches Nuklearsicherheitsinspektorat</i>), before 1.1.2009: Nuclear Safety Inspectorate.
EP	Waste Management Plan (<i>Entsorgungsprogramm</i>)
EPFL	Swiss Federal Institute of Technology, Lausanne (<i>Ecole polytechnique fédérale de Lausanne</i>)
ESDRED	Engineering Studies and Demonstration of Repository Designs (EU project)
ETHZ	Swiss Federal Institute of Technology, Zürich (<i>Eidgenössische Technische Hochschule Zürich</i>)
EURAD	European Joint Programme on Radioactive Waste Management (EURAD)
Euratom	European Atomic Energy Community, founded in 1957
EUU	Underground geological investigations (<i>erdwissenschaftliche Untersuchungen untertag</i>)
FE	Full-scale Emplacement Experiment (Mont Terri Rock Laboratory)
FEBEX	Full-scale Engineered Barriers Experiment (Grimsel Test Site)
FEP	Features, Events and Processes

Abbreviation	Explanation
FGR	Fission gas release
FORGE	Fate of Repository Gases (EU project, Euratom 7 th Framework Programme Project)
FP	Fission products
GAS	Mechanistic Understanding of Gas Transport in Clay Materials (EURAD work package)
GAST	Full-scale GAS-permeable Seal Test (Grimsel Test Site)
GC-A	Geomechanical Characterisation (Mont Terri Rock Laboratory experiment)
GD	Geochemical Data (Mont Terri Rock Laboratory experiment)
GLASTAB	Long-term behaviour of glass: Improving the glass source term and substantiating the basic hypotheses (EU project)
GME	Gas monitoring experiments at Zwiilag
GNSS	Global Navigation Satellite System
GNW	Cooperative for Radioactive Waste Disposal, Wellenberg (<i>Genossenschaft für nukleare Entsorgung Wellenberg</i>), Wolfenschiessen, dissolved in 2003
GRS	Organisation for Facility and Reactor Safety (<i>Gesellschaft für Anlagen- und Reaktorsicherheit</i> , Germany)
GTS	Grimsel Test Site
HADES	Underground Research Facility in Mol, Belgium, operated by ONDRAF/NIRAS
HE-E	In-situ 1:2 Heater Experiment (Mont Terri Rock Laboratory experiment and EU project)
HG-A	Gas paths through host rock and along seals (Mont Terri Rock Laboratory experiment)
HG-D	Reactive gas transport in argillaceous formations (Mont Terri Rock Laboratory experiment)
HIDRA	Human Intrusion in the Context of Disposal of Radioactive Waste (IAEA project)
HITEC	Influence of temperature on clay-based material behaviour
HLW	High-level waste
HMC	Hydro-mechanical-chemical processes
Horizon 2020	EU Framework Programme for Research and Innovation with nearly €80 billion of funding available over 7 years (2014 to 2020)
HotBENT	High Temperature Effects on Bentonite (Grimsel Test Site)
HTO	Tritiated water
IAEA	International Atomic Energy Agency
IDKM	Information, Data & Knowledge Management initiative of the OECD/NEA
IFEP	International features, events and processes

Abbreviation	Explanation
IGD-TP	Implementing Geological Disposal of Radioactive Waste Technology Platform
IGSC	OECD/NEA Integration Group for the Safety Case
ILW	Long-lived intermediate-level waste
I-NERI	US DoE/Euratom International Nuclear Energy Research Initiative
InSAR	Interferometric Synthetic Aperture Radar
IRF	Instant Release Fraction
ISRAM	Information System for Radioactive Materials
JRC	Joint Research Centre of the Institute for Transuranium Elements (also JRC-ITU) (Germany)
JSS	Japanese – Swiss – Swedish project
KBS-3	Technology for disposal of high-level radioactive waste (abbreviation of <i>kärnbränslesäkerhet</i> , nuclear fuel safety) based on three protective barriers (copper canisters, bentonite clay and the Swedish bedrock) developed by <i>Svensk Kärnbränslehantering AB (SKB)</i>
<i>KKB</i>	Beznau nuclear power plant
<i>KKG</i>	Gösgen nuclear power plant
<i>KKL</i>	Leibstadt nuclear power plant
<i>KKM</i>	Mühleberg nuclear power plant
<i>KS21</i>	2021 Cost Study (<i>Kostenstudie 2021</i>)
L-Shaft	Shaft for ventilation (<i>Lüftungszugang</i>)
Lazarus	Experimental programme to study the influence of dry interim storage conditions on the mechanical properties of spent fuel assembly structural material
LC-xy	Different types of L/ILW disposal containers
LES	Laboratory for Waste Management at the Paul Scherrer Institute (Switzerland)
LOT	Long-term Test of Buffer Material (Äspö experiment)
L/ILW	Low- and intermediate-level waste
LLW	Low-level waste
LUCOEX	Large Underground Concept Experiments (EU project, Euratom 7 th Framework Programme Project)
MA	Microbial activity (Mont Terri Rock Laboratory experiment)
MA-A	Platform microbial studies (Mont Terri Rock Laboratory experiment)
MARIE	Model-based assessment of repository-induced effects
MHF	Micro-hydraulic fracturing
MIR	Medicine, industry and research
MIRAM	Model Inventory for Radioactive Materials (<i>Modellhaftes Inventar für radioaktive Materialien</i>)
MIS xy	Marine Isotope Stage

Abbreviation	Explanation
MODATS	Monitoring Equipment and Data Treatment for Safe Repository Operation and Staged Closure (EURAD work package)
Modern2020	Development and Demonstration of Monitoring Strategies and Technologies for Geological Disposal (Euratom project)
MOX	Mixed oxide fuel, blend of UO ₂ and PuO ₂
MX-80	Sodium bentonite from Wyoming (USA)
NAB	Nagra <i>Arbeitsbericht</i> (Work Report)
nBaBG	Nuclear Construction Licence (<i>nukleares Baubewilligungsgesuch</i>)
nBeBG	Nuclear Operating Licence (<i>nukleares Betriebsbewilligungsgesuch</i>)
NDA	Nuclear Decommissioning Authority
NEA	Nuclear Energy Agency of the OECD
	ALSO:
	Nuclear Energy Act (<i>Kernenergiegesetz</i>)
NEO	Nuclear Energy Ordinance (<i>Kernenergieverordnung</i>)
NF-PRO	Near-field Processes (Euratom 6 th Framework Programme)
NPP	Nuclear power plant
NSG	Nagra exploratory request (<i>Nagra Sondiergesuch</i>)
NTB	Nagra Technical Report (<i>Nagra Technischer Bericht</i>)
NUMO	Nuclear Waste Management Organization of Japan
NWMO	Nuclear Waste Management Organization, Canada
NZA-BL	Combined auxiliary access facilities for ventilation and operations
OECD	Organisation for Economic Co-operation and Development
OFA	Surface facility (<i>Oberflächenanlage</i>)
OFI	Surface infrastructure (<i>Oberflächeninfrastruktur</i>)
OPA	Opalinus Clay
ONDRAF/NIRAS	Belgian National Agency for Radioactive Waste (Organisme national des déchets radioactifs et des matières fissiles)
ORANO	French nuclear fuel cycle company
PA	Performance Assessment
Posiva (Oy)	Finnish nuclear waste management company
PREDIS	Pre-disposal Management of Radioactive Waste (Euratom project)
PSI	Paul Scherrer Institute (Switzerland)
PSR	Periodic Safety Review
RA	NPP reactor waste (Reaktorabfälle)
RBG	General licence application (<i>Rahmenbewilligungsgesuch</i>)
RCM	Requirements and Configuration Management
RD&D	Research, Development & Demonstration

Abbreviation	Explanation
RK&M	Preservation of Records, Knowledge and Memory across Generations initiative of the OECD/NEA
RPG	Spatial Planning Act (<i>Raumplanungsgesetz</i>)
RPO	Radiological Protection Ordinance (<i>StSV, Strahlenschutzverordnung</i>)
RWM	Radioactive Waste Management, the U.K. government organisation tasked with planning for a geological disposal facility for radioactive waste in the United Kingdom
SA	NPP decommissioning waste (<i>Stilllegungsabfälle</i>) ALSO: Safety Assessment
SC	Safety case
SF	Spent fuel (assembly)
SFC	Spent Fuel Characterisation and Evolution until Disposal (EURAD work package)
SFL	Sweden's Final Repository for Long-lived Radioactive Waste (<i>Slutförvar för långlivat radioaktivt avfall</i>)
SFOE	Swiss Federal Office of Energy (<i>Bundesamt für Energie, BFE</i>)
SFR	Sweden's Final Repository for Short-lived Radioactive Waste (<i>Slutförvar för kortlivat radioaktivt avfall</i>)
SGT	Sectoral Plan for Deep Geological Repositories (<i>Sachplan geologische Tiefenlager</i>)
SHA	Seismic Hazard Assessment
SIMAN	SIMulated ANnealing, fuel-loading optimisation programme for disposal canisters
SKB	Swedish Nuclear Fuel and Waste Management Company (<i>Svensk Kärnbränslehantering AB</i>)
SPIM	Stream Power Incision Model
SURAO	Radioactive waste repository authority of the Czech Republic
TBM	Tunnel boring machine
TBO	Deep boreholes (<i>Tiefbohrungen</i>)
THC	Thermo-hydro-chemical processes
THERAMIN	Thermal Treatment for Radioactive Waste Minimization and Hazard Reduction (Euratom project)
THM	Thermo-hydro-mechanical processes
THMC	Thermo-hydro-mechanical-chemical processes
TRU	Transuranic waste
TS	Tunnelling Support experiment or Testing Different Tunnelling Support in Sandy Facies during Excavation of Gallery 2018/19 (Mont Terri Rock Laboratory)
UMAN	Uncertainty Management Network within EURAD

Abbreviation	Explanation
UPC	Universitat Politècnica de Catalunya, Spain
URL	Underground rock laboratory
US DoE	Department of Energy United States
USG	Environmental Protection Act (<i>Umweltschutzgesetz</i>)
UTA	Underground facilities (<i>Untertageanlagen</i>)
VA	Packaging system (<i>Verpackungsanlage</i>)
WA	NPP reprocessing waste (<i>Wiederaufarbeitungsabfälle</i>)
WAC	Waste acceptance criteria
WBS	Work breakdown structure
WIPP	Waste Isolation Pilot Plant, Carlsbad, New Mexico, United States; deep geologic long-lived radioactive waste repository. WIPP permanently isolates defense-generated transuranic waste 2,150 feet underground in an ancient salt formation
WMO	Waste management organisation
ZET	Working Group on Interim Storage, Waste Management and Transport of swissnuclear's Nuclear Fuel Committee (<i>Arbeitsgruppe Zwischenlagerung, Entsorgung und Transport (ZET) der Brennstoffkommission swissnuclear</i>)
ZHAW	Zurich University of Applied Sciences (<i>Zürcher Hochschule für Angewandte Wissenschaften</i>)
ZWIBEZ	Waste storage facility located at Beznau nuclear power plant
Zwilag	Centralised interim storage facility located in Würenlingen, operational since 2002 (Zwilag Zwischenlager Würenlingen AG)

1 Background and context of this report

Nagra's mission is to develop and implement safe and sustainable long-term solutions for all radioactive waste arising in Switzerland from the use of nuclear energy and from medicine, industry and research. This should be realised in a timely manner, in compliance with the Swiss regulations (NEO 2004) and at justifiable cost. Nagra must develop the plans for implementing the repositories and the scientific and technical basis for evaluating their safety and is also responsible for assessing the overall costs.

The planning strategy involves developing proposals and preparing the corresponding general licence applications according to the planned timetable. This will involve a proposal for the siting of one repository where two separate facilities for the two waste types, i.e. spent fuel (SF) and vitrified high-level waste (HLW) as well as low- and intermediate-level waste (L/ILW) including alpha-toxic waste, are co-located at the same site, referred to hereafter as a "combined repository". However, in the unlikely case that the "combined repository" is not preferred, proposals will be developed for two separate repositories, referred to hereafter as HLW repository and L/ILW repository. Provided the general licences are granted and validated, underground geological investigations (*EUU, erdwissenschaftliche Untersuchungen untertag*) will be carried out, for which facilities (*BEUU, Bauten für erdwissenschaftliche Untersuchungen untertag*) will be constructed. These geological and other investigations will lead to nuclear construction licence applications and later to operating licence applications. In this document, the combined repository is generally referred to as the current Nagra repository project and comprises a HLW repository (area) and a L/ILW repository (area).

After almost 30 years of work by Nagra aimed at developing the scientific basis for safe deep geological repositories¹, the Swiss Federal Government concluded in June 2006 that, with *Projekt Entsorgungsnachweis* (Nagra 2002c), Nagra had successfully demonstrated the technical feasibility of disposal of SF, HLW and long-lived intermediate-level waste (ILW) in Switzerland; the demonstration 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 Sectoral Plan for Deep Geological Repositories (*SGT, Sachplan geologische Tiefenlager*) (SFOE 2008). The Sectoral Plan defines the repository site selection process, which will culminate in the general licence applications. This will be the next major milestone in the RD&D Plan. The Sectoral Plan clearly defines the roles of the different stakeholders based on the Nuclear Energy Act (NEA 2003), as well as the decision-making process and the input needed for this decision-making. The present status of the Sectoral Plan is described in Section 5.1.

Once the general licences have been granted, Nagra will construct the *BEUU* at the selected site(s) (NEA 2003). The information provided through characterisation and experiments in these facilities and further technological developments will lead to the submission of the construction licence applications for the repositories. Operations will start when the subsequent operating licences have been granted. The entire disposal programme therefore spans multiple decades. This multi-licencing process strongly determines Nagra's strategy on how to proceed with the disposal programme.

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.

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 activities contributing to the implementation of the combined repository or, in the case where is not preferred, of two separate HLW and L/ILW repositories, and a technical work programme consistent with the strategic objectives.

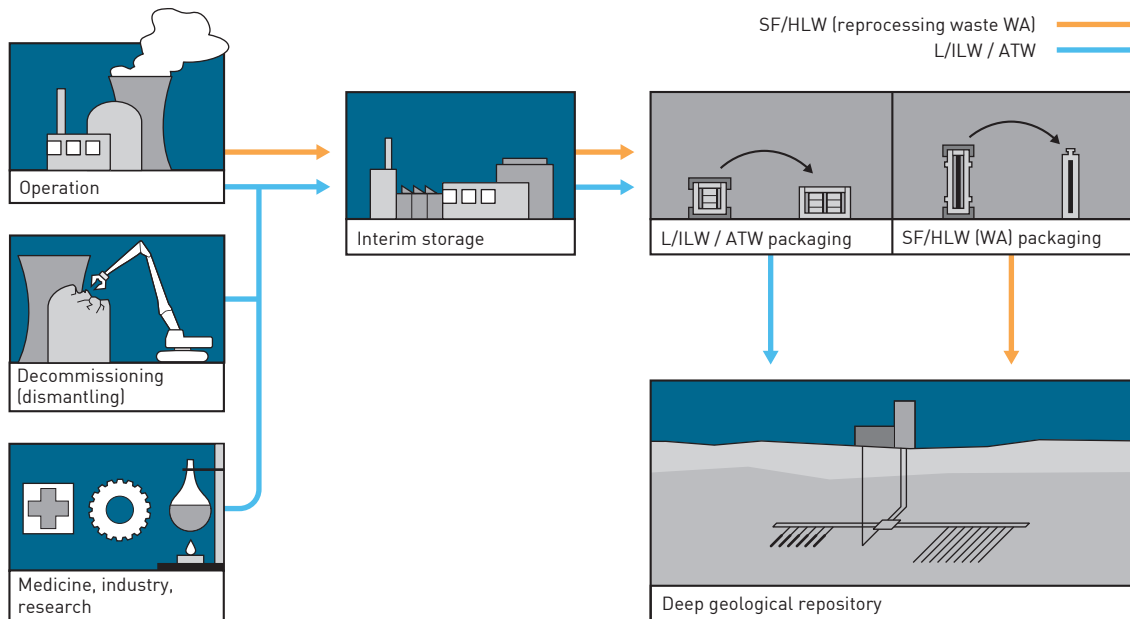


Fig. 1-1: Schematic illustration of the main elements of radioactive waste management in Switzerland

1.1 Waste Management Programme, RD&D Plan and Cost Study

The Federal Government requires the waste producers to submit updates of the following documents every 5 years:

1. the Waste Management Programme (submitted by Nagra)
2. the RD&D Plan (submitted by Nagra)
3. the Cost Study (Nagra is responsible for the disposal costs)

Nagra's strategy underlying the response to the issues set out in Box 1-1 is of particular relevance to the RD&D Plan and the Waste Management Programme.

Box 1-1: Key issues in federal law relating to the Waste Management Programme

Art. 52 NEO

The waste producers must include the following information in the Waste Management Programme:

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

The RD&D Plan documents the objectives, scope, nature and timing of future RD&D activities and describes how existing open questions are being addressed.

The previous Waste Management Programme, RD&D Plan and Cost Study were submitted by Nagra in 2016. These documents underwent a detailed review by the authorities. In November 2018, the Federal Government approved the documents and formulated conditions to be addressed in the next versions. The new Waste Management Programme (Nagra 2021h), aims to address these conditions. The full list of conditions, and where they are addressed in the Waste Management Programme and the RD&D Plan, is included in Appendix 1. To address the conditions comprehensively, the following separate reports have been published in the course of 2021:

- Optimisation of the implementation of the disposal programme (Nagra 2021a, *in German*)
- Pilot Repository Monitoring: First concept Report (Nagra 2021d)
- Generic sealing and closure concept for the repository (Nagra 2021g, *in German*)
- Concept for the facilities for underground geological investigations (Nagra 2021b, *in German*)

These reports are referenced further in this document.

1.2 Role of RD&D in the Nagra disposal programme

RD&D plays an important and evolving role in any disposal programme, as it underpins major decisions. In the early stages of the Nagra disposal programme, RD&D efforts largely focused on developing the understanding required to formulate the safety case. Gradually, the building blocks for the safety case were established, which resulted in the demonstration of disposal feasibility (*Projekt Entsorgungsnachweis*; Nagra 2002a, 2002b, 2002c). These documents, and the reviews thereof, acknowledged that uncertainty could be further reduced in the subsequent programme steps. Aside from addressing uncertainty and maintaining a state-of-the-art knowledge base, a significant part of the RD&D programme since 2006 has been dedicated to supporting activities in the Sectoral Plan and its main focus, namely site selection. These efforts will be integrated into the updated safety case supporting the general licence applications and the justification of the site selection.

The reasons for carrying out RD&D and the drivers for identifying RD&D needs have evolved considerably during the course of Nagra's work since the programme's inception in the 1980s. In the early years, and in common with other developing national programmes on geological disposal, Nagra carried out exploratory RD&D on basic scientific and technological options underlying the evolving geological disposal concept. Today, RD&D focuses on contributing to the highly specific requirements arising from having an established repository conceptual design and safety case for a specific geological formation, and a specific legal and regulatory framework for Nagra's disposal programme. The drivers for Nagra's RD&D have thus changed over the last three decades and now focus on the need to meet requirements identified in the Sectoral Plan and Nagra's Requirements and Configuration Management (RCM) system.

RD&D planning is the product of a logical approach, driven throughout by the need to support Nagra in attaining its ultimate goal:

1. Nagra (and thus its overall management) has to meet various external regulatory requirements (NEO 2004, ENSI 2020), stakeholder requirements and internal (Nagra-defined) requirements (including boundary conditions) in order to achieve its objectives: these requirements drive the Nagra programme.
2. To this end, Nagra traditionally relies on three main instruments for specifying internal requirements and capturing external requirements:
 - the Sectoral Plan process for site selection
 - the structure and elements of safety cases
 - the RCM system which, at the (lower) repository system levels, comprises safety-related and implementation-related requirements and specifications.
3. The Sectoral Plan process ends with the granting and validation of the general licences for the selected site(s), and its role as a driver for RD&D will thus cease at that point, leaving the safety case and the RCM system as the drivers that specify RD&D needs.
4. Defining, adapting and/or meeting external and internal requirements necessitates an RD&D programme that will continue into the operational period of the repository.
5. In the earlier stages of the RD&D programme, many of the results supported the establishment and evaluation of the structure and the elements of the safety case. The concept of capturing a large part of the programme requirements in a formal RCM system is a relatively recent development (both for Nagra and internationally), having evolved only over the last decade.

6. Currently, Nagra is in the process of integrating the safety case (structure) and the RCM system. The safety case provides a mature basis for aspects of the RCM structure, but also builds on certain central requirements which are themselves captured in the RCM system. RD&D work to date has shown that external safety requirements (e.g. dose criteria) can be met, provided specific internal requirements (e.g. safety functions) are defined and met.
7. An important aspect of recent RD&D planning is that, in the future work described in this RD&D Plan, most of the RD&D will be expected to support the optimisation of the repository system in terms of safety and implementation. This will allow lower-level design requirements and design specifications to be finalised and demonstrably met.
8. To manage the Nagra disposal programme, and to ensure that all internal and external requirements are met on schedule, the Nagra Disposal Programme Roadmap (Nagra Roadmap) has been introduced. The Roadmap captures the activities needed to address external and internal requirements for the disposal programme and outlines the RD&D required to achieve this. Key topics are defined as "aspects of the Nagra disposal programme with a significant RD&D component".
9. Tracking whether RD&D has provided adequate support so that all requirements can be met is one of the roles of the Nagra Quality Management System (QMS) and is handled through the RCM system.

In the current stage of the disposal programme, RD&D activities thus contribute principally to optimising and improving an already robust, well-supported and well-evaluated system. Activities are then planned to demonstrate aspects of this system at various scales in space and time. The RD&D programme is in a mature state, and fundamental research is only required to optimise safety and feasibility. The mature status of the RD&D programme is further enhanced by progress made and knowledge gained from similar disposal programmes elsewhere in Europe (Finland, Sweden, France). These nations are further advanced in their programme implementation than Switzerland and are planning to construct, or are already constructing, their HLW repositories.

Therefore, supporting the optimisation of the repository projects will be the major driver of Nagra's RD&D activities in the upcoming decades. As part of this optimisation process, alternative solutions will also be evaluated at each licensing step, thus allowing Nagra the flexibility to take advantage of relevant technical developments as they arise in the future.

The RD&D Plan (externally imposed on the waste producers to aid regulatory control) is an integral part of the Nagra QMS and one of the key elements enabling strategic long-term planning by Nagra and the Swiss waste producers.

The RD&D Plan provides input to:

- the RD&D priority plan and annual budget process, by indicating the resources needed to address the priorities identified
- calculations of the costs of implementing disposal, which are updated every five years as input to the financial planning by the NPP operators for the Waste Disposal Fund (financing the disposal of radioactive waste; see Nagra 2021h)
- the strategic planning of resources, including the human resources required by Nagra and its RD&D platforms (i.e. underground research laboratories (URLs) and competence centres) for carrying 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 collaborative 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

The methodology adopted to meet this challenge includes the following elements:

- the Nagra Disposal Programme Roadmap up to the closure of the repositories and the needs associated with the various steps involved in planning, licensing and implementing the two types of repositories foreseen in Switzerland (discussed in Chapters 3 and 4)
- the assessment of the current status of RD&D in Switzerland and worldwide, and the identification of optimisation opportunities and detailed developments that will have to be addressed for future licensing stages (Chapters 5 and 6)
- multi-level planning with a detailed description of the planned RD&D activities for the next five to ten years, general planning for each of the licensing steps and a more detailed roadmap up to the operation of the repositories for programme aspects with a significant RD&D component (Chapters 7 and 8)

The integration of multiple disciplines is key to the success of this process. Although many specialists are involved in the activities, a significant number of people engaged in the programme must have a broad skillset suitable for maintaining an overview, given the many different scientific disciplines involved.

1.3 Overall objectives and scope of this report

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 broad planning assumptions presented in the following sections and drawing on syntheses of earlier and ongoing technical work.

To do so in a meaningful way, the RD&D work programme has to be placed in the broader context of the Waste Management Programme, addressing the long timescales that are involved in its realisation and the specific nature of the geological context and Nagra concepts that have been selected. Special attention is given to addressing RD&D aspects that will have to be resolved in the future, together with information on how and within what timeframe Nagra will address these in order to contribute to timely decision-making.

Part 1 – Chapters 1 – 5

The first part of this report focuses on providing the programme context (Fig. 1-2), i.e. the roadmap for the stepwise implementation of the combined repository and the planning assumptions consistent with these requirements. This includes 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 implementation. It also includes the key reports and deliverables required at each licensing step. The staged licensing process triggers the continuous optimisation of safety and implementation. Both aspects are closely linked as the repository projects progress towards their realisation from the current conceptual stage to the operational phase. RD&D activities support this optimisation process as needed.

The current status of work is also described in Part 1 of this report and includes the progress of the Sectoral Plan process and the preparations for the submission of the general licence applications, currently foreseen for 2024. This also includes the planned structure of the safety case that will be submitted with the licence applications, and the changes to the Nagra repository project since 2016. The current international status of HLW (and L/ILW) disposal is documented and defines the starting point for the RD&D activities over the remainder of the Nagra disposal programme. Finally, the key principles regarding RD&D resources and competence management are highlighted.

Decision-making in the context of the site selection process as part of the current *SGT* Stage 3 or the general licence applications is not part of the Waste Management Programme and the RD&D Plan. Development of the arguments and the resulting decisions is reported in the dedicated documents for the general licence applications.

Part 2 – Chapters 6 – 8

In the second part of the report, the focus is 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 optimising the concepts and 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 *sensu stricto* as RD&D. As part of this optimisation process (safety, feasibility, implementation and thus also cost), this also includes the development of alternatives at all levels to ensure flexibility in terms of including future developments in the concepts.

Given the very broad nature of the activities involved and the need to keep the document sufficiently succinct, the initial focus is on the planning of the RD&D programme for the remainder of the implementation period of the programme up to repository closure and the return to a green-field state. This is described in Chapter 6 and includes the main objectives of the planned activities in the facilities for underground geological investigations as well as their approximate timing.

Chapter 7 describes how Nagra plans to tackle the identified programme aspects with a significant RD&D component. These generally span multiple aspects and thus contribute to the optimisation cycle. Chapter 7 also describes which major activities are foreseen both in the near and more distant future and how this will ultimately allow decisions to be made for the different licensing steps.

Chapter 8 provides a detailed overview of the progress made in the last five years and the achievements realised in the various domains. It continues with a description of the technical work programme over the next five to ten years, including the general licence applications foreseen for 2024. It also discusses the scope of work in the various areas in the period beyond the general licence applications. The progress made since the previous RD&D Plan (Nagra 2016b) is highlighted with an emphasis on the major lines of reasoning and the main arguments. The underlying documents (reports and papers) providing these substantiations of the main arguments are referenced for the specialist reader.

With a few exceptions, the status of the work captured in Chapters 5 and 8 refers largely to the status achieved by January 2021. It is therefore possible that reports and papers published more recently are not cited.

The primary target audience of this report are the Swiss authorities and their experts followed by other Swiss stakeholders. The international waste management community, Nagra's partner organisations and collaborators are also important target groups.

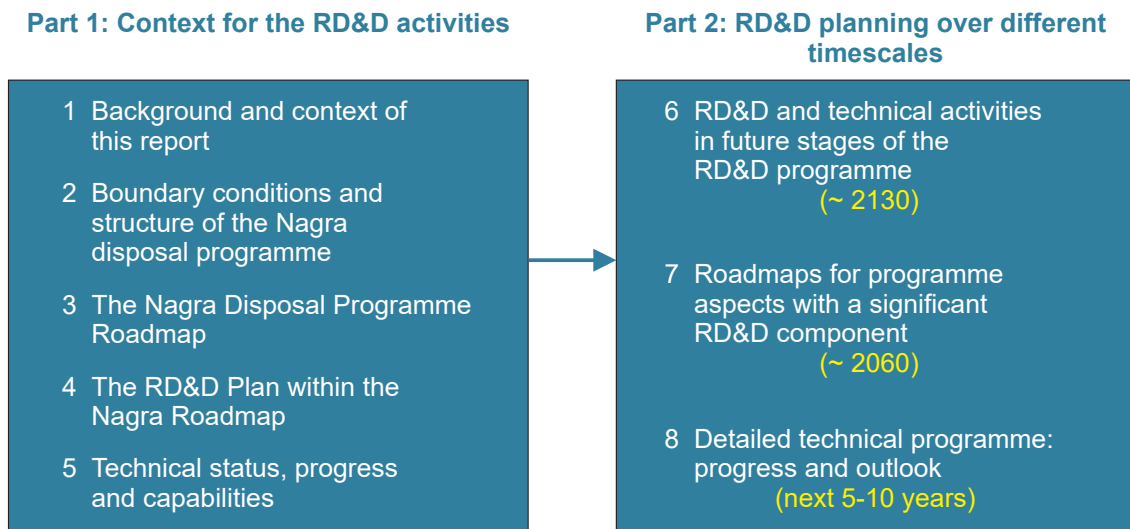


Fig. 1-2: Overview of the chapters in this report

An extensive overview of the RD&D progress made in the last 5 years is captured in Chapter 8.

2 Boundary conditions and structure of the Nagra disposal programme

This chapter provides a brief overview of the overall Nagra disposal programme and the external requirements that control its objectives, schedule and structure. As described in the following chapters, the RD&D Plan is situated within this programme structure.

2.1 Drivers and requirements controlling the Nagra disposal programme

2.1.1 Inventory, implementation plan and financing agreed by all stakeholders

As discussed in Chapter 1, implementing a combined deep geological repository or two individual repositories in Switzerland – one for SF/HLW and one for L/ILW – involves a staged process.

For the combined repository, the implementation steps are defined according to the schedule set out in Fig. 2-1 (Nagra 2021h) and are based on the assumption of a nuclear power programme with the existing power plants operating for 60 years (apart from the Mühleberg nuclear power plant (NPP) which operated for 47 years and was shut down in December 2019). The schedule is driven by the duration of the consultation and approval steps for the various licensing steps and the time required for underground geological investigations, as well as construction and operation of the repository.

Similar schedules for individual HLW and L/ILW repositories are outlined in Nagra (2021h) and are also based on the assumption of a nuclear power programme with the existing plants operating for 60 years (apart from NPP Mühleberg). These schedules 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 work programme for the coming years is clearly defined. In 2022, Nagra will announce the site(s) for the combined repository (or two individual repositories) for which the general licence applications will be prepared and submitted. The location of the surface infrastructure (*OFI, Oberflächeninfrastruktur*) will be decided in collaboration with the siting regions. The current waste management programme assumes that the general licence applications will be submitted to the Swiss Federal Office of Energy (SFOE) in 2024.

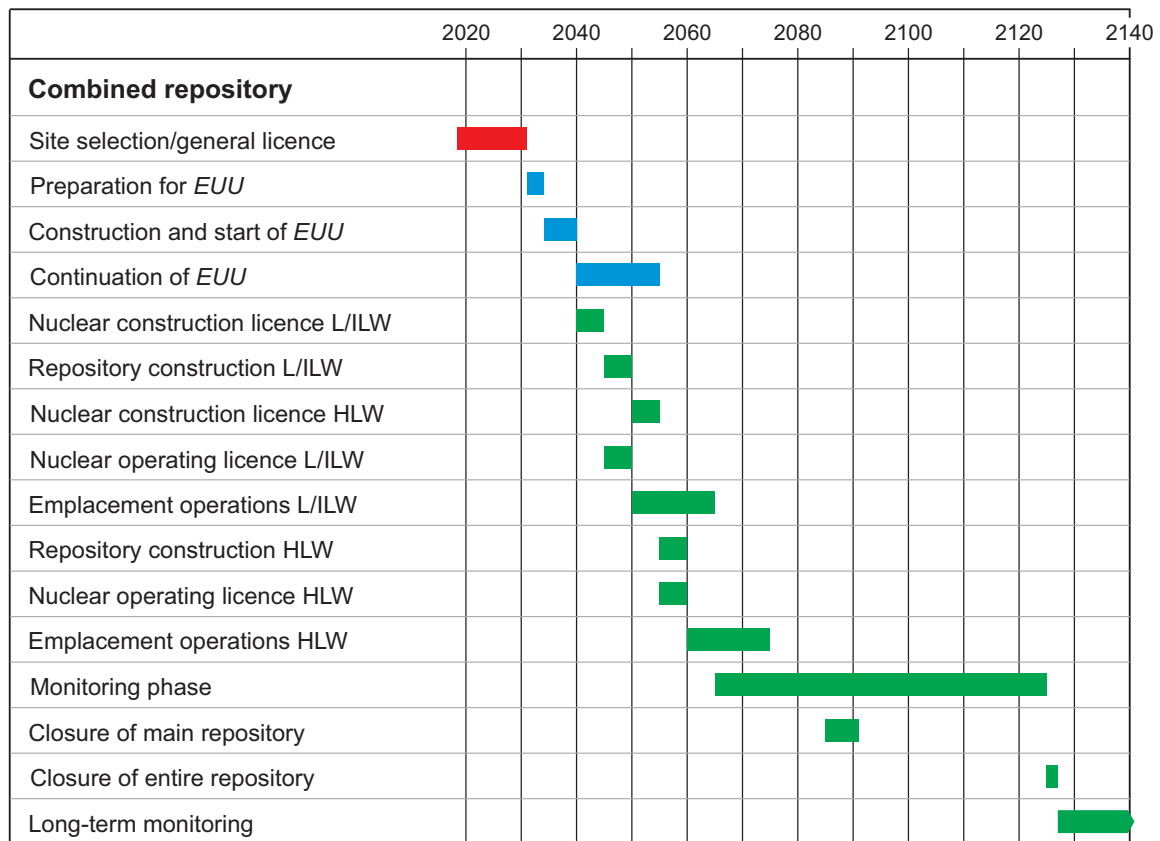


Fig. 2-1: Realisation timetable for the combined repository based on current planning (Nagra 2021h)

EUU: underground geological investigations.

2.1.2 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 expense. The waste management costs that arise during the operation of the nuclear power plants (e.g. for reprocessing of spent fuel up to 2005, investigations conducted by Nagra, construction of interim storage facilities) are met 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 producers into two independent funds, the Decommissioning Fund and the Waste Disposal Fund.

To fix the contributions to the two Funds and to secure the level of reserves in the Funds, the expected decommissioning and waste disposal costs are re-calculated every five years. The plant owners provide the required information and, based on this, Nagra calculates the costs of the deep geological repositories. The information provided by the NPP owners is reviewed by the Swiss Federal Nuclear Safety Inspectorate (ENSI). The funds are supervised by the federal authorities.

The previous estimate of the decommissioning and waste disposal costs was carried out in 2016 (Swissnuclear 2016). The 2021 Cost Study (*KS2I*) specifies the annual contributions for the period 2022 to 2026. More details on financing can be found in Nagra (2021h) and *KS2I* (Swissnuclear 2021), both in German.

2.1.3 Types and volumes of radioactive waste

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

1. high-level waste (HLW)
 - a) spent fuel assemblies (SF)
 - b) vitrified fission product solutions from reprocessing of spent fuel (HLW)
2. alpha-toxic waste (ATW)
 - a) waste with a content of alpha-emitters exceeding a value of 20,000 Becquerels per gram of conditioned waste
3. low- and intermediate-level waste (L/ILW)
 - a) 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

The current Waste Management Programme (Nagra 2021h) is based on a bounding scenario with regard to the data on the volumes and arisings of the waste with time.

Boundary conditions for the so called "60-year scenario" include:

- 60-year operation of the NPPs Beznau, Gösgen and Leibstadt and 47-year operation for Mühleberg.
- The exemption limits were modified in the 2017 revision of the Radiological Protection Ordinance (RPO 2017). For the first time, this revised RPO forms the sole basis for the expected waste volumes used in the Nagra Waste Management Programme (Nagra 2021h).
- Inclusion of decay storage: in line with Art. 117 RPO, the decay storage period is 30 years after the original material was last used.

According to the Sectoral Plan (SFOE 2008), the siting process should result in deep geological repositories that can accommodate the waste from the existing NPPs, their decommissioning and dismantling and the waste from medicine, industry and research.

In terms of the nuclear fuel cycle, the Swiss disposal concept considers both reprocessing and direct disposal. Up to 2005, when a moratorium on reprocessing was introduced, around 1,140 tonnes of fuel (uranium/heavy metal) had been sent for reprocessing. In 2018, a permanent prohibition on reprocessing entered into force. The remaining fuel (around 2,930 tonnes of uranium/heavy metal) 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 (around 2065) is assumed. This includes waste from small producers as well as from large research facilities (e.g. Paul Scherrer Institute (PSI) or the European Organization for Nuclear Research (CERN)) and decommissioning waste from research reactors.

The waste volumes for the "60-year scenario" are shown in Tab. 2-1. These are the volumes of conditioned waste. As waste is generally packaged in disposal containers before emplacement in the repository, the volume of the packaged waste is also given in brackets.

Tab. 2-1: Waste volumes in cubic metres for 60-year operation (Beznau, Gösgen, Leibstadt NPPs) and 47 years for the Mühleberg NPP ("60-year scenario")

The total waste volumes given here may show slight deviations from the sum of the rounded, individual waste volumes.

		Origin							Total
		SF (NPP)	WA (NPP)	BA (NPP)	RA (NPP)	SA (NPP)	MIR	BEVA/ OFA	
Category acc. to NEO	HLW	1,367 ¹ (8,892)	114 ² (377)				9 ⁵ (11)		1,490 (9,280)
	ATW		99 ² (432)			25 (25)	165 (524)		289 (981)
	L/ILW			11,100 ⁴ (29,691)	407 (1,436)	19,239 (24,951)	11,762 (15,614) ⁶	220 (582)	42,727 (72,274) ⁶
	Total	1,367 ³ (8,892)	213 (809)	11,100 (29,691)	407 (1,436)	19,264 (24,976)	11,936 (16,148) ⁶	220 (582)	44,506 (82,534) ⁶

¹ Corresponds to 2,929 tU.

² Waste resulting from reprocessing of 1,139 tU.

³ Full loading of the disposal canisters (no empty positions considered) would result in a volume of 7,506 m³.

⁴ These figures include 2,736 m³ of conditioned waste from the disposal of transport and storage casks, which is equivalent to a packaged volume of 2,938 m³.

⁵ Fuel assemblies from the DIORIT reactor and waste from PSI's Hotlab research facility.

⁶ These figures also include 2,399 m³ waste from the CERN reactor.

Sufficient capacity for interim storage of all waste is available in various facilities in Switzerland. The main centralised interim storage facility is Zwiilag, which has been fully operational since 2002. Additional spent fuel storage capacity exists at ZWIBEZ (the SF/HLW waste storage facility at the Beznau NPP that has been in operation since 2007) and the wet storage facility at the Gösgen NPP (commissioned in 2008). Each of the nuclear power plants also has fuel pools and interim storage for L/ILW from operations. In addition, the Swiss Federal Interim Storage Facility (BZL, *Bundeszwischenlager*) for waste from medicine, industry and research (MIR) is operated at the site of the Paul Scherrer Institute (PSI).

2.2 Stages and milestones in the Nagra disposal programme

The structure and the main stages and milestones of the Nagra disposal programme are stipulated by law. The procedural requirements in the Nuclear Energy Act (NEA 2003), the Nuclear Energy Ordinance (NEO 2004), the guideline for Swiss nuclear installations (ENSI 2020) and the conceptual part of the Sectoral Plan (SFOE 2008) as well as the Environmental Protection Act (USG 1983, *Umweltschutzgesetz*) that apply to the implementation of geological repositories are summarised in Nagra (2021h; Appendix A).

Site selection in accordance with the conceptual part of the Sectoral Plan is carried out in three stages (see Section 5.1 and Appendix 2). Once the site(s) and the repository concept have been defined in the general licences, further nuclear licences are required in accordance with the Nuclear Energy Act and Nuclear Energy Ordinance, i.e. construction licence, 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 throughout further repository implementation, as well as concepts for monitoring and closure of the repository. A preliminary protection zone is defined, and the first stage of an Environmental Impact Assessment (EIA) 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 EIA is carried out.
- **Nuclear operating licence:** The operating licence defines the capacity of the repository, measures for monitoring the environment and stages for starting up operations, the start of which requires a clearance from the authorities. It also defines the requirements applying to the waste, 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 humans and the environment can be ensured. After closure, the Federal Government can order a further limited period of monitoring.

2.3 General licence applications

The general licence applications must cover a broad range of issues (Tab. 2-2), most of them at the conceptual level.

Tab. 2-2: Documents required for the general licence applications (ENSI 2018c)

Site selection report
Safety report
Security report
Concept for monitoring and closure of the facility
Argumentation report and document structure
Reference reports
Environmental Impact Assessment
Compatibility with spatial planning requirements

After Nagra submits the general licence applications, 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 potential disposal zone due to lack of suitability. Stage 3 of the Sectoral Plan is complete when 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.

2.4 Programme stages after granting and validation of the general licence

After the general licence has been granted and validated by the federal authorities, the following programme stages are envisaged:

- construction and operation of a facility for *EUU* 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 Chapter 3 and are based on the assumption that a combined repository will be constructed.

3 The Nagra Disposal Programme Roadmap

The Nagra Disposal Programme Roadmap (Nagra Roadmap) supports planning, coordination and visualisation of the expected forward programme and is based on current boundary conditions. It is a tool for specifying, planning and communicating the entire, integrated programme.

The Roadmap is built over three integrated tiers, each with a different focus:

- Tier 1: Programme, captures a high-level description of the Nagra disposal programme all the way up the return of the site(s) to a greenfield state around 2126. Tier 1 covers the iterative repository design and safety assessment process and the legally binding repository licensing process. It sets out the overarching framework against which programme activities are mapped at Tier 2 and Tier 3.
- Tier 2: Optimisation, captures the activities at the core of the programme, up to the return to greenfield. Specifically, Tier 2 covers the development and optimisation of the repository design from the perspective of safety during construction, operation and post-closure; it also covers implementation to ensure technical feasibility and practicability.
- Tier 3: RD&D, captures the underpinning RD&D activities necessary to optimise and realise a Swiss repository up until first HLW emplacement around 2060. Tier 3 covers all RD&D activities required to support specific optimisation work at Tier 2, communicating the necessity and sufficiency of the Nagra RD&D programme.

The Nagra Disposal Programme Roadmap, or Nagra Roadmap, has been developed to support programme planning, coordination and visualisation of the upcoming implementation of the disposal programme. Important steps from the past (1980 – 2021) are illustrated, but the Roadmap primarily specifies the scope of the programme for the planning period from 2021 up to the return to a greenfield state roughly 100 years later (2126). The Roadmap focuses on well-defined activities in the near future (the next ten years) and outlines activities for the more distant future; both are coupled to major programme milestones and licensing stages. The time dimension used in the Roadmap is based on the combined repository timeline (see Fig. 2-1).

The Nagra Roadmap addresses several conditions formulated by the Federal Government when reviewing previous versions of the Waste Management Programme and the RD&D Plan (see Appendix A1 for a full list) and also incorporates the outcomes of additional discussions with the regulatory bodies.

The Roadmap defines the major products (the "what") that must be developed in each phase of the disposal programme (the "when") to deliver (design, construct, operate and close) a deep geological repository. The Roadmap covers the period from the start of the programme (approximately 1980) to the expected return of the site to a greenfield state (around 2126). However, the primary focus of the Roadmap is the period from the present (2021) to the beginning of HLW emplacement (2060) during which most of the activities will take place, including the vast majority of the underpinning RD&D activities. The Roadmap uses a Work Breakdown Structure (WBS) and multiple tiers (the "how") to clearly detail interdependences between activities and how all these activities, including RD&D, feed into key products, decisions, proposals and, ultimately, milestones.

The Roadmap is complementary and supplementary to the Waste Management Programme and the RD&D Plan. It is a summary and extract of the Nagra-internal roadmap which is used as a management planning instrument. The Roadmap-specific terminology is included in Appendix A3.

The Roadmap builds on international best practice in project management. It also aligns with best practice across the international radioactive waste management sector and the development of roadmaps to visualise and structure multi-disciplinary, multi-decade repository projects. In recent years, several European geological disposal programmes have adopted the use of roadmaps to improve strategic planning. A key driver has been for advanced programmes, with origins in a research- and safety-case-driven programme, to demonstrate implementation readiness for key project milestones. This has necessitated a shift in the communication of planning away from text-heavy documentation towards the use of planning tools and roadmaps to provide confidence that projects are needs-driven and integrated within the wider programme management plans. International examples of roadmaps used for geological disposal programme planning include:

- International Atomic Energy Agency (IAEA), Roadmap for Developing a Geological Disposal Programme, in press 2020 (IAEA in prep.)
- EC, European Joint Programme on Radioactive Waste Management (EURAD) Roadmap (Publications | Eurad (ejp-eurad.eu)); and
- RWM (UK), Science and Technology Plan (IAEA 2011).

The Roadmap identifies and incorporates all the activities envisaged for the realisation of a deep geological repository and is based on the current Nagra repository project of a combined repository. The activities are organised in a tiered structure:

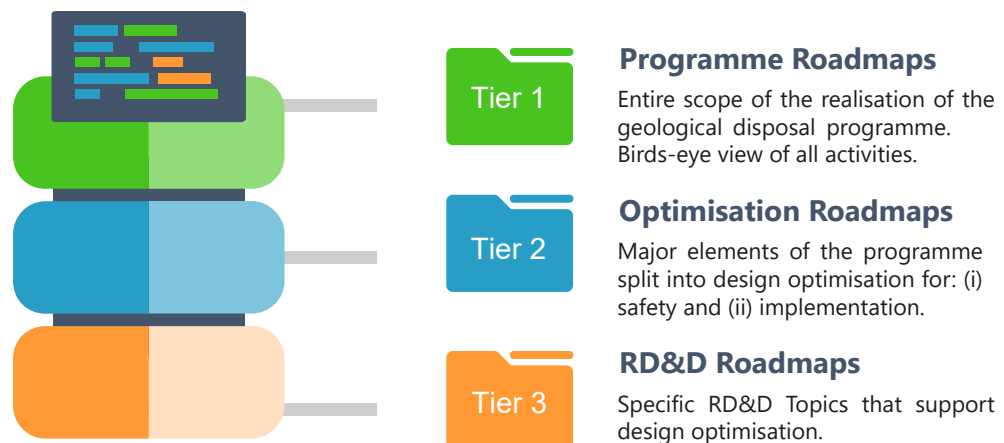


Fig. 3-1: The tiered structure of the Nagra Roadmap

- Tier 1 provides the framework on which the Nagra Roadmap is built. It shows the main regulatory and schedule drivers, the overall timeframe, programme milestones, major decision points, facilities to be constructed and the main areas of activity to be undertaken.
- Tier 2 is the core of the Nagra Roadmap. It identifies the timings and inter-relationships of all the key activities that must be undertaken to develop and optimise the design and safety concept already delivered for an eventual, specific site.
- Tier 3 identifies the detailed RD&D that will be undertaken to support the optimisation activities in Tier 2.

At each Tier, the activities presented are grouped according to:

- **Tier 1:** One roadmap, structured in time against "Programme Elements"
- **Tier 2:** Two roadmaps, structured in time against workstreams which cover design development and optimisation from the perspectives of post-closure safety and repository implementation. Implementation covers the construction, operation and closure of the repository and includes operational safety. Links between the Tier 2 Optimisation Roadmaps communicate the safety-integrated nature of repository implementation.
- **Tier 3:** Ten roadmaps, structured in time against aspects of the Nagra disposal programme with a significant RD&D component, defined as RD&D topics. The Tier 3 roadmaps capture, in a detailed manner, the RD&D that supports the progress of the Nagra disposal programme. The integrated nature of the Nagra RD&D programme means that these roadmaps are inter-linked with one another, as shown in Fig. 3-2. This also shows that they are connected to the Tier 2 Optimisation Roadmaps, where outputs from specific RD&D activities relate to a wide range of disciplines, such as post-closure safety and engineering feasibility.

All roadmaps in Tier 3 are connected to the Tier 2 Optimisation Roadmaps and both roadmaps in Tier 2 are connected to the Tier 1 Programme Roadmap, as illustrated in Fig. 3-2.

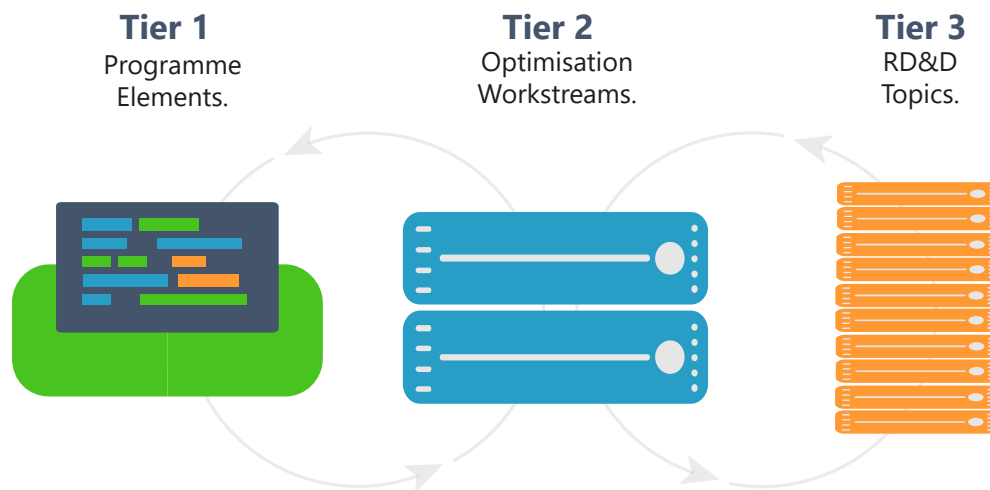


Fig. 3-2: The expansion of the hierarchical roadmap structure, illustrating the number of roadmaps at each tier and their interconnectivity

All roadmaps align with a common, overarching combined repository timeline that is split into Programme Phases and features Programme Milestones. This is illustrated in Fig. 3-3 which shows a strategic summary of the Roadmap. This overview presents the common, overarching timeline with which all of the roadmaps are aligned, along with the ten Programme Elements used in Tier 1. The strategic summary communicates only broad objectives for each Programme Element at each point in time. While the timeline in Tier 1 is defined broadly, the workflow in Tier 2 and Tier 3 is described using realistic estimations for completing the activities. As such, the Roadmap illustrates that the programme can be realised in the broad timeline used for Tier 1. The Roadmap thus demonstrates a possible realisation of the programme, but not the only one, as the broad timeline will inevitably be impacted by developments in the next decades.

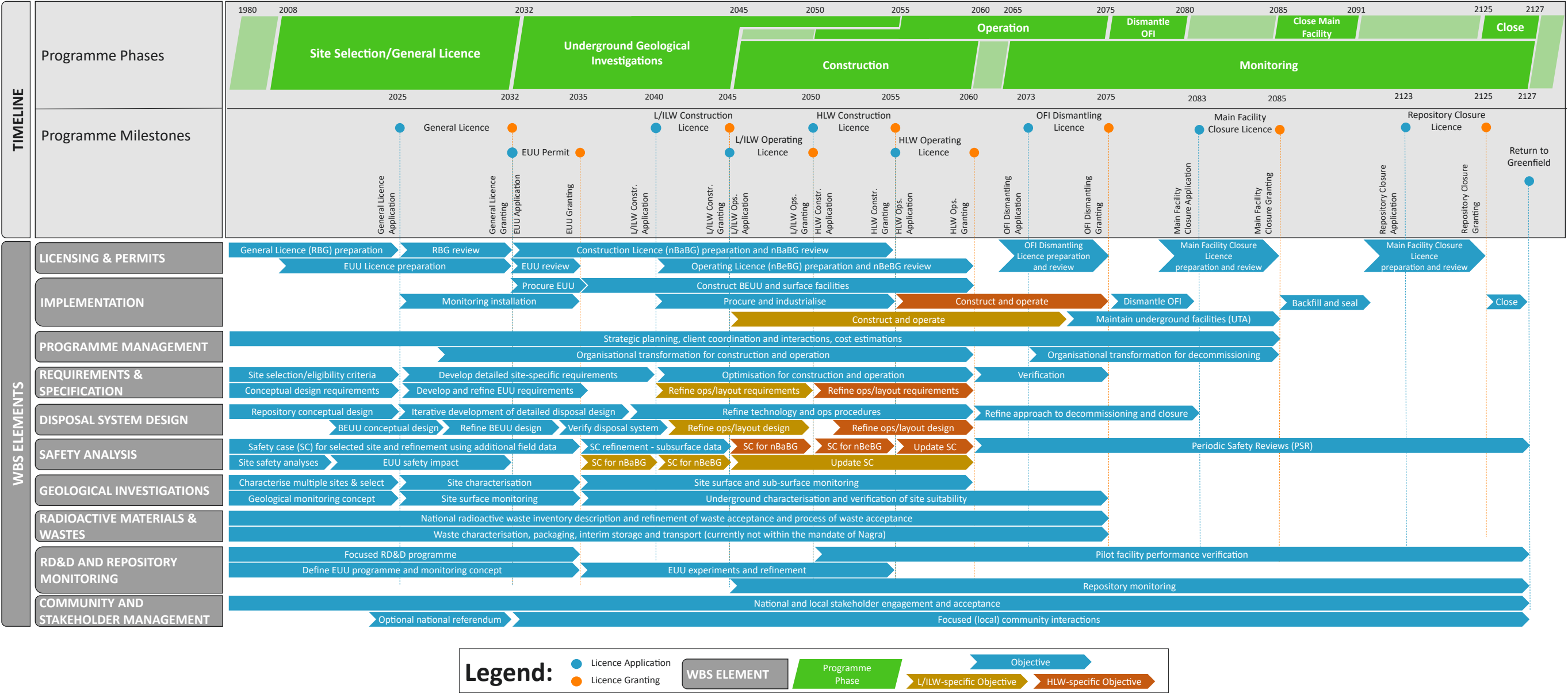


Fig. 3-3: Strategic summary of the Nagra Roadmap, defining the objectives for each of the Work Breakdown Structure (WBS) Elements during each Programme Phase to achieve each Programme Milestone as specified in the common, overarching timeline

3.1 Programme Roadmap: Tier 1

The Programme Roadmap can be found in Appendix A3, Fig. A3-1.

Tier 1 communicates the overall schedule and scope of the entire Nagra disposal programme, capturing the work necessary for Nagra to plan and safely construct, operate and close a deep geological repository in a timely manner in line with the Swiss regulatory framework. The scope outlined in Tier 1 illustrates the expected path of the programme, based on the current boundary conditions within which Nagra operates. Tier 1 illustrates when Nagra expects to deliver the most important products, decisions, proposals and licence applications to meet the specified combined repository timeline set out in Fig. 2-1.

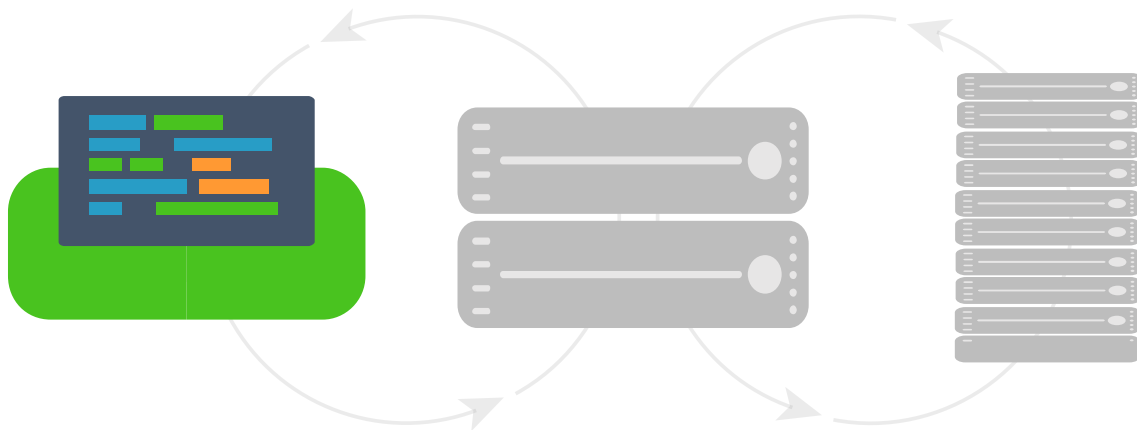


Fig. 3-4: The Tier 1 Programme Roadmap highlighted within the Nagra Roadmap structure

Tier 1 establishes a framework for the Nagra disposal programme by setting ten Programme Elements against a timeline.

The timeline captures the programme lifecycle from its initiation in the 1980s until the return to a greenfield state approximately 150 years later, thereby covering the complete lifecycle of the repository. It is formed by Programme Phases that are structured around the Programme Milestones. This timeline is used to structure all the roadmaps at each tier.

The Programme Elements collectively encompass all the disciplines necessary to support Nagra in delivering a deep geological repository:

1. **Licensing and Permits** – Preparation of documents for review by government and regulatory bodies, the monitoring and implementation of approval procedures and ensuring compliance with Federal Government requirements
2. **Implementation** – Creation of the necessary infrastructure for *EUU*, repository construction, repository operation, repository monitoring and the final closure of the repository
3. **Programme Management** – Periodic updates of the strategy for deep geological disposal, including the Waste Management Programme. Provision of the necessary leadership, management and planning processes, including those for quality, knowledge, Requirements and Configuration Management, cost studies
4. **Requirements and Specifications** – Updating and refining the hierarchically structured requirements and documentation of the stipulations made, based on the input from the various Nagra Work Breakdown Structure (WBS) elements

5. **Disposal System Design** – Design of the repository, accounting for each stage (construction, operation, monitoring and closure), including the inputs for the various licence applications and cost studies
6. **Safety Analysis** – Analysis of nuclear operational safety (including radiation protection, safety and safeguards) and post-closure safety, as well as feedback on site selection and optimisation of the repository design. Provision of the necessary safety reports and evidence for the licence applications
7. **Geological Investigations** – Regional and local geological investigations of the properties and long-term geological evolution of the areas of interest. Preparation of synthesis reports, including geological datasets as a basis for safety and design
8. **Radioactive Materials and Wastes** – Management of, and updates to, the inventory of existing and future radioactive waste and materials. Waste characterisation and further development of waste characterisation methods. Support for waste logistics, however responsibility for this is not within Nagra's mandate
9. **RD&D and Repository Monitoring** – RD&D experiments according to the requirements of the other Nagra WBS elements as well as monitoring of the repository
10. **Community and Stakeholder Management** – Interacting with relevant stakeholders and providing the necessary information in a targeted manner

Within this framework, Tier 1 summarises the expected Nagra disposal programme by capturing the work that will have to be delivered across each Programme Element over time.

A short description of the content of Tier 1 (as well as the strategic summary in Fig. 3-3) is given in the paragraphs below.

Programme initiation (1980s) to present (2021)

The Nagra disposal programme is built on a foundation of many years of work aimed at assessing the feasibility of geological disposal in Switzerland and finding a suitable site. In 2006, the Swiss Federal Government approved Nagra's demonstration of HLW disposal feasibility submitted in 2002. This was preceded by the approval of the demonstration of disposal feasibility of L/ILW in 1988.

The *SGT* was published in 2008 and describes the process of identifying suitable sites in three stages, starting from a so-called "white map of Switzerland", and defines the role of the various stakeholders in the process. In Stage 1, Nagra proposed six siting regions for HLW and L/ILW repositories, which were confirmed by the Federal Government in 2011. By 2018, *SGT* Stage 2 had resulted in a further narrowing down to three siting regions to be taken forward in *SGT* Stage 3. All three proposals are based on the assumption that disposal of all wastes will be in the Opalinus Clay (OPA) host rock.

The first Cost Study after establishing the Decommissioning and Waste Disposal Funds requested by the Federal Government was published in 2006 and the first Waste Management Programme followed two years later. To synchronise the information, the Federal Government stipulated that the Waste Management Programme, Cost Study and RD&D Plan should be submitted together, and this has been complied with since 2016. Each of these reports has to be updated every five years.

Period from 2021 to general licence applications (2024)

Updated versions of the Waste Management Programme, Cost Study and RD&D Plan are delivered in 2021. The periodic publication of the RD&D Plan will most likely take place until the granting of the licences for the dismantling of the surface infrastructure. At that point, no further RD&D will be necessary, given the closure of the L/ILW emplacement caverns and HLW emplacement drifts. The Waste Management Programme and Cost Study will be updated and published until the end of operations to ensure that sufficient budget is available to complete the disposal programme until closure and return to greenfield.

Announcement of the selected site(s) for preparation of the general licences (*ASR, Auswahl der Standorte für die Vorbereitung der RBG*) is anticipated in 2022. At the same time, the final decision will be made regarding the number of repositories and sites: either a single combined repository with separate L/ILW and HLW underground areas, as is assumed for the Roadmap, or two individual L/ILW and HLW repositories that do not share surface or underground facilities. The *ASR* will mark a shift towards the site-specific design stage of the disposal programme.

The general licence applications will mark the first step in the licensing process laid out in the Nuclear Energy Act (NEA 2003) and will be submitted with numerous supporting documents towards the end of 2024.

The site-comparative technical construction dossier will include all the data and information used to compare the three remaining sites and will identify the most suitable site for hosting a repository from a technical perspective. The justification of the site selection will provide a comprehensive overview of the factors which resulted in, and justify, the decision to choose the preferred site(s) within the framework of the Sectoral Plan. Forming part of the site selection documentation will be the geodossiers, which describe the individual sites and allow for optimisation of the design for each respective site, resulting in a fair comparison.

The site-specific design will capture the overarching conceptual design developed to meet the RCM document and the inventory captured in the Model Inventory for Radioactive Materials (MIRAM). The design will be supplemented with spatial planning information, infrastructure and operational procedure information and decommissioning and closure conceptual plans, all of which will give stakeholders an insight into the planned surface infrastructure, which is of particular importance to the local communities.

The site-specific design will be underpinned by a site-specific safety case. An overarching site-specific safety report (*Sicherheitsbericht*) will be published based on an operational safety report and a post-closure safety report for the purpose of supporting the general licence applications.

The site context will be drawn from geological data. The geosynthesis will provide a complete interpretation of the data acquired at the selected site(s) and will be periodically updated and published with each licence application.

At this stage, a concept for the monitoring phase will be developed and delivered as part of the *RBG*. This will ensure that the full lifecycle of the disposal programme is considered at this early stage. A Level 1 Environmental Impact Assessment (EIA) will also be conducted, which will be expanded to Level 2 later in the disposal programme as more information becomes available.

A security report will be submitted to outline key considerations for securing the proposed site as a nuclear facility in the future. This document will be prepared in more specific detail in future stages and will cover the L/ILW and HLW areas of the repository separately with the submission of the respective construction licence applications.

As part of the general licence applications, Nagra will also propose the organisational structure needed to effectively move forward with the site-specific phases of the disposal programme.

Period from 2025 to granting of general licences and *EUU* licence application (2032)

The submission of the general licence applications will be followed by approximately four years of review by the regulatory authorities and a recommendation whether the application should be approved.

Since the licence granted by the Federal Government may also be subject to a national referendum, approximately three additional years of political activities are anticipated before the general licences become legally valid.

The *EUU* licence application will be supported by a full *EUU* design addressing specific requirements and an analysis of the impact on safety using the latest geosynthesis. It also contains information on operational safety as underground operations will begin once the *EUU* licence is granted. The post-closure safety report will focus on ensuring that the construction of the facilities for the *EUU* and the activities therein will not affect the repository itself, e.g. by unintentionally disturbing the host rock.

A unique feature of the *EUU* licence application will be an investigation plan detailing the site verification activities that will take place. It will also outline the plans for experimental work in facilities for the *EUU* (*BEUU*), consisting of rock characterisation, performance confirmation experiments and demonstrations. More specific details on the latter will be added at a later stage of the programme through the *EUU* plans for L/ILW and HLW demonstrations captured in the Tier 2 Roadmap for Implementation Optimisation.

Period from 2032 to granting of HLW operating licence (2060)

Interactions with the regulator will take place to refine the approach to designing and constructing the facilities for the *EUU* following the submission of the *EUU* licence application.

Construction of the *BEUU* will begin once the *EUU* licence is granted, resulting in the areas being ready for verification and demonstration experiments. *EUU* operations will begin shortly after the facilities are ready and continue until the submission of the HLW operating licence application, by which point all *EUU* experiments will be complete.

L/ILW repository construction will begin as soon as the L/ILW construction licence is granted. The surface infrastructure (*OFI*) and underground facilities (*UTA*, *Untertageanlagen*) are expected to be in place to allow L/ILW repository commissioning by the time the L/ILW operating licence is granted. L/ILW operations are expected to last fifteen years.

The HLW repository will follow a similar process, with fifteen years of operations that will end when the surface infrastructure dismantling licence is granted.

Within this period, both the applications for L/ILW and HLW construction licences and L/ILW and HLW operating licences are submitted and are expected to be granted after a planned five-year period of regulatory review and discussion for each. Each construction licence will be submitted with a set of documents for L/ILW and HLW, respectively. The same procedure applies to the operating licences.

Leading up to each of these four licence applications will be a period of updating the detailed repository design in accordance with the latest RCM requirements. In parallel with the design update, an accompanying safety case will be developed. The safety case and design updates will be based on the latest geological and waste inventory information available and will be published as geosynthesis documents and captured in MIRAM, respectively.

Each construction licence application will include a summary of its compliance with the general licence. A set of technical construction documents, i.e. a detailed construction programme, will be required to specify precisely how the L/ILW or HLW extension of the central repository area will be carried out. Many documents will be updated and can be regarded as more detailed versions of those submitted with the general licence applications. The verification of the site will have to take place prior to the submission of a construction licence. This will show that the assumptions made in the safety documents align with the findings of site-specific geological investigations.

For each operating licence, updated versions of many of the same documents will be required that were already submitted with the relevant construction licence, capturing a greater level of detail. Organisational documents for operations will be required to ensure suitably qualified and experienced staff are available and responsibilities are assigned appropriately. This will be of particular importance for legal reasons before any handling and emplacement of radioactive material takes place in the repository.

Period from 2060 to return to greenfield state (2126)

During this phase, a Periodic Safety Review (PSR) will be submitted every ten years. This will capture the approach to all safety-related aspects throughout the remainder of the programme to ensure that a high level of safety is maintained.

Similar documents will be submitted with each of the licence applications during this period: the surface infrastructure dismantling licence, the main repository closure licence and the repository closure licence. A detailed plan for dismantling, closure and full closure will be accompanied by organisational documents. These will ensure that sufficient qualifications and experience are held by those directing and conducting the dismantling and closure activities, along with the assignment of legal responsibility. The main repository closure licence application will also include the final inventory, i.e. the contents of the repository. This will be captured in MIRAM for closure. A pre-closure RCM system will document how the repository requirements have been comprehensively addressed.

Once the surface infrastructure dismantling licence has been granted, post-operational monitoring will support the other applications for closure licences. Once the repository is closed, it will have reached its final stage of passive safety and will require no further subsurface monitoring or intervention to ensure safety, unless society decides otherwise in the future.

3.2 Optimisation Roadmaps: Tier 2

Tier 2 communicates the core of the planned technical activities which make up the Nagra programme. These activities drive disposal system development in iterative cycles of optimisation to ensure that a deep geological repository is optimised for numerous, often conflicting drivers. These can be broadly grouped into items that support optimisation to demonstrate the required safety performance (post-closure safety) and items that support demonstration of the ability to implement the repository (including construction and operational safety, technical feasibility, practicability, flexibility, local/regional acceptance and cost).

Due to the technical nature of these activities, with the focus on safety and implementation-integrated design development using site-specific data, the Tier 2 roadmap content does not cover the same scope as the ten Programme Elements established at Tier 1. Tier 2 therefore represents only a subset of the scope required to fully optimise a Swiss repository, albeit at a relatively high level.

The core optimisation activities that support disposal system development are captured by two Tier 2 Optimisation Roadmaps, which cut across the different Programme Elements:

1. Safety Development & Optimisation
2. Implementation Development & Optimisation

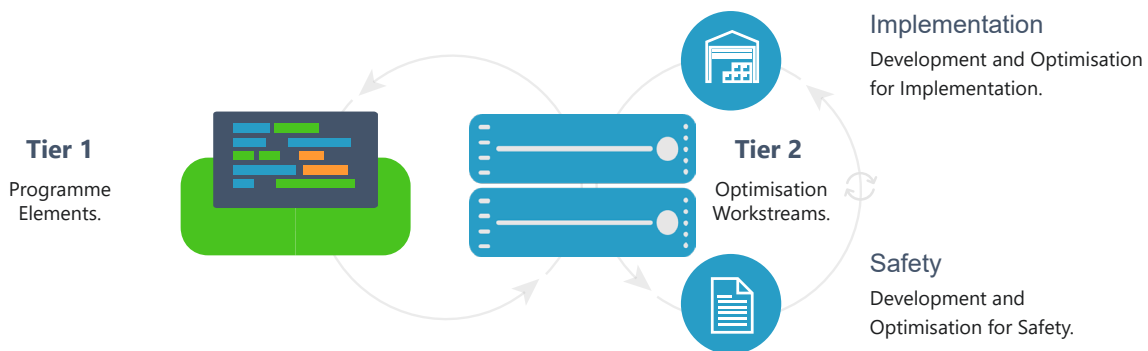


Fig. 3-5: The Tier 2 Optimisation Roadmaps highlighted within the Nagra Roadmap structure

Given the interlinked nature of Tier 2 and Tier 1, the scope outlined in Tier 2 also illustrates the expected path of the programme, based on the current boundary conditions within which Nagra operates. Tier 2 is representative of the expected path the Nagra programme will take and, hence, the logic between products, decisions, proposals and activities at Tier 2 is relatively detailed. However, as a result of changes to the boundary conditions through the investigations and decisions mapped out at Tier 2, the precise timing of specific activities and products may differ.

A short description of the Tier 2 Roadmaps is included in the next paragraphs, while a strategic overview of both Tier 2 Roadmaps is given in Fig. 3-6.

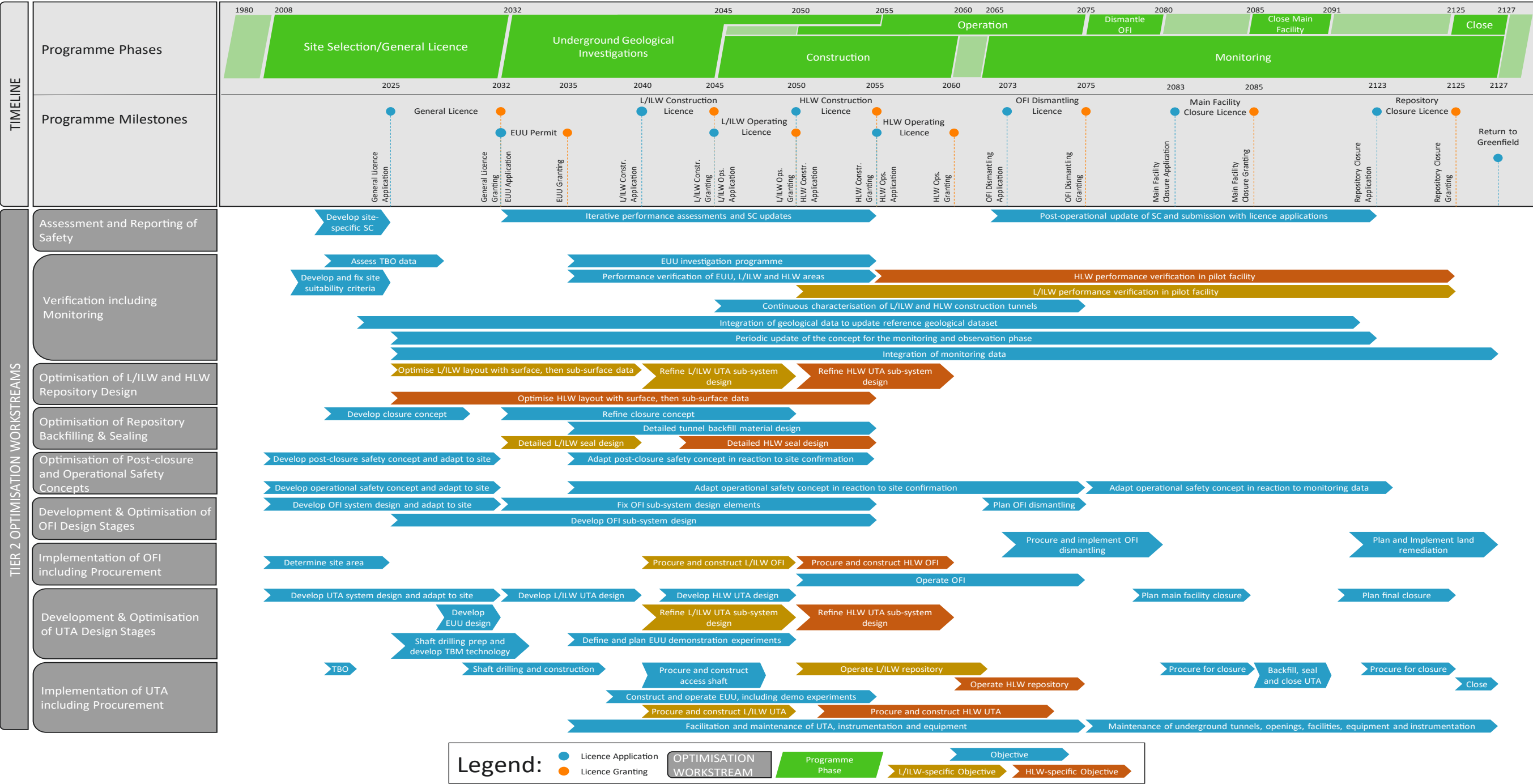


Fig. 3-6: Strategic overview of the Tier 2 Optimisation Roadmaps

3.2.1 Roadmap for Safety Development & Optimisation

The aim of the Safety Optimisation Roadmap is to communicate the further work that has to be carried out to ensure that, as the disposal system design matures, the design submitted as part of each licence and permit application is sufficiently optimised from the perspective of post-closure safety, as captured in the accompanying safety case. While the primary focus is on long-term optimisation, there are interfaces with activities related to optimisation from an implementation perspective, especially where operational safety and geological site data are concerned.

The Roadmap illustrates the cyclical process of updating those elements of the disposal system design that are safety-relevant against a progressively refined set of safety case requirements, optimising them with regard to safety and establishing certain elements as more information becomes available during the progression of the disposal programme. This includes adapting the design to take into account data arising from surface and subsurface field investigations, and information from modelling and experiments carried out as RD&D activities.

The Safety Optimisation Roadmap can be found in Appendix A3, Fig. A3-2.

The most important factor in the optimisation process is to adopt sound engineering design and technical features, and to apply sound principles of management throughout the development, operation and closure of the disposal facility. Given these considerations, protection and safety can then be considered optimised, provided that: (a) Due attention has been paid to the implications for long-term safety of various design options at each step in the development and in the operation of the disposal facility; (b) There is reasonable assurance that the assessed doses and/or risks arising from the generally expected range over the natural evolution of the disposal system do not exceed the relevant constraints over timescales for which the uncertainties are not so large as to prevent meaningful interpretation of the results; (c) The likelihood of events that might affect the performance of the disposal facility in such a way as to give rise to higher doses or greater risks has been reduced as far as reasonably possible by site selection and evaluation and/or design (IAEA 2011).

The activities in the Safety Optimisation Roadmap are organised across six distinct workstreams:

- **Assessment and reporting of safety** highlight the integration of lower-level modelling and experimentation to conduct comprehensive performance, hazard and safety assessments of the repository site, sub-systems and overarching design. This includes safety analyses and safety cases that will be developed to underpin the disposal system design as it is developed and optimised during the lifecycle of the disposal programme. This workstream aims to communicate the refinement that the post-closure and operational safety cases will undergo as more information becomes available once the *EUU* of the site are conducted and construction and operation of the repository commence.
- **Verification (*EUU*, construction, pilot repository and operation) including monitoring** aims to ensure that information acquired through the initial *EUU*, investigations in the test areas and pilot repository as well as continued investigations, excavations and monitoring that take place throughout the construction and operational phases is used to confirm assumptions and validate models.

- **Optimisation of the L/ILW repository design** aims to ensure that all L/ILW repository design aspects are optimised for post-closure safety throughout each iteration of overarching design.
- **Optimisation of the HLW repository design** aims to ensure that all HLW repository design aspects are optimised for post-closure safety throughout each iteration of overarching design.
- **Optimisation of repository backfilling & sealing** aims to ensure that the concept and plans for backfilling and sealing the entire combined repository are optimised with regard to post-closure safety throughout each iteration of overarching design.
- **Optimisation of post-closure safety concept (including safety functions)** communicates the continually developing nature of the post-closure safety concept, where the aim is to highlight the adaptations that may be necessary up until the final operating licence application is submitted. This workstream highlights important aspects of the Tier 2 Implementation Optimisation Roadmap. It is key to the development of an approach to, and concept for, post-closure safety based on which implementation-focused design work can be carried out.

Present (2021) to general licence applications (2024)

The focus on safety optimisation in the lead up to the submission of the general licence applications will include work that underpins the site-specific safety case. This will involve the analysis and interpretation of data obtained from the deep borehole campaign (*TBO*, *Tiefbohrungen*) being conducted in the three siting regions that have been taken forward as potential repository host sites. The campaign will be completed by early 2022.

The *TBO* data, coupled with the interpretation of 3D seismics, will contribute to the site-specific geological information (geodataset) that will be used as evidence for claims in the post-closure safety case and the supporting performance assessments (PAs) carried out during this period. These data will also provide key input to the site-comparative safety analysis. Site selection criteria that have to be defined in the context of the Sectoral Plan will be evaluated for each of the three siting regions. This evaluation will support the *ASR*, which will take place in 2022. Site suitability criteria will be defined during this period and submitted with the general licence applications. These criteria will include exclusion criteria, which, if demonstrated as a result of future site-specific findings, will halt the progression of the programme at that specific site.

During the lead up to the submission of the general licence applications, an initial concept for the closure of the repository and for monitoring the repository throughout its lifecycle will be developed and delivered.

Period from 2025 to granting of the general licences and *EUU* licence application (2032) and granting of the *EUU* licence (2035)

Following the submission of the general licence applications, and subsequent interactions with the regulator for providing additional information if needed, the focus of the safety optimisation activities will switch to the planning of subsurface investigations, identifying the needs and specifying the disposal programme that will be outlined when the *EUU* licence application is submitted.

L/ILW and HLW disposal concept optimisation as well as further optimisation of the repository design will continue throughout this period, implementing the state of the art, particularly as more site-specific subsurface data become available (e.g. through shaft drilling investigations).

Period from 2035 to L/ILW construction licence application (2040)

Once the *EUU* licence has been granted, site performance verification will take place simultaneously with the construction of the shafts and *EUU* facilities, where characteristics such as rock properties will be investigated as excavation takes place. Subsurface mapping, sampling, drilling and measurements will be carried out as construction of the *EUU* facilities progresses. Monitoring equipment will be installed at the surface and underground, providing additional data for verifying site characteristics.

Throughout the programme, a formal, updated safety case is developed for publication at the same time as the applications are submitted for the general licence, L/ILW construction licence, L/ILW operating licence, HLW construction licence and HLW operating licence. The Safety Optimisation Roadmap highlights the ongoing work required to underpin these safety cases as the verification process takes place and the understanding of the site matures. This process of safety case development and periodic publication aligns with the stepwise repository licensing process. However, the publication of a full safety case is not required for the *EUU* licence application. Next to ensuring safety during the construction of the *EUU* facilities, it will be demonstrated that the *EUU* does not affect the safety of the repository to be constructed later. To integrate the knowledge obtained through field work and shaft drilling, an intermediate safety case will be put together for internal decision-making purposes around 2035, bridging the fifteen-year gap between the site-specific safety case, published with the submission of the general licence applications, and the pre-construction L/ILW safety case, published with the submission of the L/ILW construction licence application.

The acquisition of site-specific data will be used to complete the development of L/ILW container and HLW canister designs, the allocation of waste in the repository layout and plans for repository monitoring, sealing and closure. Design developments will be integrated with updated technical performance assessments and the analyses integrated and published via the L/ILW pre-construction safety case.

Period from 2040 to L/ILW operating licence application and granting of L/ILW construction licence (2045)

Continued acquisition of site-specific data will provide input for continuing container and canister design development, updating monitoring and closure plans as well as more specific aspects such as the HLW repository layout and L/ILW repository sealing. Once again, the developments will be integrated with updated technical performance assessments and the analyses integrated and published via the L/ILW pre-operational safety case. This process of updating the safety case for each licence application will occur periodically throughout the subsequent phases of the programme.

The L/ILW underground facilities sub-system design will be refined from a post-closure safety perspective. This will be done through engagement with the regulator in the lead-up to the granting of the L/ILW construction licence, which will occur simultaneously with the submission of the L/ILW operating licence.

The refinement of the L/ILW underground facilities sub-system design during this period will enable Nagra to propose a final set of L/ILW waste acceptance criteria (WAC). The L/ILW WAC will be specified at the same time as the pre-operational L/ILW safety case publication and the submission of the L/ILW operating licence application.

Period from 2045 to HLW construction licence application and granting of L/ILW operating licence (2050)

During this period, performance confirmation experiments will take place in the *EUU* facilities, for processes later to be confirmed again in the pilot repository. Demonstrations for the L/ILW in the *EUU* facilities will also be finalised.

As construction of the L/ILW repository progresses, rock characterisation and geological monitoring information will provide input to any required design modifications. The constructed repository will be ready for operation once the L/ILW operating licence is granted by the authorities, as will the design of both waste containers, i.e. for nuclear power plant (NPP) operational waste and for NPP decommissioning waste.

Period from 2050 to granting of HLW operating licence (2060)

Analogous to the L/ILW process, in the lead up to the submission of the HLW operating licence application, the HLW underground facilities design will be refined from a post-closure safety perspective through interactions with the regulator. The HLW WAC will be specified with the publication of the pre-operational HLW safety case and the submission of the HLW operating licence application. As the stepwise construction of the HLW underground facilities takes place, continuously updated geological information will be used to verify HLW design performance. If modifications are necessary between the granting of the HLW construction and operating licences, they will most likely be limited to questions concerning seals and backfill materials.

Period from 2060 to return to greenfield state (2126)

The overall safety of the repository will be reported through a Periodic Safety Review (PSR) submitted to the authorities every ten years. The PSRs will incorporate the specific post-closure and operational safety cases which will be developed before the submission of each licence application: surface infrastructure dismantling, main repository closure and final closure. These safety cases will integrate monitoring data to assess the short-term evolution of the repository in the approximately seventy years between the start of HLW operations and the repository site's return to a greenfield state by 2126.

3.2.2 Roadmap for Implementation Development & Optimisation

The aim of the Implementation Optimisation Roadmap is to communicate the further work that must take place to ensure that all aspects of the Nagra disposal system can be implemented and optimised with respect to engineering, construction and operational safety, costs, stakeholder requirements, scheduling, flexibility and other factors.

This Roadmap covers the implementation of the surface infrastructure within the framework of the *SGT* as part of community and stakeholder management efforts, the structures required to allow underground geoscientific characterisation, development and demonstration work to take place, and covers the underground facilities that, altogether, form the required repository system. This includes the process of updating and optimising the disposal system design against a progressively refined set of technical and stakeholder requirements. It also extends to the development, adaptation and optimisation of technology in response to progressing site characterisation, modelling, experimentation and demonstration activities.

Furthermore, the Implementation Optimisation Roadmap highlights the elements of the repository system that must be decided and become fixed at various points in the programme. Fixing certain elements is necessary for planning purposes, and the required lead-times between decisions and related follow-on activities are illustrated in the Roadmap. Proposals for fixing other elements must be made for the purpose of repository licensing and, in these cases, the Roadmap shows how these proposals to the relevant authorities will be communicated through each step of the repository licensing process.

The Implementation Optimisation Roadmap can be found in Appendix A3, Fig. A3-3.

The Implementation Optimisation Roadmap is strongly linked to the Safety Optimisation Roadmap because relevant considerations in the optimisation of protection and safety measures are particularly relevant for implementation. These include the separation of mining and construction activities from waste emplacement activities, the use of remote handling equipment and shielded equipment for waste emplacement where necessary, the control of the working environment to reduce the potential for accidents and their potential consequences and minimising the need for maintenance in supervised and controlled areas. Contamination has to be controlled and prevented to the greatest extent possible (IAEA 2011). A balance has to be struck between safety optimisation and the need for the project to be measured from an efficiency and economic point of view.

The activities in the Implementation Optimisation Roadmap are organised across five distinct workstreams:

- **Development & optimisation of the surface infrastructure design stages** illustrate the sub-systems that make up the surface infrastructure, ensuring that the decisions that must be made and design aspects that must be fixed are carried out in a timely manner to allow sub-surface design and implementation to progress according to schedule. The scope of this workstream includes those considerations necessary to discuss the expectations of the community with regard to the environmental impact and spatial planning of the repository. This workstream ensures that mature designs are in place to allow surface infrastructure implementation to be realised according to schedule and in line with foreseen costs, as captured in the periodically updated Cost Study.
- **Implementation of the surface infrastructure including procurement** highlights the preparation, procurement, construction, operation and closure of the surface infrastructure. It communicates the realisation of the supporting surface infrastructure sub-systems, which allows a hand-off to the subsurface aspects of the Implementation Roadmap, and the waste treatment and packaging/encapsulation plants, which are key surface infrastructure sub-systems for waste emplacement operations.
- **Development & optimisation of the design stages of the underground facilities** illustrate the sub-systems that make up the underground facilities, ensuring that the decisions to be made and design aspects to be fixed are carried out in a timely manner to allow repository commissioning and waste emplacement operations to progress according to schedule and in line with foreseen costs, as captured in the periodically updated Cost Study. This workstream ensures that mature designs are in place to allow implementation of the underground facilities to be realised.
- **Implementation of the underground facilities including procurement** highlights the preparation, procurement, construction, operation and closure of the underground facilities. It communicates the realisation of the individual HLW and L/ILW repositories and their respective underground sub-systems.
- **Optimisation of operational safety concept** communicates the continually developing nature of the operational safety concept, where the aim is to highlight the adaptations that may be necessary up until the end of the operational period. This workstream also highlights important aspects for the Tier 2 Safety Optimisation Roadmap. It is key to the development of an approach to, and concept for, operational safety based on which implementation-focused design work can be carried out.

Present (2021) to general licence applications (2024)

The announcement of the *ASR* will take place in 2022, once the data interpretation of the sites has advanced sufficiently. Alongside the *ASR*, Nagra will communicate the area defined for the surface infrastructure at the selected site(s) and whether the HLW encapsulation plant (*BEVA*) will be located on- or off-site.

Through this process, the expectations of stakeholders will be considered thoroughly as specified in the Sectoral Plan. The basis for communication will be a site-adapted project for the major repository systems: the surface infrastructure and the underground facilities. Following the *ASR*,

discussions with the host community will continue and the surface infrastructure will be refined so that a Level 1 Environmental Impact Assessment (EIA) and a report on coordination with spatial planning can be submitted as part of the general licence applications.

In parallel with this process, the conceptual underground facilities system design will be further developed in accordance with the operational and post-closure safety concepts and submitted as part of the general licence applications.

Period from 2025 to granting of general licence (2032) and the *EUU* licence (2035)

The focus from an implementation perspective for this period will be the provision of functioning *EUU* facilities. Following the approval of a Nagra exploratory request, exploratory shaft drilling activities at the chosen site will provide additional subsurface information. Specifically, this drilling will provide underground information along the axes of the shafts that will be constructed once an *EUU* licence is granted.

At the beginning of this period, the optimised concepts for operational and post-closure safety will support the optimisation of the conceptual design of the surface infrastructure and underground facilities systems. Submitted as part of the *EUU* licence application, the final *EUU* design will include the design of the shafts for operations² (*Betriebszugang*, B-shaft) and ventilation (*Lüftungszugang*, L-shaft) and the surface infrastructure shaft head installations (*Nebenzugangsanlage*, *NZA-BL*) needed to operate the *EUU* infrastructure and the fixing of many design aspects of the repository as a whole. These design aspects will integrate the surface infrastructure and underground facilities systems into the final repository as licensed nuclear facilities later in the programme. Continued updates of the concepts for operational and post-closure safety will also be used to help develop the surface infrastructure and underground facilities design for the duration of the pre-construction, construction and operational periods. Following the submission of the *EUU* licence application, procurement for the construction of the *EUU* facilities, including the shaft head installations, will occur in parallel with the *EUU* licence application regulatory review.

Period from 2035 to L/ILW construction licence application (2040)

Once the *EUU* licence has been granted, the shafts at the shaft head installations will be constructed, which is scheduled to require approximately three years for completion. With access to the underground, the L/ILW *EUU* facilities will be constructed and, once ready for operations, will start to host L/ILW experimental setup and monitoring activities. During construction, these initial excavation and investigation activities will support the periodic update of the geological dataset, providing new and highly relevant information to other areas of the programme, particularly the validation of safety-related assumptions. Optimisation of excavation techniques and the excavation process, minimising risks and costs will be a major aspect during this period.

² The current Nagra repository project (see Section 5.3) is the basis for the Roadmap and currently foresees a combined repository with shaft access.

Period from 2040 to L/ILW operating licence application and granting of L/ILW construction licence (2045)

Following decisions on the L/ILW construction method and other aspects of the L/ILW underground facilities sub-system design such as the repository architecture and when the L/ILW *EUU* facilities will be incorporated into the L/ILW repository, procurement for the L/ILW underground facilities will be carried out in parallel with the procurement for access shaft construction.

EUU experiments and demonstration activities will provide evidence for verification of the L/ILW and HLW repository designs. Discussions with the regulator may result in adaptations and refinements of the L/ILW underground facilities from an implementation perspective. During this period, procurement of all remaining L/ILW surface infrastructure sub-systems will begin to provide sufficient lead time for construction activities.

Period from 2045 to HLW construction licence application and granting of L/ILW operating licence (2050)

During this period, the focus will shift to aspects that are unique to the HLW repository. The HLW repository surface infrastructure and underground facilities sub-system designs will be finalised, incorporating the latest subsurface data and updates to the concepts for operational and post-closure safety.

The L/ILW surface infrastructure and underground facilities sub-systems, including the access shaft, will be constructed during this period, ensuring their readiness for operations once the L/ILW operating licence is granted.

Period from 2050 to granting of HLW operating licence (2060)

Prior to L/ILW emplacement operations, a commissioning stage will take place during which operational testing can be carried out across the surface infrastructure and underground facilities using first non-nuclear, then nuclear materials. Following commissioning, the L/ILW repository will become operational and L/ILW emplacement will begin.

Following the decision to finalise the HLW repository construction method, procurement will take place for construction of the HLW underground facilities and HLW-specific surface infrastructure such as the waste encapsulation plant and the treatment facility for transport and storage casks (*TLB, Transport- und Lagerbehälter*). This will be supported by refinements to the design from an implementation perspective as a result of interactions with the regulator. Once the HLW construction licence is granted, HLW underground facilities and surface infrastructure construction will take place.

Period from 2060 to return to greenfield state (2126)

The construction of HLW-specific surface infrastructure sub-systems will be completed by the time the HLW operating licence is granted. However, the HLW underground facilities will continue to be constructed in parallel with the operation of the HLW repository. Initially, a commissioning phase, similar to that of the L/ILW repository, will take place before waste emplacement begins in constructed underground tunnels. For the majority of the HLW operational phase – i.e. when HLW canisters are being emplaced – new HLW emplacement drifts will be excavated simultaneously.

Following the start of HLW operations, adaptations to the operational safety concept will continue to take place as more site data become available and monitoring data are continuously integrated. Based on these continuously updated data, the operational safety concept will continue to be periodically updated to consider implementation activities.

Shortly before the end of HLW operations, Nagra will finalise an approach to surface infrastructure dismantling and begin procurement in line with that approach. The formal dismantling plan will be published with the submission of the surface infrastructure dismantling licence application. A two-year period of regulatory interaction and refinement to the plan will end in the granting of the surface infrastructure dismantling licence and cessation of the vast majority of surface infrastructure and underground facilities operations. However, the common underground areas, such as various tunnels, openings and facilities, along with the monitoring equipment and instrumentation, will be maintained. Surface infrastructure dismantling will take around five years, at which point the surface infrastructure will be considered closed.

In approximately 2080, the approach to the closure of the entire main repository will be defined and work will begin on finalisation and procurement. A closure plan will be published with the submission of the main repository closure licence application. This will be followed by a two-year period of regulatory interaction and refinement to the plan before the licence is granted by 2085. At this stage, all underground areas will be closed and backfilled. The L/ILW and HLW repository seals will be put in place and the main repository, including the HLW and L/ILW underground facilities, will be considered closed by around 2090.

A similar process will be conducted for the final closure of the repository, starting in around 2123. The final closure licence is expected to be granted by 2125 and the final backfilling and sealing to be completed by 2126, at which point surface work will take place to return the site to a greenfield state.

4 The RD&D Plan within the Nagra Roadmap

The RD&D Plan forms an essential part of the Nagra Roadmap up to the operational phase of the repositories. It will continuously support the disposal programme implementation, and its outcomes will be integrated into the decisions and concepts submitted at each of the licensing steps.

The specification, planning and implementation of RD&D is a needs-driven process, where the general drivers are the optimisation processes which must be carried out from the perspectives of safety (recurring safety cases at each milestone) and implementation (confidence underpinning the feasibility of the design at each milestone). The ongoing development of repository variants currently represents an important share of the RD&D activities.

These drivers follow from the products, decisions, proposals and activities at Tier 2 of the Roadmap, and Tier 3 communicates the manner in which they are addressed through RD&D. Tier 3 of the Roadmap covers all RD&D activities to be managed by Nagra, but the current focus is on ten specific programme aspects with a significant RD&D component. For these aspects, the Roadmap illustrates how the Nagra RD&D Plan meets the evolving needs of the programme, where the licensing process necessitates an increasing level of refinement in the various elements of the disposal programme.

Nagra's approach to RD&D is based around strategic decisions to carefully maintain in-house expertise, support expertise development through collaborative efforts or rely on bringing in external expertise. In each case, the decision is adapted to the specific needs associated with each licensing step.

4.1 Identifying RD&D needs and activities

As discussed in Section 1.2, future RD&D activities are identified to provide information needed to meet requirements emerging from the integration of the safety case and the RCM system. A systematic derivation of the requirements for repository design from the point of view of post-closure safety aims to ensure that the decisions, justifications and interdependences of the information gathered on deep geological repositories are comprehensible, and that changes to this information can be traced and communicated (including optimisation of the repositories). These form an important element of RCM. In RCM, requirements are structured at five hierarchical levels (see Section 5.2.3 for more detail). Nagra's repository project is being used to develop and test the RCM system and is described in Section 5.3 of this report.

RD&D activities will contribute to demonstrating that requirements on individual components and their implementation can be met, or that the safety margins towards meeting the requirements can be increased. The outcome of RD&D may also lead to changes in the individual concepts if requirements are not demonstrably met. RD&D may also lead to the amendment of requirements, for example if additional information shows that a requirement is overly cautious in its original form. Since 2016, Nagra has further developed and expanded the RCM system in view of the upcoming general licence applications, with the goal of applying a consistent approach to the development, documentation and management of the requirements for the deep geological repository.

In the earlier stages of the disposal programme, concepts were developed, and options were formulated while providing flexibility to accommodate future developments. As the implementation programme develops over the coming years, more elements will gradually be defined during the

optimisation process, e.g. the site will be determined with the granting and validation of the general licence applications. However, as repository realisation begins to take place, i.e. the detailed concept is refined and decisions around options and alternatives are made, the level of flexibility in the disposal programme will decrease.

As indicated in the Roadmap, this process will take several decades. To make some of the decisions required for future licensing steps, so-called "programme aspects with a significant RD&D component" will require input from RD&D over the same timescale. These aspects differ from the larger number of other disposal programme aspects that will be developed using classical engineering and planning without significant reliance on RD&D support. Constructing the geological repositories will show many similarities with the realisation of major civil engineering infrastructure projects. Both rely largely on state-of-the-art engineering practices for the development of the operating concepts and the construction itself.

Aspects that do require significant RD&D over longer periods need special attention given the timescales involved. These include considering how the overall system will be implemented technically and temporally, how the individual RD&D activities will interact with each other, and how they are connected with the Roadmap milestones and decisions. The Roadmap describes how each aspect will be dealt with, up to the first emplacement of HLW, and shows when key research projects and development activities will start and when they will be completed.

Nagra and other waste management organisations worldwide already possess a considerable amount of relevant technology, knowledge and expertise. 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 supports the delivery of projects in line with the required milestones in an optimised manner while making full use of available relevant technology, knowledge and expertise and monitoring relevant developments elsewhere. In doing so, Nagra will use its human and financial resources efficiently and share resources where appropriate.

The work related to design, technology development and safety assessment is structured and planned in such a way as to support the needs of the Tier 2 Optimisation Roadmaps and thus, indirectly, the Nagra Roadmap. 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 disposal programme stage. The RD&D needs are represented in Tier 3 of the Roadmap.

Selected variants will gradually be integrated into the repository project as the programme matures. Technology development will form an important part of the RD&D programme in anticipation of the submission of the construction licence application.

The objectives and nature of RD&D activities foreseen beyond the submission of the general licence applications are described in Chapter 6, which provides a broad overview of the content supporting future licensing steps, including activities in the *BEUU*. The RD&D is broadly grouped into the following categories, in line with the WBS of the Roadmap and the structuring of the RD&D activities in the Cost Study (Swissnuclear 2021).

- geological investigations
- radioactive materials and wastes
- design and technology development
- safety assessment and safety-relevant properties of the engineered barrier system
- monitoring
- international collaboration and competence management (also partially integrated into the bullet points above)

RD&D is necessary to validate methodologies, verify assumptions, test processes and generally underpin the development and optimisation of the repository design. Tier 3 of the Nagra Roadmap serves as a tool to communicate all the RD&D necessary for the realisation of a Swiss repository.

However, to clearly demonstrate how specific RD&D activities contribute to the realisation of a safe and implementable repository design, specific aspects of the disposal programme with a significant RD&D component are selected and described in ten integrated Tier 3 RD&D Topic Roadmaps (see Fig. 4-1.).

As such, the Tier 3 RD&D Topic Roadmaps represent only a subset of the scope required to fully underpin the realisation of the repository. They communicate the specific RD&D necessary to support specific optimisation work, based on the current boundary conditions within which Nagra operates.

A short description of the Tier 3 Roadmaps is included in Chapter 7. An overview of the entire RD&D programme up to closure of the repository is provided in Chapter 6, while a detailed description of the activities over the next five to ten years is provided in Chapter 8.

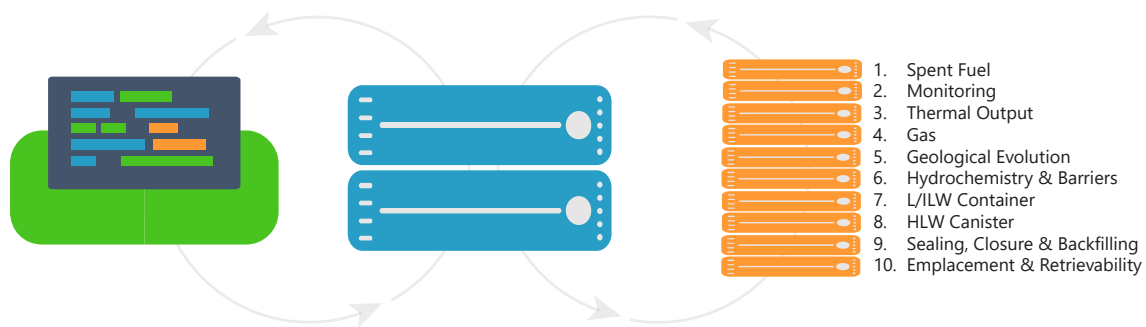


Fig. 4-1: The Tier 3 RD&D Topic Roadmaps highlighted within the Nagra Roadmap structure

4.2 RD&D in support of the upcoming licensing milestone

In the current stage of the Nagra disposal programme, the RD&D programme focuses strongly on providing all the information needed to address the requirements of the Sectoral Plan, as well as providing the basis for designing, developing and assessing the operational and post-closure safety of the HLW and L/ILW repositories.

Within the Sectoral Plan, there is a strong emphasis on geological investigations and safety assessment, as the principal objectives are to characterise, 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 was proposed by Nagra in *SGT* Stage 2 and, in the RD&D programme, further work is 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 could also provide input to potential modifications of the current concept aimed at keeping perturbations at an acceptable level. Another important area is assessing the construction feasibility of the repository components taking into account the site-specific conditions and the geomechanical properties of the Opalinus Clay host rock at the selected site(s).

Additional requirements for the general licence applications (Tab. 2-2) will result in an increased need for information in a broader range of areas, e.g. monitoring, description of the waste types and barrier performance, all of which contribute to the development of a full safety case. Additional requirements formulated by the SFOE in 2018 (see Appendix A1) in response to the submission of the Waste Management Programme and the RD&D Plan in 2016 (Nagra 2016a, 2016b) are also addressed.

With the granting and validation of the general licences, the sites for the respective repositories are fixed, including the approximate size and location of the most important facilities as well as the waste categories and the maximum disposal capacity. This 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 licences, 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.

The detailed repository design, including the exact location of emplacement caverns and drifts and their detailed design as well as the detailed layout of the engineered barrier system, will take place only after the underground has been explored (including results from the *BEUU*). This will be done in conjunction with the nuclear construction licence. In anticipation of the construction licence, the materials for the engineered barriers will finally be selected. Up to that point, feasible reference materials will have been identified, 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 SF/HLW disposal canister and the backfill.

Chapter 8 focuses on the RD&D activities planned for the next five to ten years and thus includes the submission of the general licence applications and the progress made since 2016 when the previous RD&D Plan was published (Nagra 2016b).

4.3 Implementation of RD&D activities

The general approaches for how to address RD&D priorities are summarised in Tab. 4-1, 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 in Nagra in the 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 in Nagra and at the competence centres, and the opportunities for resolving some issues because strong scientific competence already exists in certain areas
- the possibility to learn from others and to limit the duplication of work
- cost effectiveness

The importance of these factors for individual activities evolves over the different licensing steps of the disposal programme.

Tab. 4-1: Approaches available for resolving outstanding issues and uncertainties

Possible approaches	Issues appropriate for this approach
A 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 disposal programme (e.g. producing the overall syntheses for geoscience, engineering projects and safety; waste inventory definition and associated characteristics).
B Manage RD&D projects for which technical work is undertaken by Nagra-external competence centres	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 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 "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 that Nagra is capable of managing such projects.
E Monitor developments internationally	International developments will of course be monitored in all relevant areas. It may, however, be the <i>sole</i> approach if: • 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. This nevertheless requires the capabilities at Nagra to oversee the relevant scientific-technological area of work.

5 Technical status, progress and capabilities

This chapter describes the current status of the technical programme, the progress that has been achieved since the last RD&D Plan was published in 2016 and the resources Nagra will provide for future RD&D activities.

5.1 Status with respect to the Sectoral Plan (site selection and general licences)

The general licensing process requires the definition of various high-level aspects and boundary conditions for the final repository, a full safety case and the repository conceptual design.

Since the start of the *SGT* process in 2008, Nagra has worked with stakeholders and used increasingly detailed geological information to assess various regions in Switzerland against thirteen criteria for site evaluation defined to ensure the safe and feasible implementation of geological disposal:

- *SGT* Stage 1 led to the proposal of three siting regions for a HLW repository and six regions for a L/ILW repository.
- *SGT* Stage 2 led to the further narrowing down to three siting regions in which a safe HLW, L/ILW or combined repository could feasibly be implemented and the designation of locations where surface infrastructure would be located for each.
- *SGT* Stage 3 is ongoing and involves more detailed examinations and supplementary geological investigations which will lead to the announcement of the site(s) for which general licence applications will be prepared.

The geological exploration in Stage 3 is currently well underway, and a range of technologies continue to be used to develop geodossiers for each of the three potential siting regions. Working closely with various interest groups, Nagra is also currently optimising the arrangement of the surface infrastructure.

This ongoing process will allow a transparent comparison of the siting regions in accordance with a set of well-established criteria. These activities are on course for the selection and announcement of the preferred site(s) in 2022.

The *SGT* stipulates the conditions for the disposal of radioactive waste in Switzerland. It was approved by the Federal Government on 2nd April 2008 and describes the process for obtaining the general licences for the two repositories under the direction of the Swiss Federal Office of Energy. The general licences define the site(s) 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. It also specifies the suitability criteria to be observed in further repository implementation, as well as concepts for monitoring and closure of the repository. A preliminary protection zone is defined, and the first stage of an Environmental Impact Assessment is carried out.

The Sectoral Plan clearly defines the roles of the different stakeholders as well as the decision-making process and the input needed to select the repository site(s) (SFOE 2008). To assess safety and technical feasibility, the Sectoral Plan defines 13 criteria, grouped into four broad areas (Fig. 5-1), and three main stages of site selection as follows:

Criteria for site evaluation from the viewpoint of safety and technical feasibility	
Criteria group	Criteria
1. Properties of the host rock and the effective containment zone	1.1 Spatial extent 1.2 Hydraulic barrier effect 1.3 Geochemical conditions 1.4 Release pathways
2. Long-term stability	2.1 Stability of the site and rock properties 2.2 Erosion 2.3 Repository-induced influences 2.4 Conflicts of use
3. Reliability of geological findings	3.1 Ease of characterisation of the rock 3.2 Explorability of spatial conditions 3.3 Predictability of long-term changes
4. Engineering suitability	4.1 Rock mechanical properties and conditions 4.2 Underground access and drainage

Fig. 5-1: Criteria for site evaluation from the viewpoint of safety and technical feasibility as specified by the Sectoral Plan

From SFOE (2008). Criteria in Group 1 assess current conditions, those in Group 2 the long-term evolution, Group 3 evaluates uncertainty and Group 4 the engineering feasibility.

Stage 1: Selection and approval of geological siting regions for L/ILW and HLW

The focus of Stage 1, which started in 2008, was on formulating proposals followed by an official review of potential geological siting regions based on a scientific screening process and on setting up regional participation. Nagra's responsibilities were to:

- propose geological siting regions for both repositories based on existing information
- inform the stakeholders, as requested, and respond to questions
- contribute to the development of the evaluation methodology with respect to spatial planning
- provide information on land-use planning for the proposed siting regions

In October 2008, and based on a five-step approach documented in Nagra (2008c), Nagra proposed three geological siting regions for the HLW repository and six for the L/ILW repository, whereby three siting regions for the latter are almost identical to those proposed for HLW (Nagra 2008b). After an extensive review by the authorities and a public consultation phase, Stage 1 was completed with the approval of Nagra's proposals by the Federal Government in November 2011.

Stage 2: Selection and approval of at least two siting regions for each of the repositories

In Stage 2, the goals were to identify locations for surface facilities together with the regional conferences and to narrow down the number of siting regions to at least two per repository type. Nagra's responsibilities were to:

- develop a site-specific layout for the repository surface facility for at least one site in each region in collaboration with the respective cantons and regions
- perform provisional safety analyses
- define the activities and initiate preparatory work for the Environmental Impact Assessment
- obtain the basic input for the evaluation of spatial planning aspects and contribute to socio-economic studies
- propose at least two siting regions for each of the repositories

Based on additional geological information collected in Stage 2 and a safety-based, overall comparative assessment of the geological siting regions and the associated disposal parameters, Nagra proposed Jura Ost and Zürich Nordost as geological siting regions in which a repository for each category of radioactive waste or a single combined repository for both categories would be feasible. Nagra's proposals were submitted and published by the SFOE in December 2014 (Nagra 2014c, 2014d, 2014b). Following a detailed review, the Swiss Federal Nuclear Safety Inspectorate (ENSI) concluded that, in addition to the two proposed geological siting regions, the Nördlich Lägern siting region should also be further examined instead of being placed in reserve. This view was shared by the Federal Nuclear Safety Commission (NSC) and approved by the Federal Government in November 2018.

In addition, and under the lead of the SFOE, Nagra worked closely together with the proposed siting regions to identify and designate locations for the placement of the surface facilities. The findings were summarised in a socio-economic and ecological impact study (BFE 2014), and the selected locations were registered in object sheets (BFE 2018).

Stage 3: Selection of a site for each deep geological repository and preparation of the applications for the general licences

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

In the ongoing Stage 3, the sites selected at the end of Stage 2 are therefore subject to a more detailed examination, and supplementary geological investigations from the surface are performed (see next section). Nagra plans to publicly announce in 2022 the site(s) for which the general licences will be prepared, preferably as a combined repository or, alternatively, as two separate repositories. For the selected site(s), the repository projects are then defined in greater detail in collaboration with the regional participation bodies (regional conferences), and the socio-economic aspects are subjected to closer scrutiny. The work and activities in Stage 3 also provide the basis for the first stage of the Environmental Impact Assessment (see Section 5.1.2).

Around 2024, Nagra will submit the general licence applications for the deep geological repositories. These applications will have to be reviewed by the relevant authorities and undergo an approval process which is explained in more detail in Section 2.3 and Chapter 3.

5.1.1 Status of the ongoing geological investigations and synthesis integration efforts

The currently ongoing exploration programme in *SGT* Stage 3 relates directly to the legal requirements and aims to

- identify the most suitable areas in the siting regions
- provide the required data for site selection
- provide the data supporting the safety case for the general licence applications
- provide the basis for placement of the main repository elements

Important information for site comparison and differentiation relates to the depth, thickness and properties of the host rock and the adjacent clay-mineral-rich confining units, including the local tectonic overprint. Also relevant for site selection are datasets constraining the Quaternary erosion history as, together with the repository depth, these data are important for the development of robust site-specific erosion scenarios for the next 10^5 to 10^6 years.

The exploration programme mainly consists of 3D seismic campaigns, a deep borehole campaign (*TBO*) penetrating the host rock layer and investigations of the Quaternary sediments in the region by means of geophysical methods and boreholes. The results will complement the existing database from previous investigations, which comprises the following: (1) 2D seismic surveys and Nagra's deep boreholes drilled in the 1980s that focused on the crystalline rocks of Northern Switzerland but also cored and tested sections in the Opalinus Clay and 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 related 3D seismic investigations performed within the framework of the Project Opalinus Clay Safety Report (Nagra 2002a), (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 amount of third-party data or participation in third-party projects (boreholes of various depths for geothermal purposes but also geological surface mapping, tunnelling projects, 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 (Fig. 5-2). 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 1990s and demonstrated that faults with vertical offsets down to approximately 10 metres can be identified and geometrically described in areas with flat-lying sedimentary strata (Birkhäuser et al. 2001).

Between autumn 2015 and spring 2017, two new 3D seismic datasets were acquired for the Jura Ost and Nördlich Lägern siting regions, and the existing 3D seismic data in the Zürich Nordost siting region from 1997 were complemented. Based on the initial evaluation of the 3D seismic survey, the primary exploration area was delineated (Nagra 2019a), the exploration strategy for the deep borehole campaign was further developed and the work programmes for the deep boreholes were drawn up.

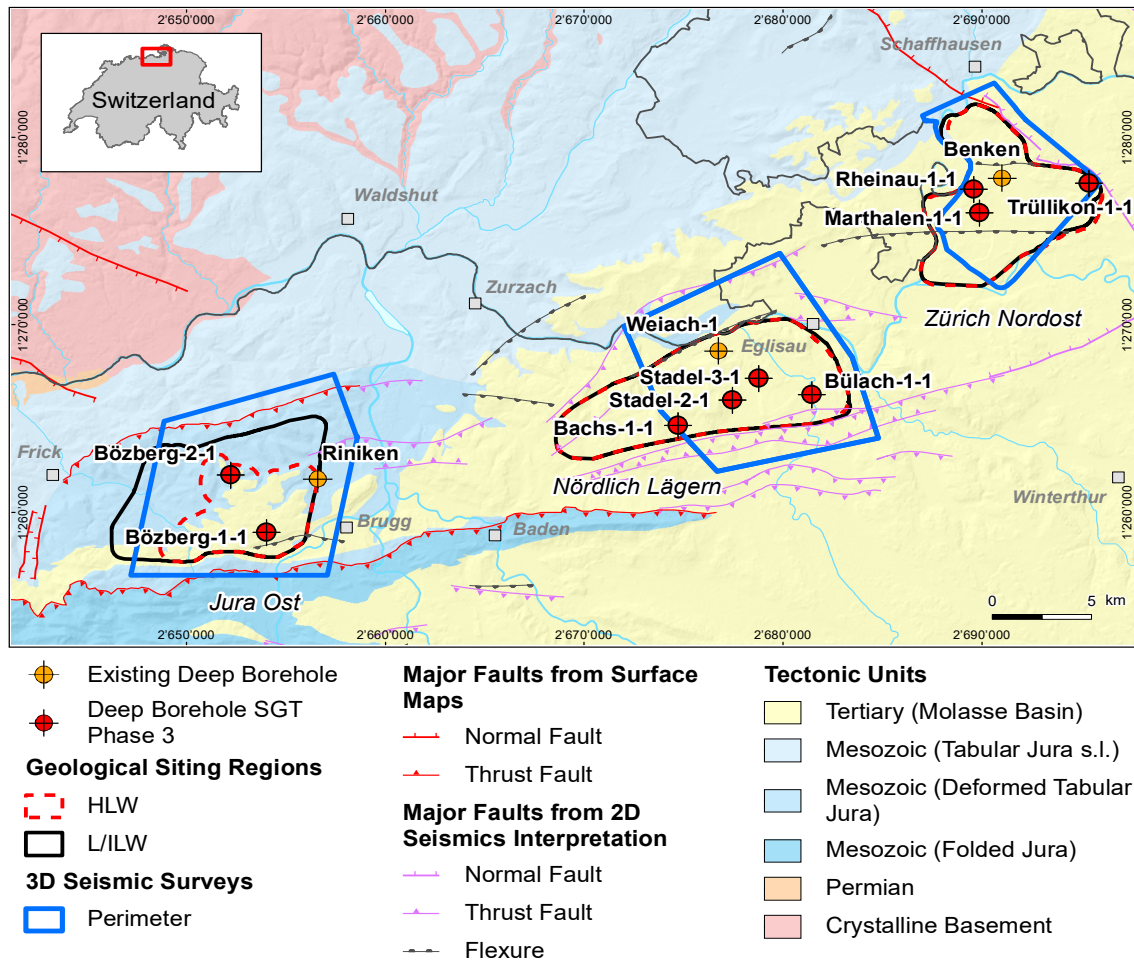


Fig. 5-2: Tectonic overview map with the three siting regions under investigation in SGT Stage 3, the outline of the 3D seismic datasets and locations of the boreholes of the deep borehole campaign

Note that the maps indicate the status of the drilling campaign by September – October 2021.

By September 2021, seven deep boreholes had been completed: Bülach-1-1, Stadel-2-1 and Stadel-3-1 in the Nördlich Lägern (NL) siting region, Trüllikon-1-1 and Marthalen-1-1 in the Zürich Nordost (ZNO) siting region and Bözberg-1-1 and Bözberg-2-1 in the Jura Ost (JO) siting region (Fig. 5-2). In September 2021, two boreholes were still active: Rheinau-1-1 in the ZNO siting region and Bachs-1-1 in the NL siting region. So far, the quality of the cores and the rock samples is excellent. After some initial problems in the first borehole (Bülach-1-1) and a subsequent change of drilling fluid, the downhole measurements and tests could essentially be carried out according to plan, with the exception of some tests planned in the lowest section of Bözberg-2-1 due to borehole instabilities. Based on an initial evaluation of the data collected so far, it seems likely that the geological site characterisation necessary for the site comparison and the general licence applications can be achieved with the nine new deep boreholes mentioned above.

The Quaternary field investigations for *SGT* Stage 3, including high-resolution 2D seismic surveys and 11 boreholes (Fig. 5-3), were completed in December 2020. The boreholes encountered the base of the Quaternary at depths between 40 and 314 metres. Together with the geophysical data, the Quaternary boreholes allow an improved characterisation of the depth and shape of the glacially overdeepened valleys in the vicinity of the siting regions. The laboratory work including facies characterisation and dating of the sediments is still ongoing. The planned integration of the data will include complementary outcrop studies and will eventually result in a consolidated description of the local fluvial and glacial erosion history during the last one to two million years.

In addition to the field activities mentioned above, regional monitoring of neotectonic activity with the help of seismological and geodetic networks is continuing and – if necessary – will be updated or amended.

First reports documenting the exploration activities of *SGT* Stage 3 have already been published. The preliminary horizon and fault interpretations of the 3D seismic datasets are documented in three reports (Nagra 2019c, 2019d, 2019e). The documentation of the Quaternary investigation programme includes a report addressing the interpretation of the high-resolution 2D reflection seismic campaign investigating the glacially overdeepened valleys (Nagra 2018) and data reports documenting the results of the Quaternary boreholes. By September 2021, the data reports for the first new deep boreholes Bülach-1-1 and Trüllikon-1-1 were available (Nagra 2021e, 2021f). The results of the field activities are continuously integrated and complemented with geoscientific system analyses and targeted studies, increasing process understanding. New findings from experiments in rock laboratories, from investigations by other waste management organisations abroad and from other relevant fields (e.g. hydrocarbon industry, geothermal energy) are also considered. For the general licence applications, the geological description of the three siting regions will be compiled in thematic geodossiers, and site selection will be justified by means of a quantitative and qualitative comparison of the three siting regions according to the criteria in Fig. 5-1 and published as part of the general licence applications (Nagra NTB 24-03 planned) and supporting documents. For the selected site(s), the geological findings will be summarised in a geosynthesis (Nagra NTB 24-10 planned) and its supporting documents. Given the mature status of the knowledge base (also based on decades of activities in the Mont Terri URL) and the advanced status of exploration programme, from a geological viewpoint, no major risks are anticipated that could affect the licence application development.

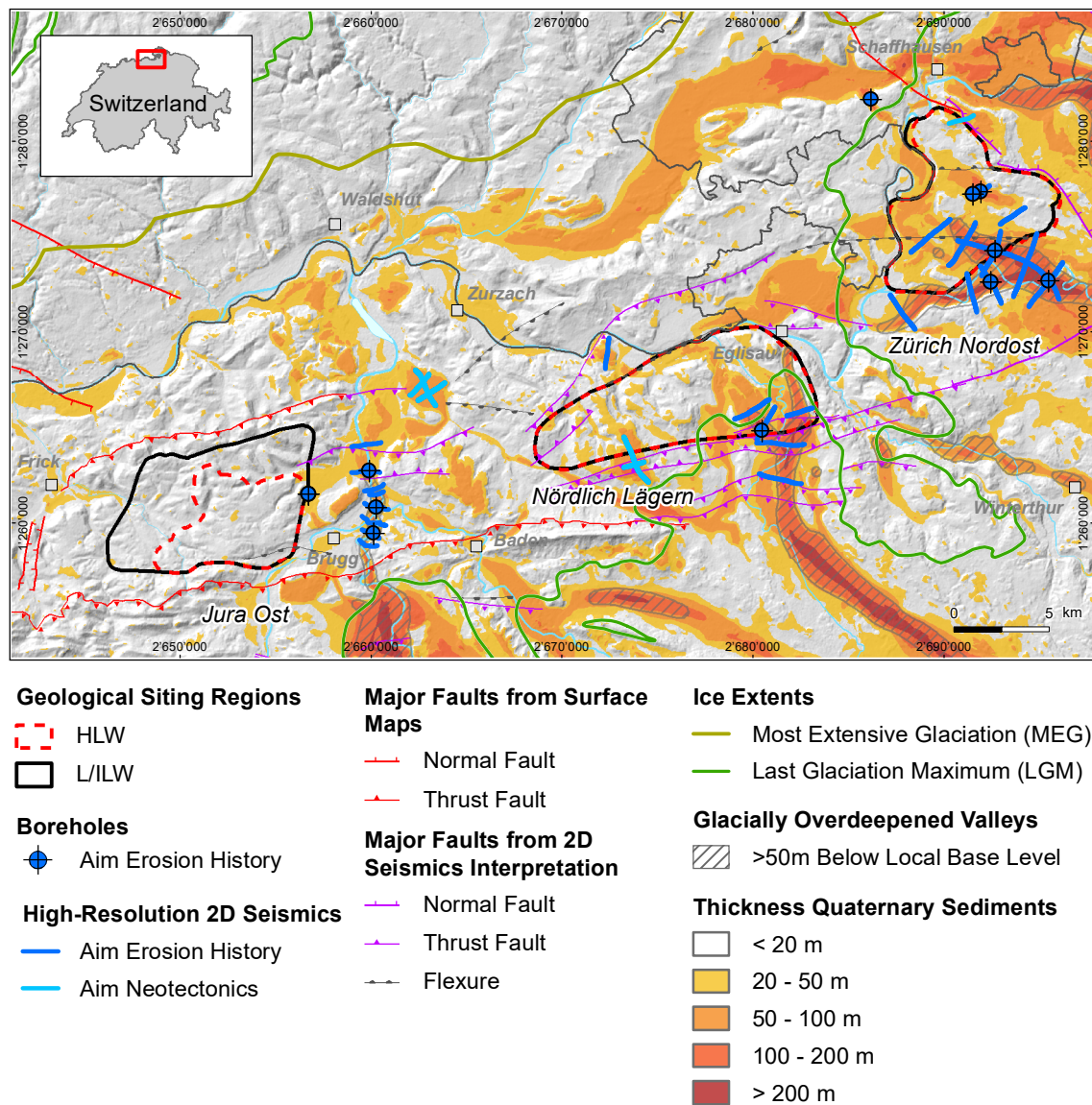


Fig. 5-3: Location of high-resolution 2D seismic data and boreholes aiming at investigation of the fluvial and glacial erosion history during the Quaternary

5.1.2 Status of engineering implementation and stakeholder engagement

The general licence applications require the development of the conceptual design of the repository (NEA 2003, NEO 2004). To fulfil the legal or regulatory requirements (i.e. ENSI 2018c) and to support stakeholder interactions, some elements of the repository are currently developed at a more detailed level. This concerns the following elements:

- structures and installations at disposal level
- access structures
- surface infrastructure including the SF/HLW encapsulation plant

For site selection, ENSI (2018c) requires a comparison of the potential sites by assessing engineering feasibility (as part of the 13 criteria in Fig. 5-1) by means of site-specific conceptual design of the subsurface elements. For this purpose, structures and installations at disposal level and access structures are being developed under consideration of the designated locations for the placement of the surface facilities (*SGT* Stage 2) and by integrating the ongoing geological investigations. In a first step, a proposal for the main underground connection area was developed for the three regions (Nagra 2019b).

In Stage 3, the arrangement of the surface infrastructure and its development is to be further detailed in close coordination with the various interest groups. The framework for this process is flexible with regard to:

- use of synergies with existing facilities or facilities to be expanded in the Zwiilag area for packaging radioactive waste, where appropriate
- arrangement of the auxiliary access facility areas within the respective perimeter
- management of the access from the existing transport network
- discussion of conceptual considerations regarding the areas for construction activities
- trans-regional discussion on the placement of the SF/HLW encapsulation plant

As a basis for the participatory process, Nagra published proposals for the specification of the surface infrastructure (Nagra 2019k), presented the advantages and disadvantages of different siting options for the SF/HLW encapsulation plant (Nagra 2020c) and provided a location-independent comparison of a combined deep geological repository versus two individual repositories with regard to construction and operating procedures and the environmental aspects (Nagra 2020b).

The results of the participatory process will be considered in updated planning studies in preparation for the site selection announcement in 2022. After site selection, engineering activities will further develop the surface facilities of each selected repository site with regard to:

- the approximate size and location of the main installations
- important information regarding organisation and personnel
- Level 1 of an Environmental Impact Assessment and the compatibility with spatial planning requirements

Where applicable, the interest groups in the regions concerned will continue to be involved, while the stakeholders in the deferred regions will be relieved of planning work. This information is then provided in the general licence applications together with site-specific concepts for monitoring and closure of the repository, to be developed based on generic monitoring and closure concepts (Nagra 2021d, 2021g).

5.2 Status of safety analysis for the general licences

To demonstrate the post-closure safety of a Swiss repository, Nagra has improved and refined its methodological approach with respect to the management of uncertainty, the establishment of requirements and safety assessment.

The concept and design of a Swiss repository are developed in an iterative process, at the centre of which is the assurance of safety, including post-closure safety. Iterations involve the establishment of requirements against the background of which concept and design development and system safety analysis are carried out in order to refine and re-baseline those initial requirements in an iterative manner (or refine the design and implementation). Nagra has also established a requirements hierarchy to structure post-closure safety requirements at various levels of detail and the subsequent assessment of safety at those levels forming part of the iterative development process.

The continuous improvement process employed by Nagra has led to the establishment of a clearly defined, robust set of terms for describing and discussing the contributions of various repository aspects towards ensuring post-closure safety. This terminology, the requirements hierarchy and the iterative methodology together provide a more systematic and transparent methodology for defining post-closure safety requirements and verifying the safety of repository concepts and designs through conformity with those requirements as the programme progresses.

The overriding objective of post-closure safety of deep geological repositories is, in accordance with the general protection objective of the Nuclear Energy Act (NEA 2003) and the ENSI-G03 Guideline (ENSI 2020), the permanent protection of humans and the environment from ionising radiation from the emplaced waste after proper closure of the repositories without imposing unacceptable burdens and obligations on future generations. The demonstration of post-closure safety for a sealed deep geological repository is based on a comprehensive and systematic analysis showing how the repository will develop, what radiological consequences will result and that the overall protection objective and the associated guidelines and protection criteria are met in accordance with ENSI-G03. This also includes an evaluation of the methods and data used, the inclusion of further supporting arguments and a systematic and comprehensive analysis of existing uncertainty and its relevance for post-closure safety.

Much of the progress since the last RD&D Plan in 2016 regarding the demonstration of post-closure safety has been methodological.

Nagra has revisited its last formal safety cases, NTB 93-26 (Nagra 1993a) and NTB 02-05 (Nagra 2002a), and intermediate safety reports prepared in the context of the *SGT*, e.g. NTB 14-03 (Nagra 2014b), and has compared the safety strategy, argumentation, and methodology to recent safety cases from other waste management organisations. This has led to an optimisation of the approach and to the definition of the cornerstones for the upcoming safety case that will support Nagra's general licence applications.

Reports with a focus on methodology have been compiled, or are currently in preparation, on the following topics:

- management of uncertainty in the assessment of post-closure safety of deep geological repositories (Smith et al. 2019)
- requirements for the design of deep geological repositories from the perspective of post-closure safety
- methodology for safety assessment, including aspects of performance assessment, scenario development, and consequence analysis

Additionally, there has been significant discussion on terminology related to the demonstration of post-closure safety to clarify and unify the use of key terms within Nagra. For example, safety assessment is now seen as a broad activity encompassing the complementary activities of the assessment of barrier performance, scenario development and the analysis of radiological consequences (see last bullet above), which is also reflected in the reporting structure. In the following sections, the definitions of key terms are placed in boxes within the main text.

5.2.1 General approach for the development and safety assessment of repository concepts

Fig. 5-4 depicts the high-level approach adopted by Nagra for developing repository concepts and designs and, at each major project milestone, carrying out a formal safety assessment, as well as, if needed for the milestone at hand, the compilation of a safety case.

Post-closure safety: The quality of the repository whereby it is unlikely to cause harm to humans and the environment after its closure.

Safety case: The synthesis of evidence and arguments gathered, and analyses carried out, in the course of safety assessment to make the case for the post-closure safety of a repository system.

Safety assessment: The process of gathering evidence and arguments and carrying out analyses of the safety of the repository system and its environment during the post-closure phase.

Performance assessment: Assessment of the strengths and potential weaknesses of the repository system or components thereof in providing the allocated functions over the course of time. This will typically involve, though is not limited to, an evaluation of adherence to the requirements on the expected performance and attendant performance indicators/indices.

(Requirements on the) expected performance: Behaviour or properties with respect to one or more phenomena that the repository system or components thereof should display over time in order to support the safety functions. The requirements on the expected performance may be (but do not necessarily have to be) framed in terms of one or more performance indicators/ indices and associated performance targets.

Indicator: Measurable or calculable quantity defined for the purpose of assessing the overall technical feasibility, performance or safety of the repository system and components thereof, as well as the suitability of a repository site.

Performance indicator: Indicator that quantifies one or more system components with respect to their requirements on the expected performance.

Performance index: A dimensionless factor derived from a related performance indicator. If the performance indicator is itself dimensionless, the performance index and the performance indicator are the same.

Performance target: A specific target value related to a performance indicator/index.

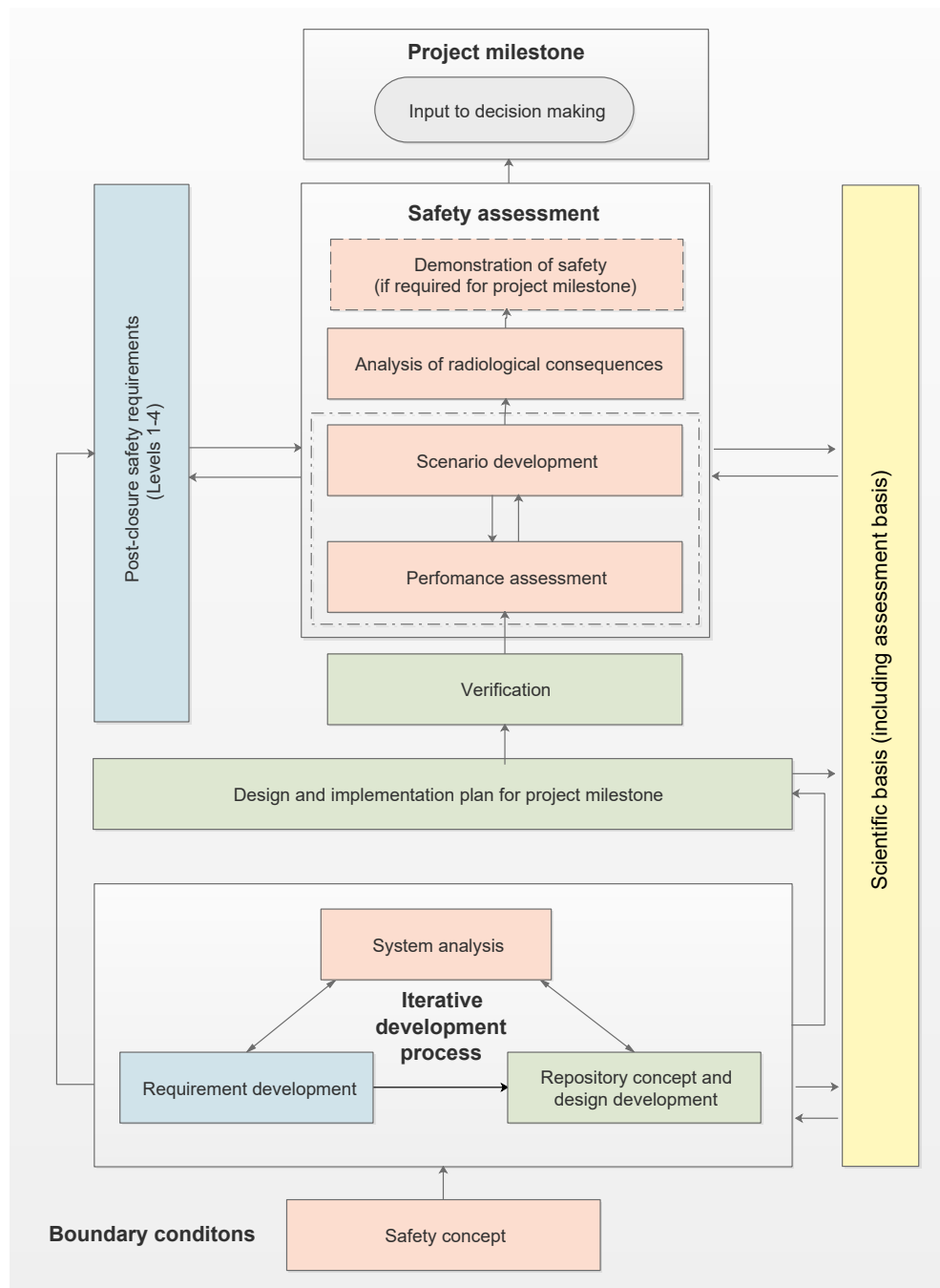


Fig. 5-4: Overview of the general approach for the development and assessment of repository concepts and designs (requirements include the legal and regulatory boundary conditions)

The figure shows that the development of a concept and design is an iterative process involving:

- the development of a set of requirements to be met, including post-closure safety requirements
- concept and design development, whereby solutions are proposed and refined in order to meet these requirements
- analyses of the system as a whole and its various sub-systems to guide the formulation of requirements and to test whether the requirements are met

These analyses may at first be rather informal, e.g. taking the form of scoping calculations to support design development. However, once a stable set of requirements has been identified and the design solutions have been judged to possess reasonable prospects of meeting the requirements to the extent needed for the project milestone at hand, then a more formal safety assessment is carried out. This consists of an assessment of the evolution and performance of the engineered and natural barriers (performance assessment), scenario development and an analysis of radiological consequences, which concerns the release, retention and transport of radionuclides through the barriers and an analysis of the consequences of any radionuclide releases to the surface environment in terms of potential harm to humans. The outcome of the safety assessment provides input to the decision at hand.

The above iterative process that focuses on (post-closure) safety aspects is, in a broader view, part of the Nagra disposal programme development that is itself iterative and that is discussed in Chapter 3 based on Tier 2 of the Nagra Roadmap.

The site selection during *SGT* Stage 3, following the recommendation by Nagra of one or more repository sites, will be based in part on a safety assessment, but no formal safety case will be compiled. A formal safety case, documented in a hierarchy of reports and summarised in a safety report is, however, foreseen for the general licence applications. The safety report will cover all aspects of post-closure safety, including the safety concept, post-closure safety requirements, performance assessment, safety scenario development and the analysis of radiological consequences (including a description of the assessment basis and the conceptualisation and parameterisation of the scenarios for the analysis of radiological consequences).

While the safety report (Nagra NTB 24-03 planned) will discuss the relationship between engineering feasibility and operational safety on the one hand and post-closure safety on the other, it will not deal with these aspects themselves; these will be dealt with in complementary reports. This documentation strategy is in line with the organisation of the Nagra Roadmap (see Chapter 3).

5.2.2 Link between post-closure safety requirements and safety assessment

The process of safety assessment involves a systematic analysis of whether a given repository concept and design meet a set of pre-defined post-closure safety requirements. The post-closure safety requirements to be met by the repository concept and design are hierarchical in nature and are identified or developed in a top-down fashion, as illustrated on the left-hand side of Fig. 5-5. At the highest level are broad protection objectives and safety principles, below which are protection criteria for the main safety indicators of dose and risk. These highest-level post-closure safety requirements are defined as "boundary conditions" as they are specified by regulations and thus represent constraints on the disposal programme at a given stage that are not under the control of Nagra. At the next level down in the hierarchy are the functions, i.e. safety functions and component-specific functions of the repository system that contribute to overall post-closure safety. Below the safety functions are requirements related to expected performance, including performance targets which concern how the repository system provides the safety functions. At the lowest level of the post-closure safety requirements hierarchy are detailed requirements on the site, the engineered system components, and the waste to be disposed of. These are set in such a way that, if met, the expected performance will also be achieved (and hence the corresponding safety functions provided) in most reasonably foreseeable circumstances.

Safety function: Functions of the multibarrier system that together ensure post-closure safety. Engineered and natural barriers and other system components contribute to one or more of these functions.

Component-specific function: Property of, or action performed by, one or more components of the repository system that contributes directly or indirectly to one or more safety functions.

The development of the hierarchy of post-closure safety requirements is discussed further in Section 5.2.3.

Having developed a repository concept and design that is judged (e.g. on the basis of system analyses in terms of safety; see Fig. 5-4) to have good prospects of meeting the post-closure safety requirements, a series of analyses are carried out, examining the adherence to requirements as well as any attendant uncertainty, from the bottom up, as illustrated on the right-hand side of Fig. 5-5. At the lowest level is validation that the site characteristics, the repository design and the waste specifications meet the corresponding detailed requirements, which is not considered part of the safety assessment.

At the next level up is the performance assessment, which examines whether the requirements on the expected performance, including any performance targets associated with the system components, are fulfilled, and identifies potential circumstances, if any, where the requirements on the expected performance may not be fulfilled, leading to the possible impairment of one or more functions. The performance assessment thus supports the derivation of a set of safety scenarios, the radiological consequences of which are assessed in the consequence analysis and compared with the regulatory protection criteria. Work on a scenario development methodology is currently ongoing, including the links between safety scenarios, safety functions, component-specific functions and requirements on the expected performance.

(Safety) scenario: A (safety) scenario broadly describes the possible path for the evolution of the repository system and its environment, starting from an "initial state" and extending into the future, generally for as long as the radioactive waste presents a potential hazard.

The process depicted in Fig. 5-5 above is broadly applicable to the demonstration of safety in the context of both the general licence applications and the preceding site selection during *SGT* Stage 3. However, in the latter context, design specifications are developed and analysed for each of the three siting regions. In the analysis, the main focus is on performance assessment, and specifically on evaluation criteria and assessment aspects defined by the regulator and on site-specific characteristics that may lead to differences between sites with respect to the performance targets defined by Nagra for these assessment aspects. For both the general licence applications and site selection, consequence analysis aims to demonstrate that the protection criteria, defined by the regulator in terms of dose and risk, are met. However, further "complementary indicators" are planned to be defined by Nagra to further test and demonstrate the performance and robustness of the repository systems, especially in the context of the general licence applications.

The management of uncertainty in the assessment of post-closure performance and safety of deep geological repositories has recently been discussed at length in Smith et al. (2019). A key aspect of the management of uncertainty is the propagation of uncertainty through the chain of analyses, as illustrated in Fig. 5-5. Each element of the analysis chain must consider sources of uncertainty identified in the previous element, as well as any additional sources of uncertainty arising, for example, from the models and data used in the analyses. Smith et al. (2019) explain how, in carrying out assessments, it is common practice to categorise uncertainty as scenario uncertainty, model uncertainty (also termed conceptual uncertainty) and data uncertainty (also termed parameter uncertainty), and this categorisation will be retained in future assessments.

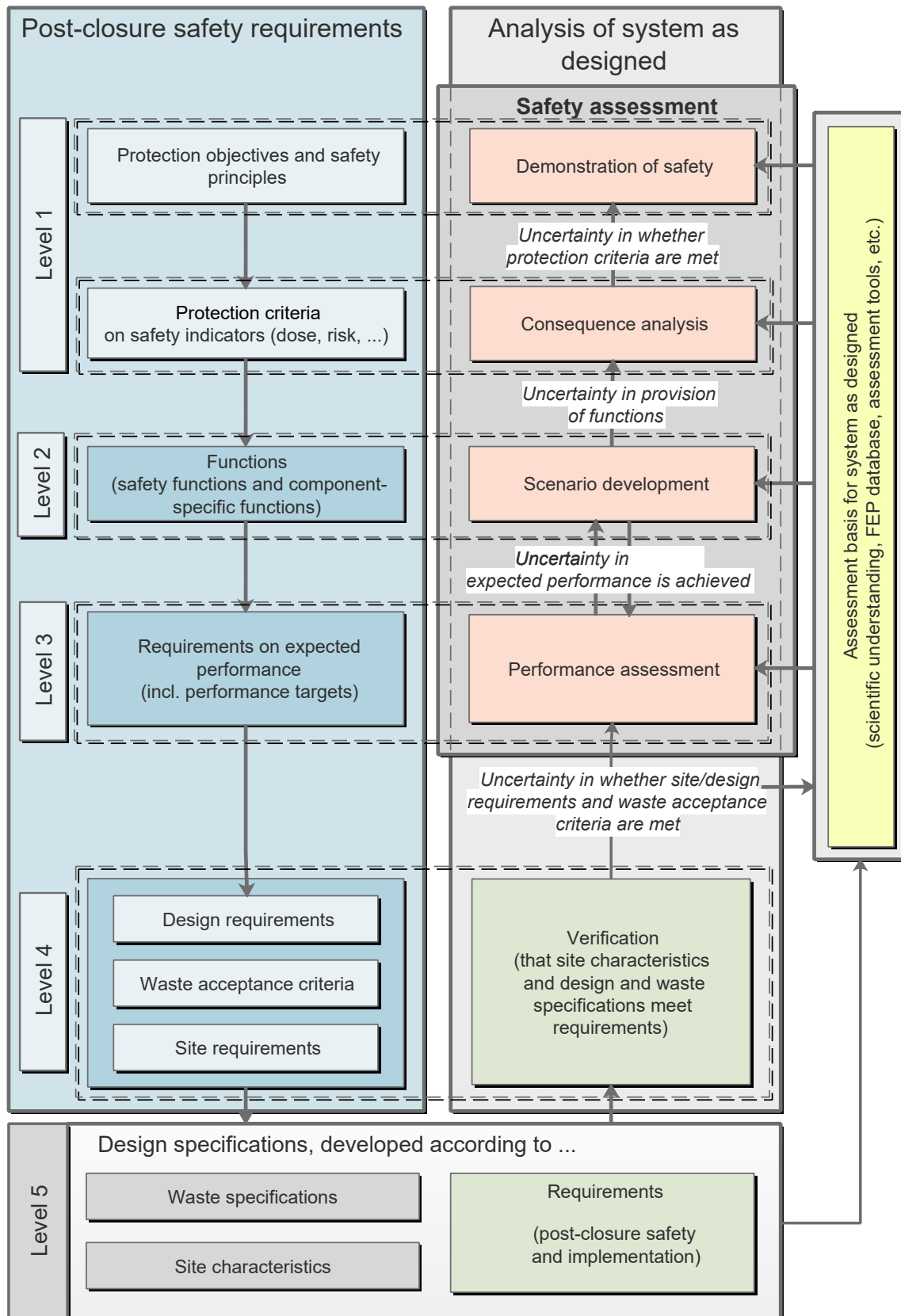


Fig. 5-5: Overview of post-closure safety requirements and their assessment to develop input to the general licence applications

The five levels of requirements are described further in Section 5.2.3.

All analysis types described above are based on scientific understanding and assessment tools, collectively termed the assessment basis. This was developed by Nagra as part of the wider scientific basis over the course of its work in the last several decades. The continued refinement and expansion of the assessment basis, with a focus on the needs for the demonstration of post-closure safety, is an important aim of the present RD&D Plan.

Assessment basis: Evidence and knowledge from the scientific basis and system concept that are applied in the safety assessment, as well as the assessment tools.

Scientific basis: Evidence and knowledge related to the repository system and its environment acquired or developed to advance the programme through successive stages.

The phenomenological description of the evolution of the geological repositories, also termed the "Storyboard" Report, the Safety Assessment Methodology Report and the Safety Scenario Report, are key elements of the documentation of the assessment basis for the general licence applications (see also Fig. 5-9).

5.2.3 Hierarchy of post-closure safety requirements on repository concepts and design

A systematic methodology has been defined to derive the requirements for repository design from the point of view of post-closure safety. The derivation of the post-closure safety requirements is currently ongoing. These requirements will contribute to the RCM process, which aims to ensure that the decisions, justifications and interdependences of the information gathered on deep geological repositories are comprehensible, and that changes to this information can be traced and communicated (including optimisation of the repositories).

Post-closure safety requirements are structured in five hierarchical levels:

- Level 1 includes the overall protection objectives and safety principles as well as the protection criteria.
- Level 2 includes two sublevels: Level 2a consists of the safety functions and Level 2b consists of the component-specific functions; both levels are described further in Section 5.2.4.
- Level 3 includes requirements on the expected performance, such as performance targets, some of which are generic, while others are specific to the Nagra repository project as described in Section 5.2.5.
- Level 4 consists of post-closure safety requirements for the design of the system components.
- Level 5 consists of specifications for repository implementation with respect to post-closure safety.

The methodology for the identification and derivation of post-closure safety requirements, which is iterative but essentially consists of four partly overlapping steps, is summarised in Fig. 5-6.

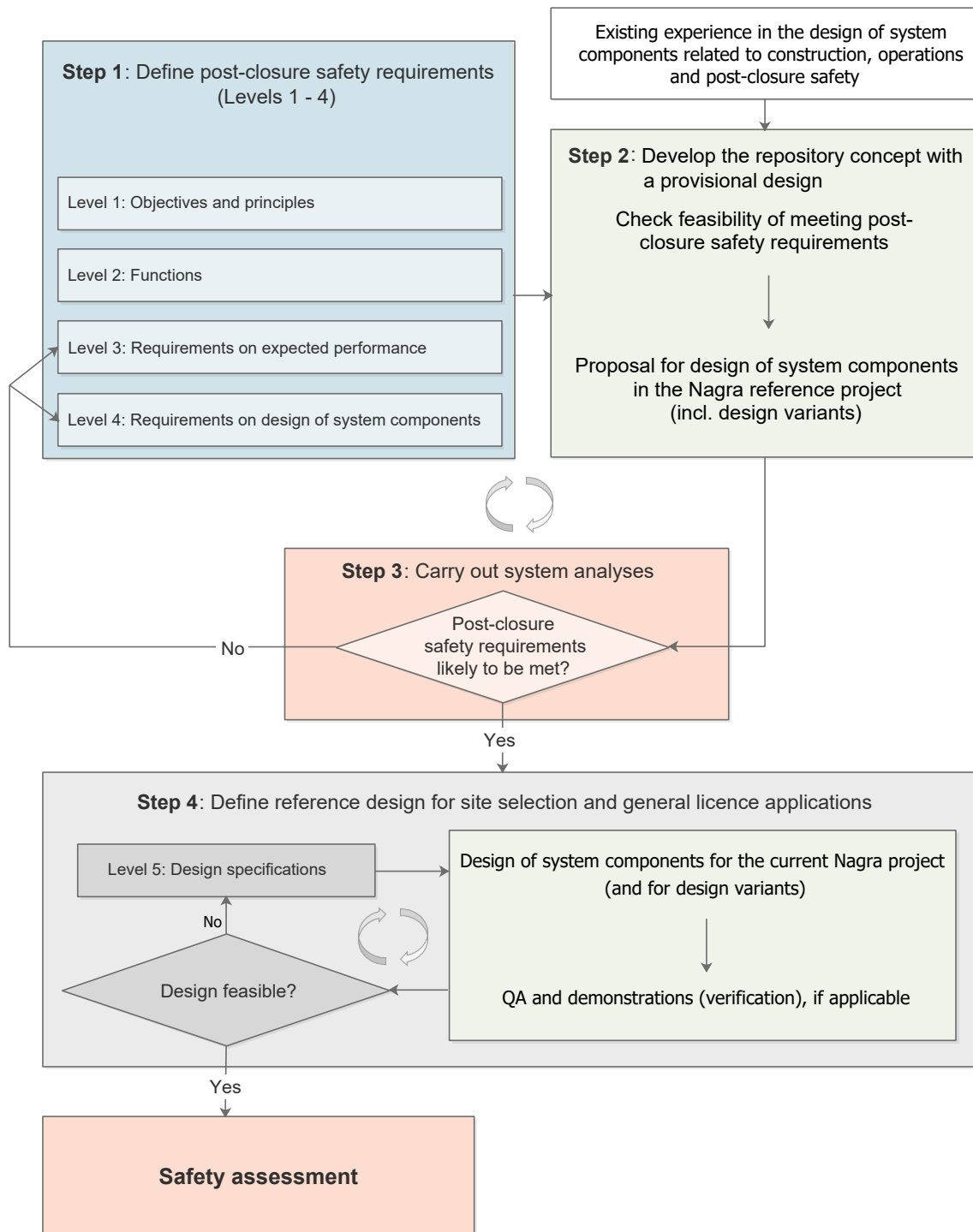


Fig. 5-6: Overview of the four-step methodology for the identification and derivation of post-closure safety requirements

In a first step, post-closure safety requirements at Levels 1 to 4 are derived in a top-down fashion. In a second step, a tentative reference design is developed, with possible design variants, accounting for the post-closure safety requirements, along with other requirements related to, for example, engineering feasibility and operational safety. In a third step, system analyses are then performed to check whether the reference design and design variants fulfil the post-closure safety requirements at Levels 3 and 4. If necessary, these steps are iterated until a suitable solution from the point of view of post-closure safety is identified; this is the iterative process depicted in Fig. 5-4, indicated by upper pair of circling arrows. In a fourth step, a reference design for analysis in support of site selection or the general licence applications is defined in a further iterative process in sufficient detail for the purposes of the safety assessment.

The reference designs will be adapted to the specific site(s). The design specifications for repository implementation are developed to the level of detail required for the project milestone at hand. For the general licence applications, the design will, however, still correspond to a conceptual design stage, i.e. the detailed design will be developed for the construction licences.

5.2.4 Safety functions and component-specific functions

The safety functions at Level 2a in the hierarchy of post-closure safety requirements are functions of the multibarrier system that together ensure post-closure safety. Engineered and natural barriers and other system components contribute to one or more of these functions. The safety functions themselves, however, are generic in the sense that they do not refer to specific physical features or components of a repository. These safety functions are:

- **isolation** of radioactive waste from the surface environment
- **complete containment** of the radionuclides for a period of time
- **immobilisation, retention and slow release** of radionuclides
- **compatibility** of the elements of the barrier system and radioactive waste with each other and with other materials
- **long-term stability** of the barrier system with respect to long-term geological and climatic processes

Below these safety functions, at Level 2b in the hierarchy of post-closure safety requirements, is a larger set of component-specific functions. These are still being developed by Nagra. However, a tentative example would be the function of the host rock to retard, dilute and disperse radionuclides, which contributes to the safety function of immobilisation, retention and slow release of radionuclides.

Although under development, the component-specific functions are closely related to the roles of the barriers that have previously been defined by Nagra and are illustrated for SF, HLW and L/ILW in the discussion of current repository concepts in the following section, in Fig. 5-8, respectively.

5.2.5 Current repository projects and safety concept

The following paragraphs describe the current Nagra generic repository project for deep geological repositories in Switzerland. New findings made before construction work actually begins (geological investigations and performance confirmation in the *BEUU*, advances in technology and materials science, experience in other programmes, etc.) will result in the optimisation and realisation of the project.

The current Nagra generic repository project envisages two disposal areas, one for SF and HLW (HLW repository) and one for L/ILW (L/ILW repository), co-located at the same site in a combined repository. The final decision as to whether to build two individual repositories or a combined repository will be the result of site selection in line with *SGT* Stage 3 and made prior to the general licence applications.

In the combined repository, as illustrated in Fig. 5-7, the emplacement drifts for SF and HLW would be spatially separated from the emplacement caverns for L/ILW.

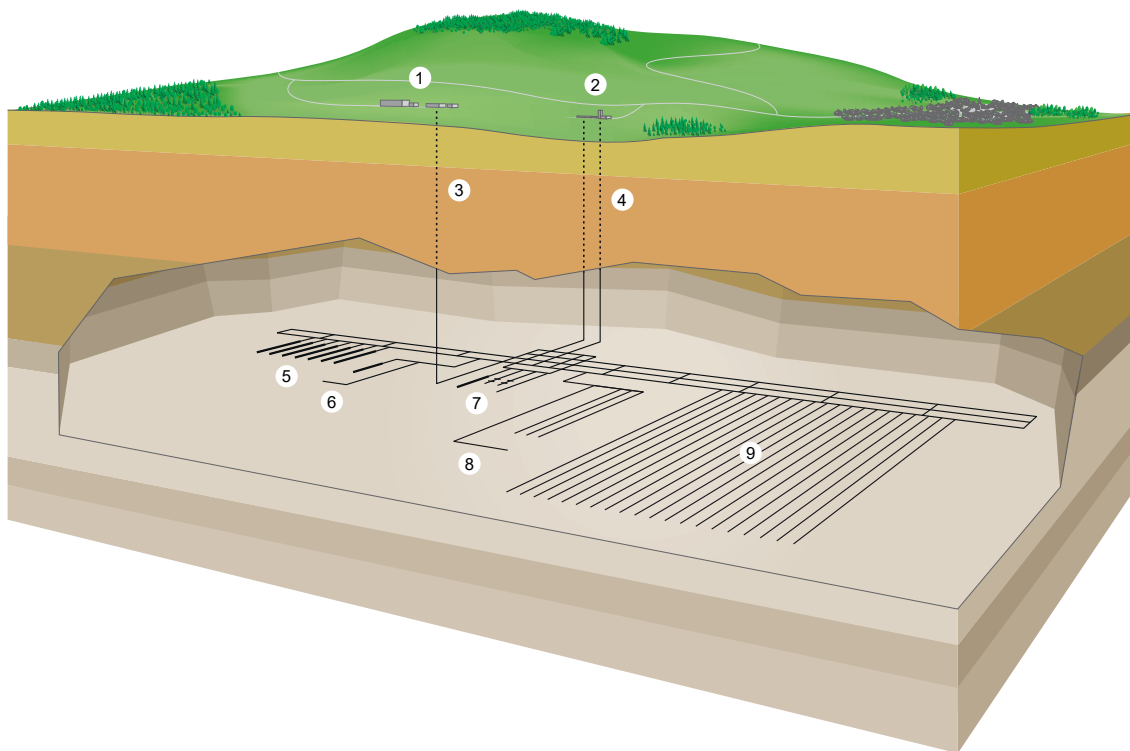


Fig. 5-7: Illustration of a combined repository for SF/HLW and for L/ILW (Nagra 2021h)

Legend: 1) Surface facility 2) Auxiliary access facility 3) Access shaft (main access) 4) Operations and ventilation shafts (auxiliary accesses) 5) Main repository L/ILW 6) Pilot repository L/ILW 7) Underground geological investigations/test areas 8) Pilot repository HLW 9) Main repository HLW.

The underground part of the combined repository will be constructed in Opalinus Clay at a depth of a few hundred metres below the surface, with the exact depth depending on the selected site. It will include a series of dead-end emplacement drifts for SF and HLW with initial outer diameters of around 3.5 metres, which are supported by segmental lining elements and annular gap-filling material. The lengths of the drifts range from around 300 metres up to around 1,000 metres. The combined repository will also include dead-end emplacement caverns for L/ILW with internal widths of around 11.5 metres, heights of around 12.5 metres and lengths of around 150 to 250 metres, which will again be supported by a tunnel support system consisting of shotcrete towards the Opalinus Clay and an inner-shell tunnel support emplaced by formwork.

At the surface, spent fuel assemblies and fabrication flasks with HLW will be loaded into disposal canisters, which, according to the current Nagra repository project, are made of carbon steel. The disposal canisters will be around 5 (SF) and 3 (HLW) metres long. They will each have a diameter of around 1 metre (SF) or 0.7 metres (HLW), and a wall thickness of around 14 cm (Patel et al. 2012). The disposal canisters will be transported underground and emplaced in the drifts, co-axially with respect to the drift direction, on pedestals of compacted bentonite blocks. Immediately after emplacement, the respective drift section will be backfilled with highly-compacted granular bentonite material. The bentonite blocks and the bentonite material will together form a protective mechanical and chemical buffer around the disposal canisters. The pitch between any two successive canisters along a drift will be around 3 metres.

L/ILW will be packaged in concrete disposal containers of standard size in the surface facility. After transport to and emplacement of the containers in the caverns, the remaining void spaces within the caverns will be backfilled with a specially designed mortar, after which the caverns will be sealed with gas-permeable seals.

The safety concept for the combined repository is based on the multiple engineered and natural barriers that, either individually or in combination, perform the component-specific functions mentioned in Section 5.2.4 and, through these, collectively perform the safety functions described in the same section.

Safety concept (for the post-closure phase): The safety concept for the post-closure phase of a deep geological repository ensures the permanent protection of humans and the environment. It is based on a multibarrier system of engineered and natural barriers that is optimised with regard to post-closure safety.

As noted in Section 5.2.4, the component-specific functions are still under development, but are closely related to the roles of the barriers illustrated for both the HLW and the L/ILW repository in Fig. 5-8.

In Nagra's safety concept, the natural barrier is considered to be of primary importance, due mainly to the excellent qualities and long-term stability of the containment-providing rock zone (CRZ) in the siting regions currently under consideration. The natural barrier is complemented by a mutually compatible set of engineered barriers. A key role of the engineered barriers is the minimisation and mitigation of disturbances to the CRZ inevitably caused by the waste and its emplacement, including, for example, the effects of heat generated by the waste and the disturbance to the

rock caused by the excavation and ventilation of underground openings. The engineered barriers around the waste are expected to provide complete containment of radionuclides for a certain time period. Although the eventual release of radionuclides and their migration through the multibarrier system cannot be excluded, most radionuclides will remain immobilised in the waste forms and waste containers until they have decayed. Furthermore, those that are released will migrate only slowly towards the surface environment, with substantial attenuation by radioactive decay first within the engineered barriers and then, for any that penetrate these barriers, within the surrounding natural barrier. The location of the repositories will be chosen to reduce the risk of future inadvertent human intrusion. Nonetheless, because the possibility of inadvertent human intrusion or disturbance of the repository in the distant future cannot be completely excluded, repository design features are incorporated that mitigate its potential impact. These also form part of the safety concept.

The components and environmental conditions for the current repository concepts that are judged to be most critical to providing the safety functions are termed "pillars of safety". The current pillars of safety, which will be updated for the general licence applications, are:

- **The deep underground location of the repository** in a setting that is unlikely to attract human intrusion and is not prone to disruptive geological events and processes unfavourable to post-closure safety.
- **The host rock and its confining geological units of similar high quality (the containment-providing rock zone)** with a low hydraulic conductivity, fine and homogeneous pore structure, high sorption capacity for many radionuclides, self-sealing capacity and long-term stability, thus providing a strong and stable barrier to radionuclide transport and a suitable physical and chemical environment for the engineered barrier system.
- **The backfill and seals of the disposal areas and repository access structures** that together provide a strong and stable barrier to radionuclide transport, reduce the likelihood of inadvertent human intrusion into the repository and, for L/ILW, provide a gas transport system that prevents the buildup of potentially damaging gas pressures in the disposal areas.
- **The bentonite buffer (for SF and HLW)** with similar properties to the host rock, thus providing a strong and stable barrier to radionuclide transport, as well as a suitable physical and chemical environment favouring the longevity of the SF/HLW disposal canisters. Furthermore, the buffer provides mechanical support for the host rock after degradation of the tunnel support system, protects the SF/HLW disposal canister and, by separating the SF/HLW disposal canisters from one another, provides compartmentalisation of the waste, mitigating the impact of any inadvertent human intrusion and reducing the potential impact of heat output from the SF/HLW disposal canisters on the radionuclide retention properties of the CRZ.
- **The cementitious backfill (for L/ILW)** providing a range of geochemical immobilisation and retardation processes for radionuclides and favouring low corrosion rates and hence low gas generation rates from metals in the waste forms. Furthermore, the cementitious backfill provides mechanical support for the host rock after degradation of the tunnel support system.
- **SF and HLW waste forms** that are stable in the expected environment.
- **SF and HLW disposal canisters** that are mechanically strong and corrosion-resistant in the expected environment and provide complete containment of radionuclides for a considerable period of time.

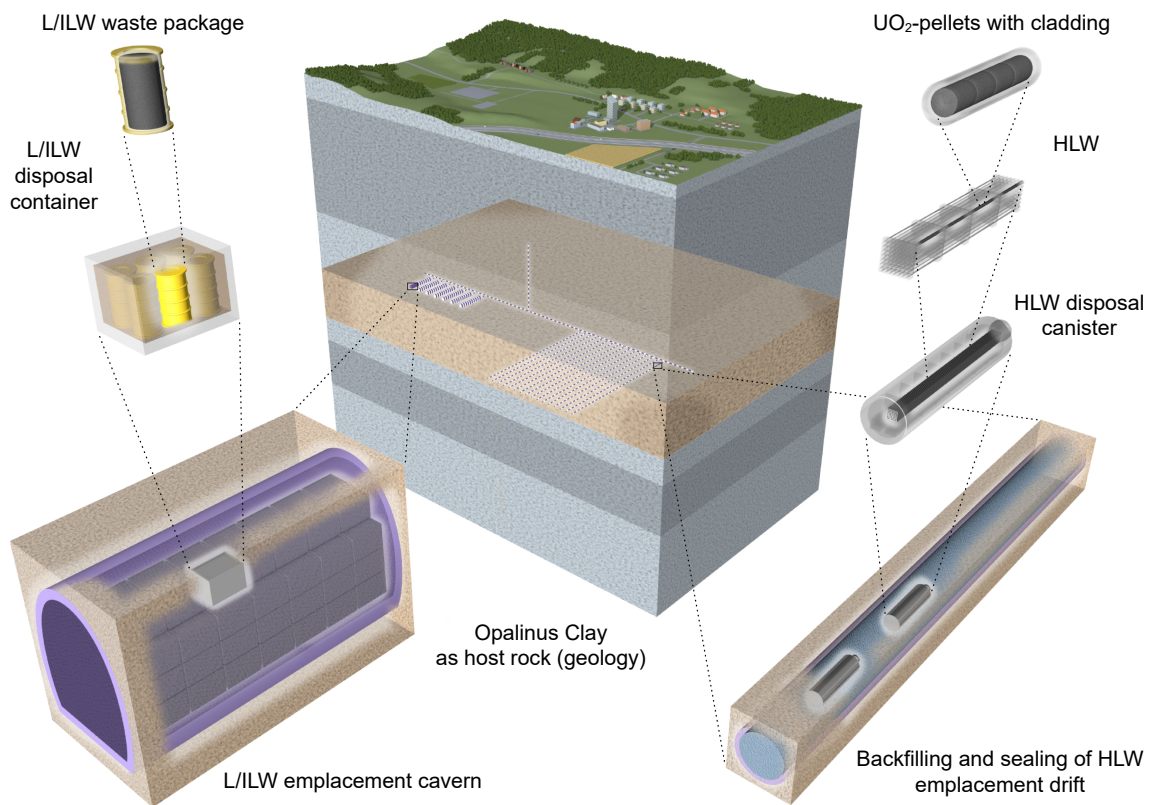


Fig. 5-8: Post-closure safety concept for the HLW and L/ILW repository according to the current disposal project (combined repository)

For HLW, as an example, SF encapsulated in a carbon steel canister with a bentonite buffer is shown (right), while for the L/ILW, as an example, a 200 l drum in an LC container in an emplacement room backfilled with M1 mortar is shown (left).

5.2.6 Tentative report portfolio supporting the safety case

The safety case for the general licence applications will be built on a broad portfolio of studies and associated reports, a tentative structure for which is illustrated in Fig. 5-9, and it will be published in Nagra NTB 24-10 (planned). The report portfolio and its structure are the result of ongoing methodological work and are described in the first paragraph of Section 5.2, namely the review of Nagra's previous safety cases and studies and adjustments to reflect project development and international progress.

The relevant RD&D outlined in the present report feeds mainly into the assessment basis, especially developing and improving the understanding of the repository system and its evolution as well as the acquisition of key data and databases.

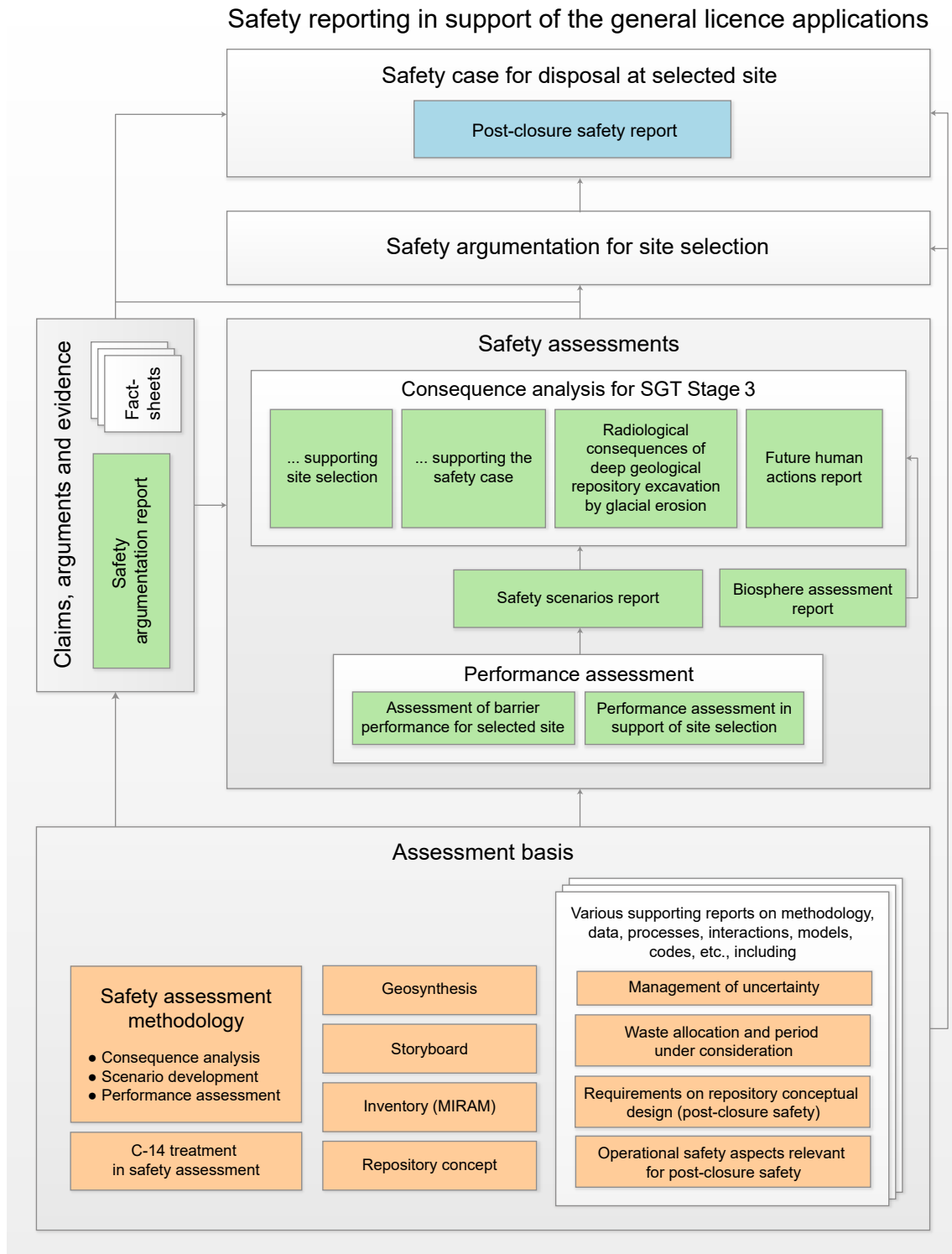


Fig. 5-9: Overview of the (tentative) report portfolio that will support the safety case for the general licence applications

5.3 Status of the Nagra generic repository project

The Nagra repository project describes the site-independent implementation of a combined repository, thereby covering all the functions and requirements of an L/ILW and/or HLW repository. Since 2016, a major evolution in this area has been the application of a systematic RCM system. This will allow the iterative concept and design development process to be managed in a more robust manner as site-specific adaptations are made in the coming years, taking into account the geological context of the selected site(s) for the general licence applications.

The repository project presents the current Nagra planning assumption as the basis for the work for the stepwise realisation of the deep geological repository (Fig. 5-10) and is based on a combined repository. The repositories for HLW and L/ILW are based on the concepts shown in Fig. 5-8. A combined repository consists of separate repository areas for HLW and L/ILW. The post-closure safety for the combined repository is ensured when HLW post-closure safety is ensured for the HLW repository area and L/ILW post-closure safety is ensured for the L/ILW repository area, and it can be shown that no safety-relevant interactions take place between the two areas.

Starting from the surface, the combined repository has three surface facilities (a main facility and two auxiliary access facilities). The access to the underground is realised by three vertical shafts. On the repository level, the HLW disposal area and the L/ILW disposal area can be accessed from the common central area. The area for the underground geological investigations is located next to the central area. The HLW disposal area has three access tunnels (construction, ventilation and operations). The L/ILW disposal area has only two access tunnels (ventilation and operations) because the area will be fully constructed before starting the waste emplacement operations. The HLW and L/ILW pilot repositories are separated from the corresponding main disposal areas. The access tunnels to the pilot repositories are also separated from the main access tunnels (operation tunnels) by short junction tunnels.

Nagra will develop its current site-independent repository project into a site-specific repository project, taking into account the geological context of the selected site(s) and the knowledge developed in recent years for the general licence applications (Nagra NTB 24-11 planned).

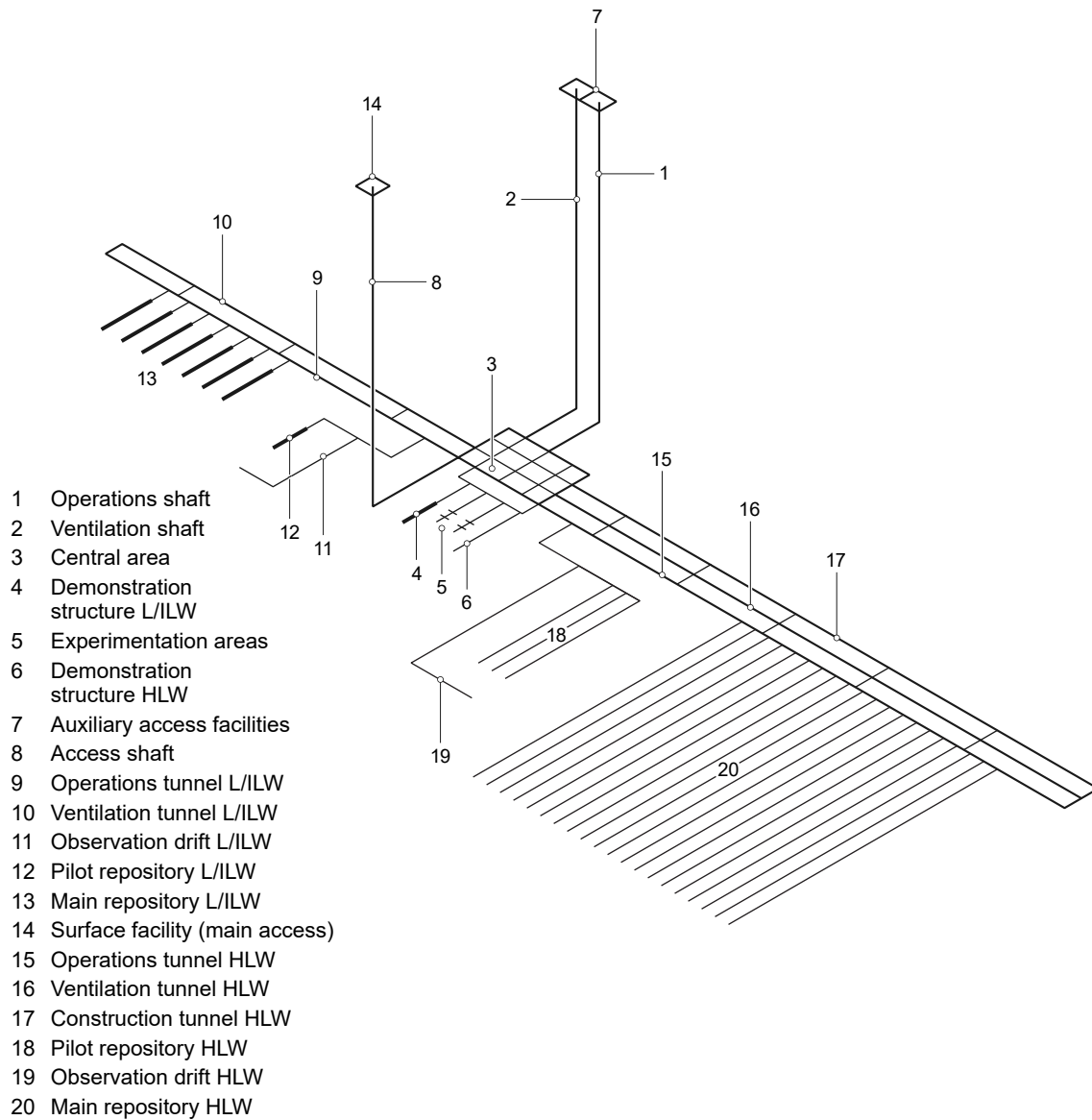


Fig. 5-10: System sketch of subsurface part of the Nagra's combined repository project (note: certain aspects include options)

5.3.1 Application of the Requirements and Configuration Management (RCM) system to the repository project

In general, 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 levels. Thus, changes at higher levels have more widespread consequences than those at 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.

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 overcautious in its original form.

Since 2016, based on the existing RCM system, Nagra has further developed and expanded its RCM in view of the upcoming general licence applications as described in the following paragraphs.

RCM objectives

- The goal of RCM is the uniform development, documentation, and management of the requirements for a deep geological repository.
- Decisions, justifications and dependences of the requirements must be traceable (references).
- Changes to requirements must be traceable (versioning).
- The content, depth, and scope of RCM represents the current project status. The depth is adapted to the respective realisation steps and objects (e.g. *OFI*, *UTA* etc.).
- The requirements must be easily accessible within Nagra.
- The underlying goal is the optimisation of the current technical solution of Nagra's deep geological repository project.

RCM content

- Nagra's RCM is focused on the technical aspect of the geological repository. It does not include aspects such as the Sectoral Plan, interim storage, waste conditioning or the inventory itself.
- Aside from the underground structures of the repository, RCM also covers the surface infrastructure and corresponding processes such as operations, ventilation, energy supply, etc. Furthermore, security and monitoring aspects such as radiation protection, occupational safety, safeguards, etc. are also included.
- Alongside to the current repository project, Nagra is developing variants at various levels, many of which are described in this document. These will be further developed and evaluated in future programme stages. The final choices of the variants will be made in the optimisation phase following the general licence applications in anticipation of the submission of the construction licences. The Nagra repository project reflects current planning assumptions.
- RD&D activities are linked to the corresponding RCM requirements.

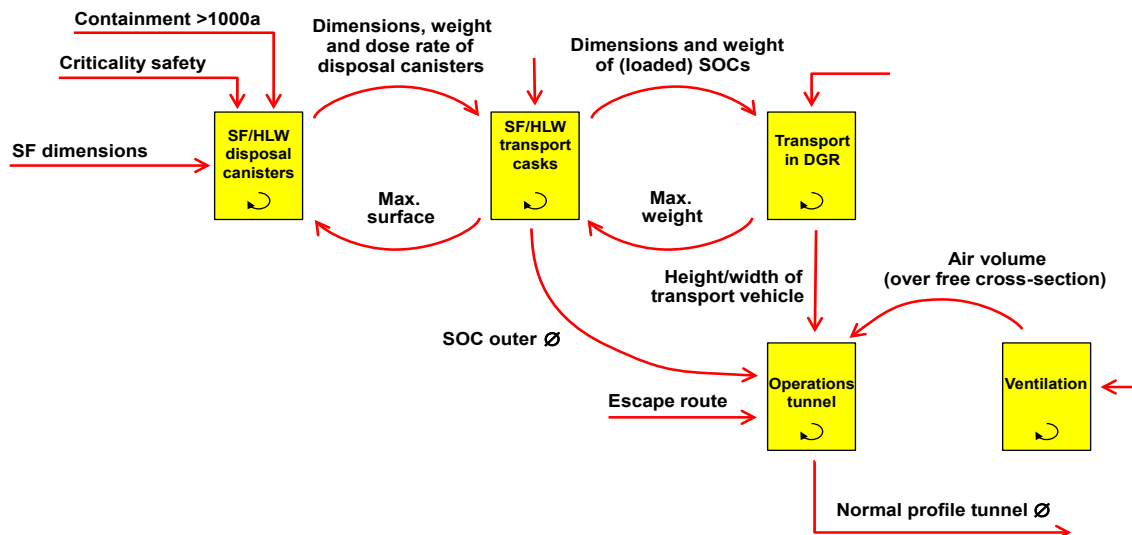


Fig. 5-11: Illustration (not comprehensive) of connections between RCM sheets (yellow bricks) via their requirements (red arrows).

SOC: shuttle overpack canister

RCM tool currently in use at Nagra

The requirements of the respective objects are recorded in uniformly structured RCM sheets. The individual RCM sheets are connected to each other via their requirements (see Fig. 5-11): requirements from the implementation (configuration) of an object (output) become requirements for a subsequent object (input). For example, the waste canister outer diameter is a result of the implementation (output) of the canister design and becomes the requirement (input) for the shuttle overpack design. Each RCM sheet has a responsible owner assigned to it.

The hierarchy of the requirements on the repository concepts and design is described in Section 5.2.3.

The anticipated benefits of RCM can be summarised as:

- Making the interfaces between the different elements visible in the project, especially where conflicting requirements exist. Requirements that are not yet met are marked as open points (that still require RCM documentation). The list of open points is the basis for efficiently managing the interfaces.
- Transfer of knowledge and knowledge management within Nagra.

The current RCM is constantly undergoing improvement and, with the structure described above, has already significantly improved compared to its precursor as described in Nagra (2016b).

5.4 International RD&D progress since 2016

Nagra maintains close relationships with other waste management organisations around the world and continues to maintain watching briefs on their disposal programme developments and collaborate in key areas of RD&D. Of particular value in this context is the return of experience which Nagra expects to gain through engagement with the French, Swedish and Finnish programmes via Andra, SKB and Posiva, respectively, as these programmes are most advanced.

The RD&D studies of the Nagra disposal programme can benefit from developments in other countries, in particular because, in some cases, these developments are more advanced than those in Switzerland.

Schedules for the implementation of deep geological repositories for L/ILW and ATW or long-lived ILW in a number of countries are given in Fig. 5-12. Near-surface disposal facilities for low-level waste (LLW), of which many are in operation worldwide, are not included, although relevant information is also available for these repositories.

Substantial operational experience exists for L/ILW repositories as some of these facilities have been in operation for over thirty years. The SFR (*Slutförvar för radioaktivt avfall*) facility for L/ILW in Sweden began operation in 1988, and an application was made by the Swedish Nuclear Fuel and Waste Management Company (SKB, *Svensk Kärnbränslehantering AB*) to triple the capacity of the repository to allow inclusion of some of the wastes from reactor decommissioning, including reactor pressure vessels. It is apparent from the operating 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. significantly limited water inflow in sedimentary rock. From a technology development perspective, the concept of controlling gas release from a L/ILW repository with a gas-permeable seal (see Section 8.5.2.2) has been unique to the Swiss programme so far but is now also being addressed in other programmes as an option to mitigate gas pressure build-up.

A similar comparison for HLW repository implementation is given in Fig. 5-13. 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.

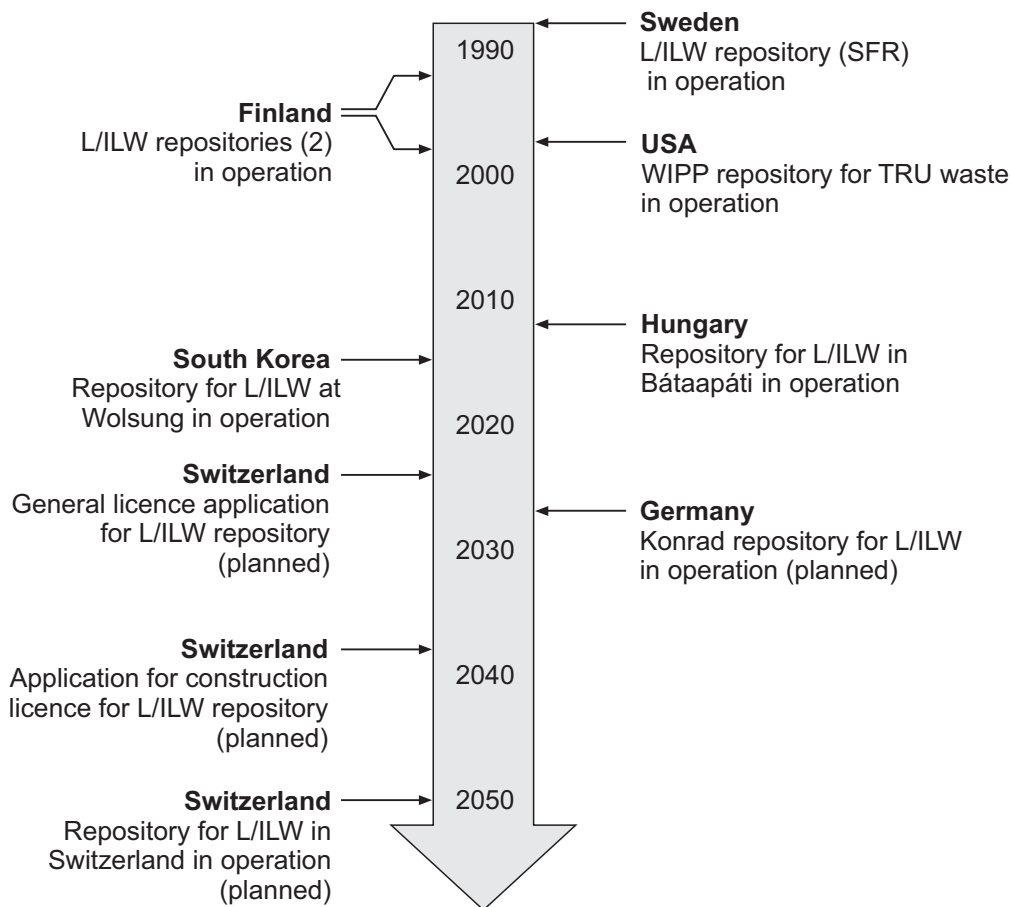


Fig. 5-12: Comparison of some key milestones for development of geological repositories for L/ILW in selected countries

TRU: transuranic waste

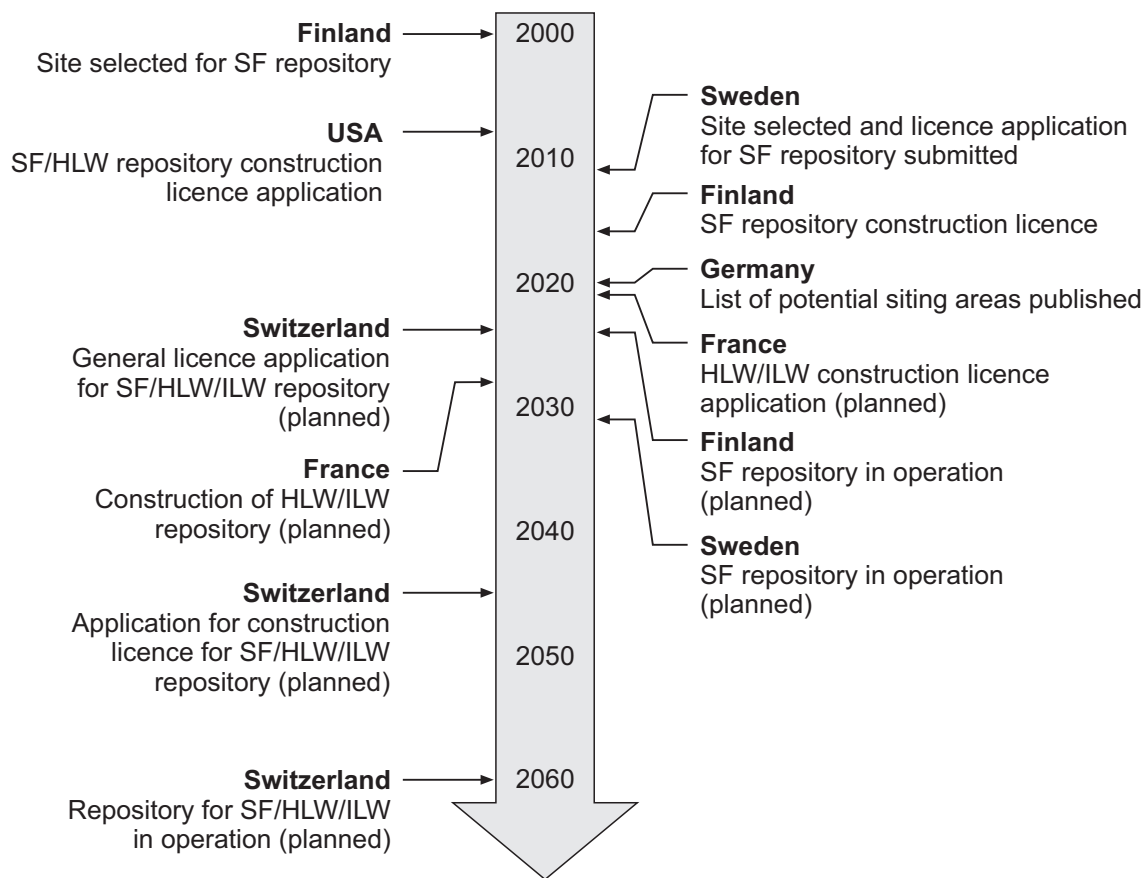


Fig. 5-13: Comparison of some key milestones for development of geological repositories for SF/HLW in selected countries

5.4.1 Status of safety case and technology development and demonstration in advanced programmes, progress since 2016

Major progress has been made by advanced HLW programmes in the last decade, while smaller programmes also moved forward. SKB (Sweden) already submitted its construction licence application for the HLW repository in 2011, the Finnish programme intends to operate its HLW repository before 2025, and the French programme is close to submitting the construction licence application for HLW and long-lived ILW (2021 – 2022). This illustrates that licence preparation and submission for HLW repositories is maturing. Recently, the NEA also concluded that (OECD/NEA 2020): *"... it can be expected that experience and knowledge will increase allowing development of deep geological repositories in other countries potentially at a faster pace than experienced for these initial facilities"*. This "learning effect", known from many other prototype and first-of-a-kind projects, is expected to be significant and to be of major benefit to the Nagra programme.

Status of the French programme and similarities with the Swiss programme

Andra, the French national agency for radioactive waste management, is responsible for *Cigéo*, the French deep geological repository project for the disposal of radioactive waste, located in Meuse/Haute Marne. It is designed for disposal of HLW and long-lived ILW produced in France. In terms of adaptability, *Cigéo* is also designed to accommodate SF and graphite, if necessary.

After more than twenty years of design studies following a step-by step development process (site selection, demonstration of disposal feasibility, precise location of underground and surface facilities, basic industrial design, etc.), 2019 saw the completion of the detailed engineering design phase of *Cigéo* for the licensing application (disposal of the entire radioactive waste inventory, including an initial phase called the industrial pilot phase). Compared to the basic engineering design phase, the detailed configuration of *Cigéo* incorporates several technical and economic optimisation measures provided by Andra to rationalise the overall cost of the project, limit the operational risks and increase operational safety management, thus maintaining the highest level of post-closure safety and enhancing safety for operators (Fig. 5-14). This includes a reduction of the environmental impact, in particular from surface facilities (nuclear facility for receiving, inspecting and preparing waste packages, etc.), the development and simplification of the network of disposal cells enabling the direct disposal of primary packages of certain long-lived ILW, and mechanised excavation using a tunnel-boring machine (Andra 2020).

The additional information requested by the French regulator in 2018 following its assessment of the Safety Options Report submitted by Andra in early 2016 has also been addressed for the licensing application submission. In particular, additional evidence had been requested concerning the repository architecture and the design of the facility to withstand natural hazards, as well as the provisions for monitoring and for managing post-accident situations.

The completion of the detailed engineering design studies for *Cigéo* is now feeding into the drafting of the construction licence application, which is expected to be completed by Andra in 2022.

Initially very active in the Mont Terri Rock Laboratory, Andra now strongly focuses on scientific and technological tests at the URL in Meuse/Haute-Marne to prepare for the implementation of the *Cigéo* project. In April 2019, a new phase of experiments called "*Chantier 4*" began for a period of six years. In total, 640 metres of additional drifts will be excavated 500 metres beneath the ground to carry out new demonstrations, test new techniques for monitoring the repository structures and support the review process of the construction licence application. In particular, Andra will develop a prototype drift of disposal cells for long-lived ILW packages on a scale similar to that of *Cigéo* (10 metres in diameter and 80 metres in length), several demonstrations of disposal cells for HLW equipped with new devices, demonstrations of closure structures (drift seals and backfill), and will excavate a four-branch intersection (X-junction) (Andra 2020).

When comparing international HLW disposal programmes, the French programme is the one currently closest to that of Nagra. This is because of large similarities in the multibarrier concept. In both programmes, the clay host rock (Callovo-Oxfordian in France, compared to the Opalinus Clay in Switzerland) acts as the major safety barrier in the post-closure phase. Furthermore, both host rocks are similar. Therefore, the knowledge base on the host rock, including elucidating the various aspects that are relevant for geological disposal, have been developed in close collaboration. These aspects are, for example, the containment properties of the host rock, the damage to the rock following excavation and the behaviour of the rock following heating. As a consequence, the safety arguments related to the host rock show large similarities with those being developed by Nagra. These have been integrated into several safety cases, the latest being Andra (2015) which has undergone international (IAEA) and national regulatory review (Andra 2016, ASN 2018). The entire knowledge base is constantly maintained and enhanced. A major instrument ensuring this enhancement is the Clay Conference series. The last conference took place in 2017 and was

organised by Nagra in Davos, Switzerland. The Clay Conference brings the international clay community together, and the resulting series of peer-reviewed publications illustrates the maturity of the understanding related to clay as a basis for the respective safety cases.

Although the host rocks have many similarities, the French and Swiss disposal concepts for both HLW and long-lived ILW are different as they result from different boundary conditions such as:

- Size and nature of the inventory: the inventory of Andra is approximately an order of magnitude larger and more diverse.
- National legal and regulatory context and programme stage: Andra will submit the construction licence application in 2022, and Nagra will submit the general licence applications for the proposed site(s) in 2024.
- Wider geological setting: *Cigéo* is located in the geologically stable Paris Basin, while Nagra's siting regions are located north of the Alps.

Therefore, a direct element by element comparison of the two concepts is not meaningful. Many RD&D aspects are, however, similar and close collaboration with Andra is taking place on multiple topics such as monitoring, sealing, gas issues, etc.

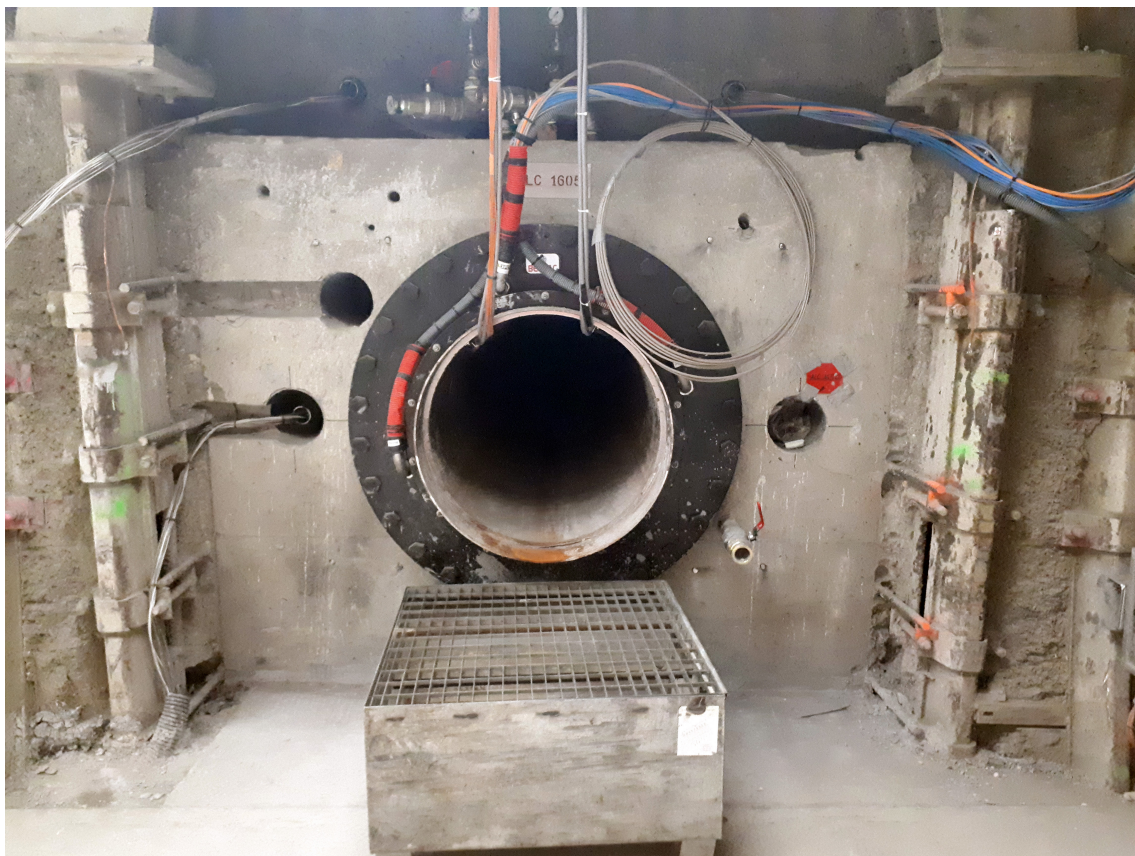


Fig. 5-14: Experimenting on a demonstrator high-level waste disposal cell in anticipation of the submission of the Andra construction licence application in 2021/2022 (courtesy of Andra)

Status of the Swedish and Finnish programmes and common RD&D interests

When finalised, the Swedish system for the management of nuclear waste will comprise three repositories: a spent fuel repository, a repository for short-lived radioactive waste (SFR) and a repository for long-lived waste (SFL). The facilities are to be constructed and operated by SKB. In the spring of 2011, SKB submitted its permit applications to build the spent nuclear fuel repository in crystalline bedrock at the Forsmark site in the Östhammar Municipality on the east coast of Sweden. The licensing process is still ongoing. However, a major milestone was passed in October 2020, when the Östhammar Municipality agreed to the establishment of a final repository for spent nuclear fuel at Forsmark. Oskarshamn Municipality had earlier agreed to the establishment of the encapsulation plant, which is also a part of SKB's final repository system for spent nuclear fuel. The SFR repository is already operational and is also located in the crystalline bedrock at Forsmark, below the Baltic Sea. Most of the waste currently emplaced in the SFR comes from the operation of Swedish nuclear power plants, although, in the future, the disposal of decommissioning waste is also foreseen once these plants are taken out of service. For this reason, at the end of 2014, SKB submitted an application to extend the SFR. Permits to construct and operate the extension are still awaiting government approval. The SFL is still at an early planning stage, and no site for this facility has yet been proposed.

In Finland, disposal facilities for operational waste at the Olkiluoto site in Eurajoki and the Hättholmen site in Loviisa were commissioned in the 1990s. The L/ILW generated during the future decommissioning of the power plants at these sites is to be placed in these facilities. In addition, another disposal facility consisting of two further geological repositories with a shared access is planned at the Olkiluoto site, with one repository for spent nuclear fuel and one for low- and intermediate-level waste from the operation and decommissioning of the spent fuel encapsulation plant. This disposal facility will be constructed and operated by Posiva, the Finnish waste implementer. In November 2015, the Finnish Government granted Posiva the licence needed to start construction. Posiva aims to submit an application for an operating licence at the end of 2021. All of the above-mentioned facilities are in crystalline bedrock.

Although the disposal facilities operating or planned in detail in Sweden and Finland are in crystalline bedrock, the engineered barriers share many common features with the facilities planned in Switzerland, including the use, where appropriate, of concrete containers and cementitious backfill for the disposal of L/ILW, and metal canisters surrounded by a bentonite clay buffer for SF. The canisters being considered by SKB and Posiva each consist of a copper shell with a cast-iron, load-bearing insert, a design that is also being considered as an option by Nagra.

Given the similarity in their disposal concepts, especially for spent nuclear fuel, SKB and Posiva collaborate extensively in their RD&D. The collaboration includes canister, bentonite and rock issues, machine design and issues linked to finding financially optimum solutions without compromising safety. SKB and Posiva have recently formulated revised and harmonised technical design requirements (Posiva & SKB 2017).

Much of the research and development work carried out by SKB takes place in its three laboratories at Oskarshamn: the Äspö Hard Rock Laboratory, the multi-purpose test facilities and the Canister Laboratory. They provide opportunities for full-scale tests and demonstrations of techniques

in realistic conditions. SKB's most recent RD&D programme was submitted to the Swedish Radiation Safety Authority in September 2019 (SKB 2019b). Areas of research of common interest to SKB and Nagra include:

- LLW and ILW, especially how organic compounds affect radionuclide transport in a repository environment, definition of the inventory, including difficult-to-measure nuclides and the development of a design for waste containers
- SF, including the solubility of the fuel after it has been exposed to water
- canisters for SF, including the properties of copper in a repository environment (especially corrosion and creep issues) and manufacturing and handling technologies
- cementitious materials, including the evolution of such materials over time and their gas transport characteristics
- clay barriers and repository closure structures, including homogenisation of the bentonite buffer and its properties after saturation, as well as piping erosion, gas composition and microbial activity during the unsaturated period
- surface ecosystems, including uptake pathways and uptake mechanisms for radionuclides in different organisms, transport and accumulation processes and the radiological, biological and chemical properties of key radioelements

The most recent review of the current status and future plans for nuclear waste management in Finland was published in 2019 (Posiva Oy 2019). According to this review, Posiva's main task for 2019 – 2021 is to prepare for the submission of the operating licence application for the SF encapsulation plant and disposal facility. Specific aims are to start construction of the encapsulation plant and to resolve open issues related to the disposal concept. The objectives of the 2022 – 2024 programme period will be to have the engineered barriers of the disposal system ready for production, to bring the encapsulation plant to a point of readiness and to construct the disposal facility to a point allowing disposal operations to be started. Currently, site characterisation at the Olkiluoto site is proceeding above and below ground, including the excavation of ONKALO, an underground rock characterisation facility. Work at ONKALO includes the Full-scale In-situ System Test (FISST). With regard to the spent fuel canisters, the focus is on the development of a manufacturing process on an industrial scale. Industrialisation measures to study the concept, manufacture, installation and performance of the SF repository buffer and backfill have also been initiated.

5.5 RD&D progress in Nagra's repository project since 2016

Nagra continues to adapt the repository project based on tangible outputs from its RD&D programme, as described in this document. Definitive decisions with respect to waste allocation in the L/ILW and HLW areas of the combined repository, an evolution towards HLW emplacement in dead-end drifts and the planned use of a shield tunnel-boring machine for the excavation of the HLW drifts have all been underpinned by activities planned in the 2016 RD&D Report.

The Nagra repository project has progressed since 2016 as it becomes more definitive. Developments are documented in the RCM system and result from both new studies and findings as well as progress in the Sectoral Plan. This includes the decision, with the finalisation of *SGT* Stage 2, that the Opalinus Clay will be the host rock for both the HLW and the L/ILW repositories. While many adaptations do not affect the RD&D programme or the repository evolution, the following four aspects do have implications and are therefore discussed in the next paragraphs.

In the previous RD&D report (Nagra 2016b) and up to the end of *SGT* Stage 2, long-lived ILW was allocated with the HLW waste to the HLW repository. The allocation of radioactive waste to the deep geological repositories is based on the L/ILW, ATW and HLW categories defined in Art. 51 NEO. The previous allocation of waste was used as the basis for developing the proposals for narrowing down the geological siting regions in the context of *SGT* Stage 2. It accounted for safety-related considerations for the HLW and L/ILW sites that were still under consideration at that time, with various potential host rock types. For this reason, some of the L/ILW repository sites could not accommodate long-lived ILW. In *SGT* Stage 3, the Opalinus Clay is the designated host rock for the remaining sites, and these have similar safety profiles. L/ILW and ATW are now assigned to the L/ILW repository as synergies are expected in the case where these are co-located. This is because their cement-based multibarrier concepts are very similar. SF assemblies and vitrified HLW from reprocessing have a bentonite-based multibarrier concept and are still assigned to the HLW repository.

While the concept for the HLW emplacement drifts as described in the 2016 RD&D Plan indicated that, after approximately every tenth canister, the liner was foreseen to be interrupted by an interjacent sealing section, the current concept is now modified in this respect. With the evolution towards dead-end waste emplacement rooms, it already became clear in the 2016 RD&D Plan and through further studies analysing the consequences in terms of impact on aqueous radionuclide transport that, even when assuming significantly increased permeabilities in the access structures and the excavation damaged zone (EDZ), no significant release path along the access structures is to be expected (Poller et al. 2014). The water flow in the repository is determined by the extremely low inflow from the surrounding host rock. As such, the current repository project no longer foresees interjacent sealing sections as they seem to offer no additional safety benefit. The granular bentonite material emplaced between the canisters contributes towards compartmentalisation after saturation.

The concept for the HLW emplacement drifts as described in the 2016 RD&D Plan still included a shotcrete liner along the SF/HLW emplacement drifts. A further development is that experience from tunnelling projects and progress in the characterisation of the geomechanical properties of the selected site(s) during *SGT* Stage 3 has led to the selection of a shield tunnel-boring machine with lining segments for the excavation of the HLW drifts in the repository project. It became clear that, according to the current state of geological knowledge, this is the preferred method for the small tunnel cross-section of the HLW drifts to ensure the required tunnelling progress rate, optimise operational safety and minimise the damage to the host rock by creating only a limited EDZ.

Furthermore, mainly in response to transport considerations, a new L/ILW disposal container for decommissioning waste was designed, and prototypes were produced and tested in close collaboration with the waste producers.

The repository project that will be submitted for the general licence applications will be described in Nagra NTB 24-11 (planned).

5.6 Ensuring RD&D capabilities and competence throughout repository implementation

Nagra is set up as a project management organisation and has approximately 130 staff. It is responsible for developing the disposal strategy in cooperation with its Board of Directors, developing the work programmes and managing the technical programme while the staff develop key strategic issues (e.g. siting strategy, safety assessment methodology, geosyntheses, safety reports and waste inventories). Nagra is responsible for communication with all interest groups. In all these activities, support is provided by a wide network of universities, companies, contractors and experts.

To maintain sufficient access to and availability of skills, expertise and scientific resources throughout the implementation of the disposal programme, Nagra actively manages competence in each research domain. The latter is done both in-house – through recruitment and knowledge management activities, and externally – through the use of the supply chain, competence centres, URL programmes and international collaboration.

Moving forward, Nagra will use activities at the selected site(s) as an opportunity to further develop and maintain specific competence which will be needed to support future licensing steps.

Ensuring and maintaining in-house competence

The management of the RD&D programme at Nagra is strongly delegated, with each RD&D core topic (see Tab. 5-1) being led by a small number of experts.

These core topic owners are:

- Responsible for the integration of the project outcomes for their topic, assessing and defining new projects where needed and proposing these to the management.
- Aware of the RD&D priorities regarding their topic in the context of safety and feasibility and assessing project outcomes in terms of bringing added value.
- Aware of (inter)national projects that address these priorities and how these projects can contribute to Nagra's work.
- Aware of their international partners and participate in networks related to their topic, maintaining the state of the art and securing Nagra's interests.

Tab. 5-1: RD&D core topics as part of the delegated RD&D management structure at Nagra

Inventory-related topics • HLW-ILW characterisation • Long-term SF/HLW and ILW behaviour • Spent fuel handling at the encapsulation plant • Gas generation in HLW and L/ILW repositories	Near-field evolution-related topics • Canister • Cement-based elements • Bentonite-based elements • EDZ and Opalinus Clay (THC) • EDZ and Opalinus Clay (THM)
Engineering-related topics • Canister development • Barrier technology and implementation • Layout/components/concepts	Safety assessment-related topics • Assessment methodologies • Radionuclide transport
Geology-related topics • Geomechanics • Hydrogeology and barrier properties • Sedimentology • Tectonics • Long-term evolution	Intergenerational information and knowledge management Monitoring

Recruiting staff who combine strong project management and integration skills with excellent technical expertise, supported by pragmatic measures for knowledge management, has proven to be a reliable combination over the last decades in terms of maintaining in-house competence.

5.6.1 International collaboration

A significant aspect of maintaining competence is international collaboration. In the European context, Nagra is a member of the executive group of the Implementing Geological Disposal of Radioactive Waste Technology Platform (IGD-TP, available online at <https://igdtp.eu/>), uniting the research interests of most radioactive waste management organisations in Europe and coordinating joint activities based on a common vision and strategic research agenda. Nagra holds the chair and the secretariat from 2019 to 2021. Furthermore, Nagra participates as a mandated actor in EURAD (EURAD | European Joint Programme on Radioactive Waste Management, available online <https://www.ejp-eurad.eu/>), the European joint programme on radioactive waste management that was launched in 2019 and is expected to define the Euratom research agenda over the next decade. Nagra also participates in various committees, working groups and projects of the OECD/NEA and is also involved in selected activities of the 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. Furthermore, 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. The important role of international collaboration is clearly visible on the Tier 3 roadmaps in Chapter 7. In relevant sections in Chapter 8, reference is made to how Nagra benefits currently and in the near future from these international collaborations.

5.6.2 Activities in existing URLs

A significant degree of competence development occurs through participating in and conducting experiments in national and international URLs. These include the Mont Terri Rock Laboratory and the Grimsel Test Site (GTS) in Switzerland (see separate textboxes), the Meuse/Haute Marne URL (operated by Andra in France) and the Äspö Hard Rock Laboratory (operated by SKB in Sweden). Furthermore, close contacts are maintained with the Belgian programme and their underground laboratory (HADES in Mol).

Currently, Nagra's focus of work to be conducted in URLs is mainly on specific issues supporting the general licence applications. In the Mont Terri URL, work related to the Opalinus Clay has largely shifted towards the site-specific characterisation of the Opalinus Clay as part of the exploration programme in *SGT* Stage 3. The GTS continues to function well as an international URL where Nagra's focus is on aspects of the engineered barrier system (EBS), including its optimisation.

Beyond the general licence applications, certain activities at the Mont Terri URL and the GTS will continue, specifically with regard to those experiments that generate long-term data as these are of key importance for supporting the safety case. Further experiments of interest will be those contributing to the optimisation process targeting future licensing steps (Vomvoris & Blechschmidt 2019).

Mont Terri Rock Laboratory

The Mont Terri Project was launched in 1996 and soon developed from a national project to an international platform for underground research. Today, the Mont Terri URL is run by the Swiss Federal Office of Topography, swisstopo. Currently, 21 partner organisations from eight countries perform experiments in the Opalinus Clay, the selected host rock for the Swiss repositories. The Mont Terri URL was constructed in the north-west of Switzerland adjacent to a motorway tunnel, allowing for easy horizontal access to the rock in the back-limb of the Mont Terri anticline (Fig. 5-15).

For the Swiss disposal programme, the Mont Terri URL can be considered as a generic URL with a lithology and mineralogy very similar to the potential siting regions in north-east Switzerland. Therefore, many safety-relevant features and processes can be readily investigated at Mont Terri, such as the reaction to repository-induced perturbations, transport properties or geomechanical behaviour. The transferability of such investigations has been discussed (Mazurek et al. 2008, Bossart 2018).

Currently, Nagra's experimental programme focuses on the investigation of fault reactivation, the geomechanical behaviour of the Opalinus Clay, cement – clay interactions, microbial activity, in-situ corrosion rates of steel and long-term heater experiments that allow completion of databases on the early evolution of the near-field.

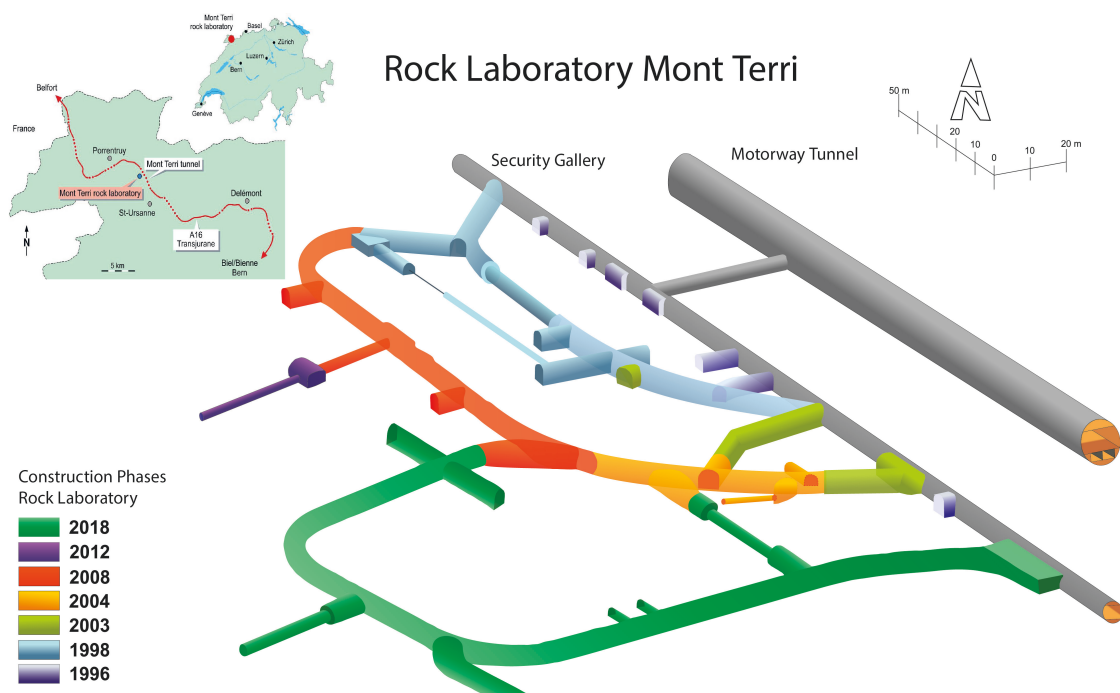


Fig. 5-15: The current layout of the Mont Terri Rock Laboratory

Grimsel Test Site (GTS)

The GTS is Nagra's own generic rock laboratory in operation since 1984. The branching tunnel system (see Fig. 5-16) of more than one kilometre in length is located at an elevation of 1,730 metres above sea-level and around 450 metres beneath the Juchlistock in the granite and granodiorite of the Aar Massif. A unique characteristic of the GTS 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).

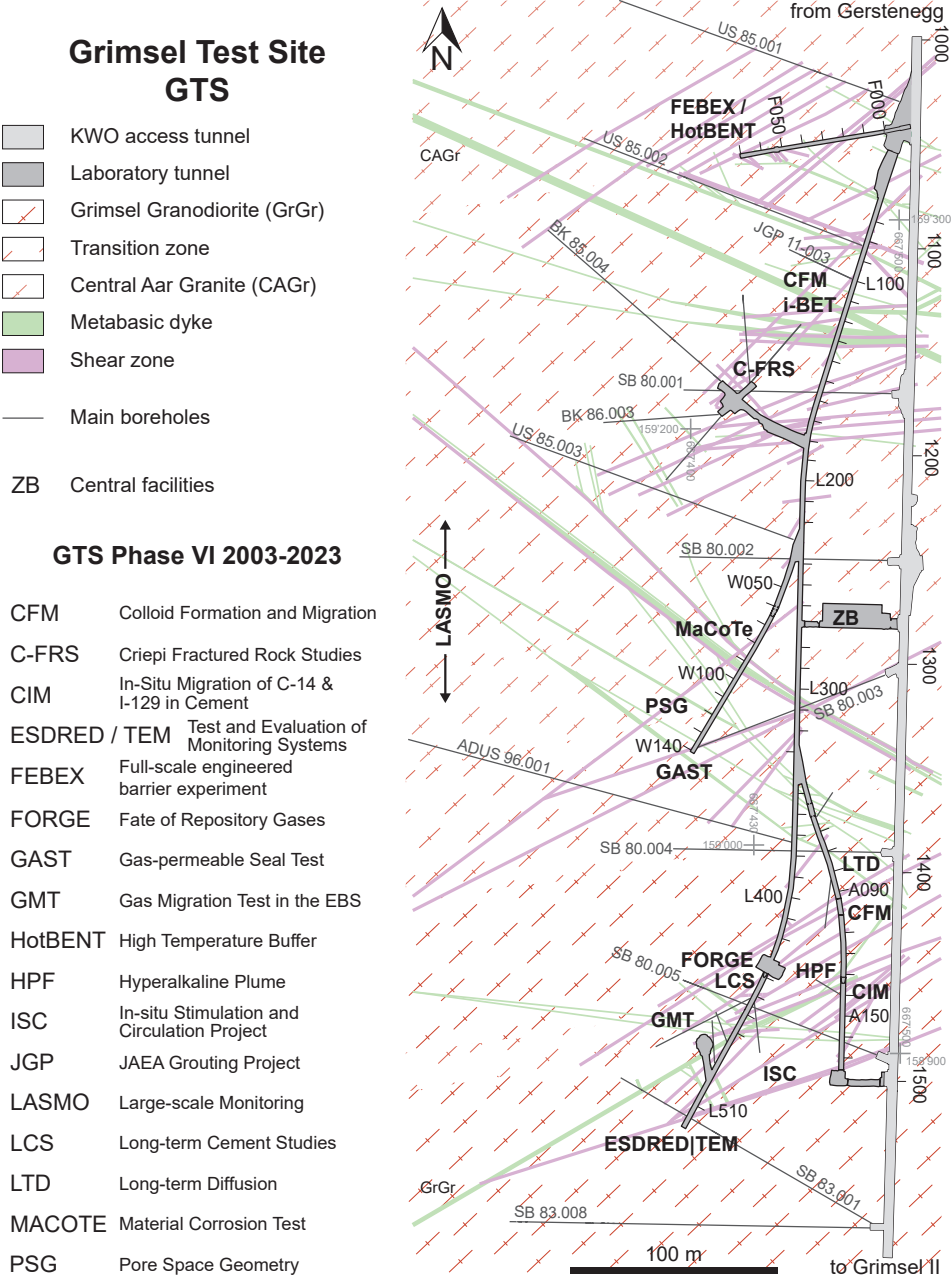


Fig. 5-16: The Grimsel Test Site with the most important experiments and their locations

The current GTS Phase VI commenced in 2003 with a much longer planning horizon than previous research phases (Vomvoris & Blechschmidt 2019). This was in response to the realisation by Nagra and its partners that major remaining challenges required experiments closer to the full-scale simulation of the repository environment and therefore also much longer durations.

As the focus of the Swiss disposal programme shifted from crystalline rock to sedimentary rock formations, the focus of Nagra's activities at the GTS has also evolved to reflect the corresponding RD&D priorities (see also Blechschmidt & Vomvoris 2015). Emphasis has therefore been placed on the behaviour of EBS components under natural conditions or repository-induced effects (heat generation, gas, etc.) at intermediate and engineering scales, as well as their interactions. These include the GAs-permeable Seal Test (GAST experiment, see Section 8.5.2.2), the Full-scale Engineered Barriers Experiment (FEBEX) and the HotBENT experiment (high temperature effects on bentonite), see Section 8.5.3.3.

More than 20 organisations and research institutes from 12 different countries as well as the European Union are participating in the various projects.

5.6.3 Construction and operation of the *BEUU*

The construction and operation of the *BEUU* will be a major milestone for developing competence for repository construction and operation in anticipation of the submission of the construction licence application (Nagra 2021b). The *EUU* will verify the process understanding gained up to this stage specifically for the selected site(s) and the actual in-situ host rock and will allow the in-situ demonstration of specified aspects. The preparations for the *BEUU* are foreseen in the second half of the 2020s and will start with drilling at the shaft location and developing the concepts for monitoring, executing the shaft sinking and installation of the service area followed by the construction of the facilities in the 2030s. Experimental test plans will have to be in place, followed by intensive rock characterisation and testing. The build-up of competence by that point will exceed that in anticipation of the *SGT* Stage 3 exploration programme and preparation for the general licence applications. At that point in the future, off-site URLs can still be used for training, equipment testing or continuing specific experiments over very long time periods.

5.6.4 Ensuring continuity of RD&D competence centres

In order to complete the RD&D activities at the required level, Nagra relies on competence centres, universities, research institutes and specialised consultancies in Switzerland and abroad.

Two competence centres have been accompanying Nagra on an ongoing basis for the last decades as they are knowledge holders for key aspects of the Nagra disposal programme.

Firstly, the Laboratory for Waste Management (LES) at the Paul Scherrer Institute (PSI) is a unique Swiss competence centre for geochemistry, multi-scale radionuclide and mass transport in argillaceous rocks and cement, and their applications to deep geological systems and Swiss radioactive waste repositories. 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.

Secondly, the Rock-Water Interaction Group at the University of Bern's Institute of Geological Sciences has been involved in all of Nagra's major field investigation programmes as well as in experiments at the Mont Terri Rock Laboratory and the GTS. The principal fields of work have been rock characterisation, natural tracer profiles, porewater investigations and modelling, hydro-chemistry 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.

Other competence centres have been involved in Nagra's RD&D programme on a project-by-project basis, providing sustained support and addressing evolving needs as they arise. This is the case, for example, for the Swiss Federal Institute of Technology in Lausanne (EPFL) that focuses on geotechnics, thermo-hydro-mechanical (THM) modelling and microbiology, or for the Swiss Federal Institute of Technology in Zürich (ETHZ) that focuses on fibre optics, seismology and dating techniques. It also includes research institutes such as the Swiss Federal Laboratories for Materials Science and Technology in Dübendorf (EMPA, *Eidgenössische Materialprüfungs- und Forschungsanstalt*) or, on an international basis, universities such as the Universitat Politècnica de Catalunya (UPC) in Spain.

Furthermore, Nagra can rely on a network of specialised consultancies in a broad range of domains to contribute scientific findings and state-of-the-art knowledge in the Nagra context.

Continuity and maintaining competence in all parts of the chain (universities, research institutes, consultancies) is ensured on a case-by-case basis through close interactions with the knowledge holders and the potential of most organisations to diversify into other domains when needed or, vice versa, being able to mobilise extra resources for Nagra's projects through recruitment or inflow from other domains.

Ensuring continuity in the RD&D supply chain is very important, however, the supply chain also has to be flexible. In the different phases of the repository implementation programme, the focus of the RD&D activities will shift significantly as topics gain sufficient maturity and no longer need intensive support in subsequent phases, while new topics addressing specific aspects in the Optimisation Roadmaps will require specific expertise.

6 RD&D and technical activities in future stages of the disposal programme

In future stages of the disposal programme, the main drivers of the RD&D programme will be the optimisation processes which must be carried out from the perspective of safety (recurring safety cases at each milestone) and implementation (confidence underpinning the feasibility of the design at each milestone). A key element in this will be the construction of the *BEUU* at the selected site(s) after the granting and validation of the general licences. In anticipation of the construction and operating licences, intensive technological development is also foreseen.

For the general licence applications, the entire knowledge base and the many RD&D activities feeding into them will be integrated into the argumentation and decision-making supporting the safety and feasibility cases for the selected site(s). A more detailed description of the RD&D activities over the next five to ten years, many of which feed into the general licence applications, is given in Chapter 8.

Chapter 6 describes the anticipated evolution of the RD&D programme beyond the submission of the general licence applications by Nagra, foreseen for 2024. Following this, the focus will be on the adaptation and optimisation of the programme in response to discussions with the regulatory bodies and the government. This period of review by the Swiss authorities is expected to end with the approval of Nagra's refined programme and the granting of the necessary general licences (foreseen for the end of 2031).

After the general licences have been granted, the RD&D programme will enter a new phase characterised by optimisation, technology development and engineering, along with subsurface characterisation at the selected site(s) and experiments and demonstrations in the facilities for underground geological investigations (*BEUU*).

Chapter 6 further provides a general overview of the RD&D programme for each of the main licensing steps. Sections 6.2 and 6.4 are structured identically to ensure traceability with the 2021 Cost Study (Swissnuclear 2021).

Chapter 7 describes the evolution of programme aspects with a significant RD&D component in more detail, starting from the general licence applications and leading up to the operation of the repositories.

6.1 Activities foreseen up to the granting of the general licences and the *EUU* licence application

In the timeframe up to the granting of the general licences, major technical activities will include:

- addressing questions from the regulatory authorities and stakeholders regarding the documentation of the safety case; accompanying the licensing process
- enhancing the geological understanding of the selected site(s)
- preparing for the *EUU* licence application
- optimisation of the repository project in all its aspects

Experience from international waste disposal programmes will be monitored and it is anticipated that, before the granting of the general licences, deep geological repositories for HLW will be operational or under construction in other countries.

Geological investigations

Following the submission of the general licence applications for the selected site(s), preparations for the construction of the facilities for underground geological investigations (*EUU*) at the site(s) will start. Prior to the field and construction work, baseline monitoring programmes will be put in place. The start of baseline monitoring is planned for the late 2020s, after the technical assessment of the general licence applications has been completed by the authorities, and measurements will be intensified prior to shaft construction.

The previously implemented regional monitoring projects will be continued (e.g. geodetic measurements, operation of a seismic network) to further complete the geological data, with the aim of distinguishing natural (e.g. natural seismicity or surface uplift) from repository-induced effects.

Increasingly detailed geological data and state-of-the-art site-specific 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-specific modelling will be a continuous process in all stages of the future disposal programme.

In anticipation of the licence applications for the *EUU*, boreholes will be drilled at the planned location of the exploration shaft and in its vicinity, accompanied by a geological exploration and monitoring programme.

The state-of-the-art scientific methods for understanding the long-term geological evolution of the wider area around the selected site(s), established for the general licence applications, will be further enhanced with the focus on the selected site(s).

Radioactive materials and wastes

The inventory will be further refined with advanced calculations to support additional operational safety, design and logistics considerations for the repository and related facilities. Optimisation of the waste packaging and handling solution(s) is an important driver for both final disposal and, even more so, the decommissioning of the NPPs. This includes the models and codes for the activation calculations leading to optimised packaging of decommissioning waste. The anticipated decommissioning activities will provide access to further samples to verify and refine the codes. This takes place in close collaborations with the NPPs.

With respect to gas production, the reference corrosion rates will be continuously refined in accordance with available experimental data and increased understanding of the evolution of conditions in the repository. The currently ongoing corrosion experiments will be extended to further increase confidence in the reference corrosion rates. The gas monitoring experiments (GME) at Zwiilag are designed for long-term operation, i.e. beyond the general licence applications. Existing experimental data on the degradation of organic polymers indicate that these materials degrade very slowly, and the resulting potential gas generation will be very low. Long-term datasets are of high value for determining reliable gas generation rates that are not overly conservative (current ongoing experiments are detailed in Sections 8.3.3.5 and 8.5.3.1).

Improvements in the understanding of processes associated with HLW and SF will be pursued. The assessment of SF integrity during longer periods of dry storage will be further detailed. The SF dissolution and release model will be further refined by integrating new developments in the field. The use of burnup credit for criticality assessments will be further investigated. These topics are expected to benefit significantly from international collaboration.

A continued follow-up on international efforts in partitioning and transmutation 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 applications. The initial focus will be on the access and infrastructure for the facilities for underground geological investigations (*EUU*) as well as on developing monitoring programmes. This information will form the basis for the licence applications for the *EUU* facilities.

Optimisation of the repository project and its elements will be an important aspect of this phase. Initial optimisation efforts will focus on the entire HLW programme in a holistic manner and will include aspects such as canister loading schemes and the associated facilities, repository layout (distance between drifts and canister pitch), repository operation and the multibarrier concept, thereby ensuring the required safety margins.

Following this, optimisation of the individual components and operational aspects will be pursued, mainly based on desk studies until the licence for the *EUU* is granted. As part of this, alternative EBS concepts will continue to be evaluated, initially at the conceptual level, but this can involve substantial RD&D effort in cases where optimisation in terms of safety, feasibility and also cost could be achieved by assuming alternative engineered barrier materials and/or repository layouts.

With respect to the buffer materials for HLW emplacement drifts, materials will be further evaluated to ensure that options are available that meet the requirements over the coming decades. The final materials will be selected in anticipation of the construction licence.

A recipe for cement-based backfill for L/ILW emplacement caverns will be developed for the general licence applications, although the possibilities of using alternative materials will be continuously evaluated; 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 made in anticipation of the construction licence. Until then, steel and copper-coated canister options will be continuously evaluated and developed to a high level of technological readiness. Further options will also continue to be examined as significant progress in materials performance and coating techniques can be expected in the next decades.

The sealing and closure concepts as well as the emplacement and retrievability concepts developed for the general licence applications will be refined and optimised for ease of construction. At this stage, the work will still be mainly desk-based.

The state of the art regarding concepts for the preservation of information and marking of the repository will be maintained. Measures for temporary closure in case of unfavourable boundary conditions will be looked at, while a detailed concept is required only in anticipation of the construction licences.

Safety assessment and safety-relevant properties of the engineered barrier system

Beyond the general licence applications, RD&D activities for the post-closure safety assessment will continue as the repository projects progress in a stepwise manner, guided by regulatory requirements. This may include, for example, the development of methods and tools to:

1. further optimise repository configurations (e.g. repository layout and design, grouping of waste types), construction and operation from the perspective of post-closure safety
2. guide the design, construction and operation of the pilot repository
3. derive more specific requirements on individual components of the multibarrier system
4. assess the effects of technical and operational measures for temporary closure, retrieval, security and the control of fissile materials on post-closure safety
5. assess consequences of monitoring and retrieval activities, both for normal operation and in the case of incidents (which may, in theory, lead to the decision to retrieve the waste)

Regarding operational safety, a broad description of repository design and sequences of operations is required to support the general licence applications (NEO 2004). Thereafter, these aspects will be further developed, resulting in increasingly refined descriptions.

The improved 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 as part of the licensing process.

The experimental programme in the Mont Terri Rock Laboratory will be continued with the focus on long-term characterisation of safety-relevant parameters. This will include the continuation of the FE experiment and of tests characterising the corrosion rates of canister materials, as well as the characterisation of chemical interactions at material interfaces (cement, bentonite, Opalinus Clay). During this period, the excavation of the heater from the HE-E (heater test) 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 field activities.

The Grimsel Test Site (GTS) will continue to act as an international rock laboratory and will further support the Nagra programme with experiments that focus on engineered barrier systems, such as the GAST (Section 8.5.2.2) and HotBENT (Section 8.5.3.3) experiments. Novel materials, technologies and monitoring equipment can be tested at the GTS as part of projects led by international consortia.

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 HLW and L/ILW near-field will be continued, and these will have to be adapted to future layout modifications and changes to the waste inventory. Advanced process models will be implemented with a view to further optimisation.

The experiment plans for the facilities for underground geological investigations will be further developed, and certain aspects may be pre-tested in the existing generic URLs or in surface laboratories.

Monitoring

The monitoring concepts for the pilot repository and the construction, operation and post-closure phases of the repository will be further developed. The activities will focus on technology screening as well as on further technology developments and testing in areas where national or international collaboration can be established. Testing of some techniques will take place in the Mont Terri Rock Laboratory. Prior to construction of the facilities for underground geological investigations, radiological baseline monitoring and hydrogeological monitoring will start.

International collaboration and competence management

After submission of the general licence applications, which requires an intense focus on the specifics of the Swiss programme, international collaboration will again increase. In the period up to the granting and validation of the general licence applications, several geological repositories are expected to be constructed or become operational and transfer of knowledge from these more advanced programmes will be highly beneficial. Increased participation in technology platforms, international working groups and initiatives will ensure that Nagra makes a successful transition from surface-based investigations to subsurface investigations at the selected site(s).

6.2 Facilities for underground geological investigations supporting the construction and operating licences

6.2.1 Introduction

With the granting of the general licences and the licence applications for the *EUU*, preparations for the construction of the facilities for underground investigations can start. Plans will be finalised for the subsurface investigation programme, and construction of the facilities for underground geological investigations will start once the licences have been granted.

At the same time, the subsurface characterisation programme will be initiated. Depending on the type of access (exploration shaft or tunnel), a construction period of between two and four years has to be foreseen to complete the first access. This period will also be used to characterise the rock sequence and update the geological information. Once the repository depth is reached, a central area will be constructed.

At that point, construction of the *EUU* facilities can be completed. The first experiments will be those with the longest durations and these are expected to commence simultaneously so that measurements can start. Less time-critical experiments and experiments that require isolation from perturbations caused by the construction activities will start once construction of the *EUU* facilities has concluded.

For the initial submission of the construction licence application for the L/ILW repository, Nagra expects to have a complementary understanding of the mechanical properties and response of the host rock needed for construction of the initial parts of the repository. The results of the performance confirmation experiments will be available at a later stage and will be submitted as a supplement to the construction licence application. For the L/ILW repository, these experimental results are foreseen around 2044. The timeline for the HLW repository will allow submission of the complete construction licence application, including full results of planned performance confirmation experiments which will become available around 2050.

A more detailed description of the construction of the *BEUU* and the investigation programme is given in (Nagra 2021b). The planned integration of the *BEUU* into the repository construction is shown in the Tier 2 roadmaps (Chapter 3 and Appendix A3, Figs. A3-2 and A3-3).

6.2.2 Rock characterisation during construction of the access

Together with the construction of the facilities for underground geological investigations, a rock investigation and characterisation programme will be conducted to verify the geological, geomechanical, hydrogeological, mineralogical and geochemical understanding of the site by acquiring new data, including spatial variability. These data are integrated into the existing conceptual understanding and the numerical models of the site.

The following activities are expected to achieve these objectives and to contribute to the performance verification of the site(s):

- characterisation of the geological sequence during the construction of the exploration shaft and tunnel (mapping and sampling), including geotechnical, hydrogeological, hydrogeochemical and paleo-hydrogeological aspects
- advancing exploration for karst phenomena
- determination and monitoring of state parameters such as temperature, hydraulic pressure, stress and deformation
- implementation of long-term monitoring stations

6.2.3 Rock characterisation and experiments during construction and operation of the facilities for underground geological investigations

Once the central 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.

6.2.3.1 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 foreseen to improve the site-specific models, finalise construction methods and reduce remaining uncertainties. This involves repeated measurements characterising the rock volume of the facility, the state parameters and the EDZ, and defining spatial patterns for the whole repository area, taking into account existing information from the boreholes already in place. Characterisation of porewater will also be performed to quantify its mobility.

6.2.3.2 Performance confirmation of the host rock and engineering applications

The main objective of the performance confirmation is to ensure that the expected performance of the host rock as described in the safety case for the general licences can be confirmed and refined at the selected site(s) at repository depth. This will form the basis of the updated safety case for the construction licences for the HLW and L/ILW repositories.

Performance confirmation from a post-closure safety perspective

Performance confirmation from a post-closure safety perspective involves repeating various experiments that have already been conducted in the laboratory and in off-site URLs such as the Mont Terri Rock Laboratory. The underlying phenomena have been investigated in detail and are sufficiently understood to support the safety case for the general licence applications. 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 consequences of repository-induced effects can be bounded. This concerns the following key safety-relevant properties.

Self-sealing processes

These refer to understanding the development and the geometry of the excavation damaged zone (EDZ) and the evolution of its hydraulic properties over time. The self-sealing processes will be confirmed in tandem with an experiment on the gas transport capacity of the EDZ. Similar experiments already conducted in the Mont Terri Rock Laboratory indicate that an experimental timeframe of two to three years has to be foreseen for the self-sealing aspects of such experiments.

Gas transport capacity in the host rock

Gas transport properties and their spatial variability will be mapped based on laboratory samples to determine whether they are within the expected range of parameter values. The gas transport capacity itself 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. Based on experience with similar experiments at the Mont Terri Rock Laboratory, the anticipated total experiment time is about one to two years.

Thermal impact on the host rock and the EBS (HLW repository only)

With the thermal properties of the selected sites already characterised at the sample scale in the laboratory, a heater test will allow confirmation of the heat dissipation capacity of the host rock at the large scale. As several large-scale tests have already been performed, this experiment can be conducted at borehole scale as it will be supported by a modelling chain that captures the process understanding. Current understanding based on the HE-E and FE experiments at Mont Terri suggests that maximum overpressures will be generated one to three years after heating starts. However, it might be worthwhile continuing these experiments over longer timeframes.

Radionuclide migration (HLW repository only)

Radionuclide sorption and transport parameters will be confirmed in the laboratory based on samples taken during the deep borehole campaign in the siting regions in anticipation of the general licence applications and again during the construction of the BEUU. Also, the upscaling of these parameters to the URL scale has already been demonstrated in the Mont Terri Rock Laboratory. Still, confirmation of in-situ migration using injection of proxy species can be considered. Based on the Mont Terri experience, these experiments require a timeframe of around five years, after which overcoring is carried out to obtain the results.

Performance confirmation and optimisation from an engineering perspective

These activities address specific construction issues that are strongly dependent on the in-situ conditions at the repository depth of the selected site(s). They are engineering activities and no longer include an RD&D component, apart from the development of the prototype tunnel-boring machine.

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 facilities for underground geological investigations and possibly thereafter, these concepts will be tested and refined. A semi-industrial prototype tunnel-boring machine will be developed and tested off-site for this purpose. This testing will contribute to the detailed description of how the repository will be constructed. Certain aspects 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)

For the L/ILW, a construction and support concept will be designed for the cavern calotte, including alternative options. An initial test will involve the construction of the central area once repository depth has been reached. During the construction of the facility and possibly thereafter, further concepts at the semi-industrial level can be tested if necessary.

Performance confirmation of the repository components

Extent and self-sealing of the excavation damaged zone (EDZ), particularly around sealing elements

The development and geometry of the EDZ and the evolution of its hydraulic and geomechanical properties over time has to be assessed at the site and will be based on experience gained at the Mont Terri URL (see Section 8.5.3.4). The EDZ has to be mapped and characterised using radial boreholes along 1:1 cross-sections of simulated repository drifts and caverns. For this purpose, specific areas will be constructed simulating the support structures of the final emplacement rooms. These facilities will also be used for technical demonstrations under in-situ conditions. The experience from these simulations and investigations will feed into the final design of the construction methods and support systems for L/ILW emplacement caverns and the design of sealing sections for the HLW emplacement drifts.

Performance tests of the sealing elements can be carried out representatively at an off-site location. However, the EDZ and, specifically, the interface of the host rock with the materials of the sealing elements subjected to resaturation will have to be investigated in situ in a scaled experiment. This experiment can be combined with the performance confirmation of the self-sealing properties. Following the self-sealing phase, which is projected to take two to three years, a second consecutive phase lasting one to two years will be used to assess the gas transport properties through the EDZ sealed by the swelling of the sealing elements and the self-sealing capability of the host rock. In total, this test is projected to take between three and five years.

6.2.3.3 Demonstration projects

Demonstration of emplacement, backfilling and retrievability of the HLW canister and L/ILW container

Once the technology for emplacement and retrieval has been developed, it will be demonstrated that this can be realised safely and in accordance with the requirements on the subsurface environment. The demonstrations for each repository type can be combined into one experiment if this is considered advantageous. The actual demonstrations will be preceded by a detailed testing programme in surface laboratories, first of the individual components and then of the entire demonstration sequence to reduce the experimental risk underground.

- For the HLW canister, the demonstration will include the emplacement of the pedestal with the canister and backfilling of the emplacement drift with granular bentonite material using remote handling if the current repository project is to be pursued. Retrieval will require the remote removal of the backfill material and the canister. Compliance with all requirements will be checked.
- For the L/ILW container, the demonstration will include the emplacement of the container and the filling of the open space with porous concrete if the current repository project is to be pursued. Retrieval will require removing part of the porous concrete and the container. The demonstration of the emplacement of the L/ILW container is expected to be less complex as no remote handling will be required.

Demonstration of the construction feasibility of a seal

The concept for the sealing and closure of the repository will be submitted for the general licence applications. The seals of the emplacement caverns (L/ILW repository) and drifts (HLW) are likely to present the greatest challenge in terms of construction. Therefore, a demonstration of the construction of the seals of the emplacement caverns and drifts on a 1:1 scale is foreseen in line with the requirements (to be defined ahead of the submission of the construction licence applications). Surface-based testing is envisaged before conducting the demonstration in the facilities for underground geological investigations. Given adequate off-site preparation, this demonstration can typically be completed in one year as no long-term performance confirmation under full saturation is envisaged. This demonstration may be combined with the emplacement and retrievability demonstrations.

Demonstration of measures for closure in the case of emergency

As measures for the temporary closure of the facility have to be developed, the construction feasibility of temporary plugs with a performance of a few decades to a few centuries is foreseen.

6.2.3.4 Monitoring

Monitoring will be an essential part of the construction and operation of facilities for underground geological investigations, with a view to the development of the monitoring strategy for the pilot repository and the strategy for the construction, operation and closure of the repository. This also includes an evaluation of next-generation instrumentation to support the objectives of the monitoring strategies.

During the *EUU* stage, the long-term monitoring networks will be implemented as far as possible and sensible given the progress of construction based on the monitoring concept included in the *EUU* design for the *EUU* licence. The goal will be to collect meaningful time sequences of the relevant parameters for the period prior to waste emplacement for later reference.

6.2.4 Optimisation of the experimental programme and its timing

The experimental programme in the facilities for underground geological investigations has to be optimised for the following reasons:

- The facilities have limited space as the construction of additional tunnels requires a significant effort and the repository area should be preserved.
- Elevated levels of safety and quality assessment will be imposed as the facility is 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 function as the main barrier in the multibarrier concept.
- The time schedule has to be such that the results can be integrated into the safety case and the feasibility assessment in support of the construction licence applications.

Whenever possible, activities will therefore be conducted off site (Mont Terri Rock Laboratory or surface laboratories). Extensive off-site testing should also take place to reduce the risk of experimental failure in the facilities. This applies particularly to EBS testing and emplacement and retrievability tests. Where possible, experiments will be combined to serve multiple objectives.

Important synergies can be expected in the case of a combined repository where the facilities for underground geological investigations share a similar geology; this concerns the rock characterisation programme and the testing of rock performance (both from a post-closure safety and an engineering point of view).

An illustration of the sequence of activities in the facilities for underground geological investigations supporting a combined L/ILW and HLW repository is shown in Tab. 6-1.

Tab. 6-1: Illustration of a potential test programme in the facilities for underground geological investigations for a combined repository

This programme is based on the objectives defined above and the time schedule as described in Nagra (2021b) and assumes the following conditions: geological expectations have been confirmed during the construction of the exploration shaft and service area, 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, and the geology encountered in the facility shows little spatial variability and is representative for the entire repository.

Date	Description	Experimental programme within this timeframe
2032 – 2034	Preparation for construction of the BEUU	No underground activities planned
2035 – 2039	Construction of the access shafts or ramp, service area and the facility, and initiation of experiments	- Characterisation during construction of access shaft or ramp, service area and facility for underground investigations, including geotechnical, hydrogeological and hydrogeochemical aspects - In-situ monitoring - Characterisation of the relevant host rock properties and their spatial variability - Experiments on mechanical behaviour of the system and rock-mechanical support systems for construction optimisation - Initiation of performance confirmation experiments on self-sealing and gas transport capacity - Initiation of performance confirmation experiment on radionuclide migration
2040 – 2044	Continuation of experiments for the L/ILW and HLW repository sections and start of demonstrations for the L/ILW repository	- Continuation of ongoing performance confirmation experiments - Investigation of EDZ development and spatial extent - Initiation of experiments on thermal impact on the host rock - In-situ monitoring - Demonstration of L/ILW seal construction - Demonstration of L/ILW emplacement, backfilling and retrieval
2045 – 2054	Continuation of experiments and start of demonstrations for the HLW repository	- Continuation of performance confirmation experiments for HLW repository - In-situ monitoring - Demonstration of HLW seal construction - Demonstration of HLW emplacement, backfilling and retrieval

6.3 RD&D supporting future nuclear licensing steps

The following paragraphs describe the main RD&D activities related to the submission of the subsequent licence applications. Besides in-situ investigations, many engineering aspects of the repository design will undergo further iterations and design finalisations. Final modifications will be based on RD&D as well as the latest findings obtained through *EUU*. Other aspects, such as the description of the inventory, most technological developments, and methodologies supporting performance assessment and the safety case will continue independently from the *EUU* activities. Nagra will also continue to follow international developments related to all aspects of the disposal programme.

6.3.1 Activities supporting the L/ILW and HLW construction licences

Once the general licences have been granted, thus securing the site(s), the RD&D programme will focus on the activities required to support the construction licences. The geological investigations and the experiments in the facilities for underground geological investigations will provide significant input.

Geological investigations

The construction of the facilities for underground geological investigations will allow subsurface characterisation. This is expected to result in a substantial gain in data to support and validate the geological and site-specific models. A detailed rock characterisation programme will accompany the construction of the facility (Section 6.2).

Prior to the construction of the *BEUU*, the state of the art regarding exploration techniques will be applied to develop detailed investigation programmes (methodologies, sensor development and data management).

The understanding of long-term evolution (erosion, tectonics) that was developed extensively in anticipation of the site selection will be updated for the wider area surrounding the selected site(s).

The entire body of information will allow a further refinement of the site-specific models as a basis for the updated safety case and the detailed design development of the repository.

Radioactive materials and wastes

The inventory will be further refined with advanced calculations to support additional operational safety, design and logistics considerations for the repository and related facilities. Optimisation of the waste packaging and handling is an important objective.

Once definitive L/ILW waste acceptance criteria have been established, it will have 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 have to be developed to ensure compliance with the definitive criteria.

Improvements in the understanding of processes associated with HLW and SF will be pursued with a strong reliance on international collaboration and initiatives. The assessment of SF integrity will be further refined and will feed into the detailed design of the encapsulation plant. The dissolution and release models for SF and HLW will be further developed, and the use of burnup credit for criticality assessments will be further elaborated.

Possibilities to optimise waste conditioning will be followed up by Nagra as an end user. This includes the models and codes for the activation calculations leading to optimised packaging of decommissioning waste as well as benchmarking with samples that are expected to become available with the decommissioning of the remaining nuclear power plants.

With respect to gas production, the reference corrosion and degradation rates will be continuously refined in accordance with available experimental data and increasing understanding of the evolution of conditions in the repository. Experimental evidence related to gas production will be integrated.

International efforts in partitioning and transmutation will be followed and implications of new developments for Nagra's disposal programme will be evaluated.

Design and technology development

In this phase, the project will be further optimised with regard to both safety and implementation. Well in advance of submitting the construction licence applications, the multibarrier concept will be decided upon (e.g. materials, dimensions), although more detailed requirements can be specified thereafter. This will allow for the prototype development of e.g. the canister. It is possible that the final multibarrier concept and other aspects of the repository project as accepted for the general licences will be re-evaluated and adjusted if they demonstrate similar or higher levels of safety in addition to other substantial benefits.

In anticipation of the construction licences, major technology development at all levels will take place to develop the machinery and tools for constructing and operating the repository.

In-situ subsurface activities

Demonstration of the tunnel design at full scale will take place and the design of the tunnel support will be finalised based on the in-situ characterisation of rock performance. A prototype tunnel-boring machine, tailored to the conditions encountered at the site, will be developed or modified based on existing technology, and tested.

The orientations of the horizontal stress magnitudes may impact the final repository layout, and the absolute values of the stress magnitudes may require modification of the support system design planned prior to going underground. Detailed cavern and drift layout and support design will have to be adapted according to the results obtained.

Surface-based activities

The final HLW 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 backfill materials, including their detailed specification, 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 be further optimised based on new information, and alternatives will be evaluated as they become available. This will be based on remote handling due to radiation protection requirements.

In anticipation of the construction licences, Nagra will develop a closure concept for 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. Measures for temporary closure of the facility will be developed (feasibility of constructing temporary plugs with a performance of a few decades to a few centuries).

The bulk of the technological development and testing will take place in surface-based laboratories and possibly also generic URLs (e.g. Mont Terri Rock Laboratory) as this provides maximum flexibility. Only in the final phase will certain demonstrations on a 1:1 scale take place in the *BEUU* in anticipation of the submission of the operating licence applications.

A detailed design for the surface facilities with the encapsulation plant, including the necessary equipment and procedures, has to be in place in line with operational safety requirements for the construction licence.

For the construction and operating licences, other aspects also have 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.

Safety assessment and safety-relevant properties of the engineered barrier system

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 refined using the subsurface characterisation and testing in the *EUU* facilities and will be optimised in terms of layout and design. The safety concepts and assessment of potential accidents will have to be continuously updated in line with these developments and consider any further general improvements in scientific and technical knowledge in Switzerland and abroad.

The methodology for performance assessment (including thermo-hydro-mechanical-chemical (THMC) analysis), applied for the general licences, will be further enhanced, taking account of future developments in numerical simulations for upscaling in time and space, sensitivity analysis and optimisation.

The rock characterisation programme and the planned experiments in the facilities for underground geological investigations will allow characterisation of safety-relevant properties and processes in the near-field. Extensive testing (see previous paragraphs) will aim at confirming understanding and refining the process models and the parameter ranges established in earlier steps. Well before submitting the construction licence applications, the safety margin with respect to the maximum temperature allowed in the engineered barriers and the host rock and the maximum allowed overpressures will be reassessed, and thermal optimisation of the entire sequence (canister loading, emplacement sequence, canister pitch, etc.) will be undertaken in anticipation of further developing the detailed design.

By the time the construction licence applications are submitted, results from long-term in-situ corrosion experiments at existing URLs and other smaller-scale laboratory tests that were monitored for ~ 20 years will be available. Novel characterisation techniques will support the development of deeper understanding.

The interaction with the French programme will be further maintained. Before the submission of the construction licence applications, 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 operations.

Monitoring

At the time of submission of the construction licence applications, the monitoring strategy for the construction phase will be in place, including a description of the parameters and locations that will be monitored as well as the technology that will be used. It will have to be demonstrated that the monitoring objectives can be achieved with the proposed technology.

The monitoring concept for the pilot repository, 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.

International collaboration and competence management

The preparation of the construction licence applications will result in a significant increase in activities for the Nagra RD&D programme, and competence centres are likely to be reinforced to deliver the required input in a timely manner.

By then, several repositories will be operational in Europe, and a maximum transfer of knowledge in repository construction and technology development can be anticipated. In terms of infrastructure, surface-based laboratories might be involved intensively.

6.3.2 Activities supporting the L/ILW and HLW operating licences

In the next step, the focus will be entirely on the activities in the *BEUU* and the repository under construction. The *BEUU* will be integrated into the repository at that stage. The RD&D activities will have decreased significantly as major decisions will have been taken as the project enters the operational stage.

The geological information will be further refined and updated based on the characterisation of the host rock during the construction stages, including construction of the first emplacement structures.

The waste inventories will be fully defined with the submission of the respective operating licence applications and described in databases as a basis for final encapsulation or packaging where this has not yet occurred. The state of the art regarding the long-term properties will be further updated.

Technologies for emplacement and retrieval will be developed before submitting the construction licence applications, and demonstrations of emplacement and retrievability will be performed in the *BEUU* prior to the submission of the repository operating licence applications.

The constructability of the sealing elements will be demonstrated either before the operating licences or during operations.

Innovative mechanised procedures will be considered with the aim of enhancing occupational safety and optimising construction efficiency as well as the expected performance of the sealing and backfilling structures.

The safety case will be updated again in anticipation of the operating licences. This is likely to require certain RD&D activities based on experience from test programmes, new technological developments and questions formulated by the regulatory authorities. No major changes in the argumentation for the safety case and the performance assessment are anticipated at this stage.

Long-term monitoring will already be implemented with the beginning of the *EUU* and continue during construction. The long-term experience gained will be integrated into the updated monitoring plans for the pilot repository and the main repository.

6.3.3 Activities supporting the licences for closure of the repositories

During the observation period, the RD&D programme will be reduced to following up the state of the art in the relevant domains.

Finally, monitoring in the pilot repository aims at providing the verification of the performance of the safety barriers up to the closure of the repository.

The closure concept, including the sealing and backfilling of the main tunnels, will be assessed again, adjusted to the state of the art at that time and finalised in anticipation of the licences for closure foreseen for the next century.

The activities described in Chapter 6 can only be a broad indication of the RD&D programme lying ahead, as the disposal programme is expected to adapt to future developments (of a scientific or societal nature) during the current and following stages.

7 Roadmaps for programme aspects with a significant RD&D component

This chapter provides an overview of the key programme aspects that have a significant RD&D component and shows their development up to the stage where the HLW repository starts operating (2060).

As described in Chapter 4, the Optimisation Roadmaps at Tier 2 describe the core activities required to achieve the milestones of the Nagra disposal programme. The activities can be considered relatively typical of a large infrastructure programme as they integrate projects associated with engineering, geology, nuclear materials, environment, etc. and are directed by a single organisation. However, certain aspects of this disposal programme have a significant RD&D component which must be addressed to support the progression of the Nagra disposal programme. The underpinning RD&D necessary to support those specific aspects is communicated at Tier 3 of the Nagra Roadmap. This means that not all RD&D activities are captured in the individual Tier 3 roadmaps, as this would be an impossible task. A basic overview of all the activities up to the closure of the repository is provided in Chapter 6, and a more detailed overview of RD&D activities over the next five to ten years is provided in Chapter 8.

Much of the RD&D is necessary to contribute towards and underpin future decision-making. While feasibility will be demonstrated at a conceptual level for the general licence applications, there are many areas of the programme where maintaining flexibility is highly beneficial. Such flexibility is particularly valuable in areas where considerable progress is expected in the medium term, e.g. specific technological developments and advances in materials science. In these cases, a specific solution chosen in the near-term may not prove to be the most beneficial from a safety, cost or other perspective once the time for implementation arrives.

Other areas of RD&D focus on the development and use of future state-of-the-art technologies to contribute towards confirming the validity of decisions made in the past or which are imminent, i.e. prior to the general licence applications, by validating assumptions with an improved degree of confidence.

The aim of the Tier 3 roadmaps is to illustrate the interdependences between RD&D activities and the core of the programme at Tier 2. While a subset of RD&D-related activities is described at the Tier 3 level with a view to optimisation, this then feeds into the Tier 2 Optimisation Roadmaps describing the development and optimisation of the entire project. The roadmaps include RD&D contributions to decision-making and provide confidence in the selection of specific technologies and approaches within the appropriate timeframes. They communicate the need to maintain options and alternatives until the programme approaches a specific milestone, with optimisation at Tier 2 as the key driver in each case. However, the RD&D roadmaps also highlight instances where decisions must be made well before the reasoning for those decisions is captured as part of a licence application. This is done to ensure sufficient lead time is available for related development activities in the interim.

Ten key aspects have been developed into ten individual Tier 3 roadmaps. Their selection was based on the following considerations:

- The programme aspect is expected to have an important RD&D component over several decades.
- The topic is of high relevance for the optimisation process at Tier 2 and/or is specific to the Swiss programme.
- The final decisions to which the topics contribute are taken in later stages of the Nagra programme, and multiple activities are foreseen in the future.
- The outcome of the RD&D activities addressing the respective topic contribute to several aspects of the Nagra programme in a complex decision-making process, made visible through its linking to Tier 2 of the Nagra Roadmap.

These ten separate Tier 3 roadmaps describe the scope of the ten RD&D topics below, up to the beginning of HLW operations, which is when the vast majority of the necessary RD&D is expected to have been completed:

1. **Spent Fuel:** assessment of properties of spent fuel assemblies and loading in the encapsulation plant
2. **Monitoring:** development and implementation of the monitoring programmes and addressing needs for technology and concept development up to the operating licences
3. **Thermal Output:** addressing the thermal output of the HLW, reducing uncertainties, increasing process understanding and potential engineering measures to meet the safety criteria up to the detailed design
4. **Gas:** addressing gas generation in the repositories, reducing uncertainties, increasing process understanding and potential engineering measures to meet the safety criteria up to the detailed design
5. **Geological Evolution:** assessing the impact of long-term geological evolution (erosion and tectonic processes) on the repository
6. **Hydrochemistry & Barriers:** description of the hydrochemical evolution of the repository and the barriers surrounding the L/ILW containers and HLW canisters
7. **L/ILW Container:** selection of the final material for the L/ILW containers and the timeframe for technology development
8. **HLW Canister:** development of SF/HLW disposal canisters and the timeframe for technology development
9. **Sealing, Closure & Backfilling:** development of the sealing, closure and backfilling plans and concepts as well as the timeframe for technology development
10. **Emplacement & Retrievability:** development of the emplacement and retrievability plans and concepts as well as the timeframe for technology development

Each of the ten Tier 3 roadmaps is described in the next sections, and corresponding graphics are included in Appendix A3.

A strategic one-page summary of the main activities in the ten Tier 3 roadmaps is provided in Fig. 7-1.

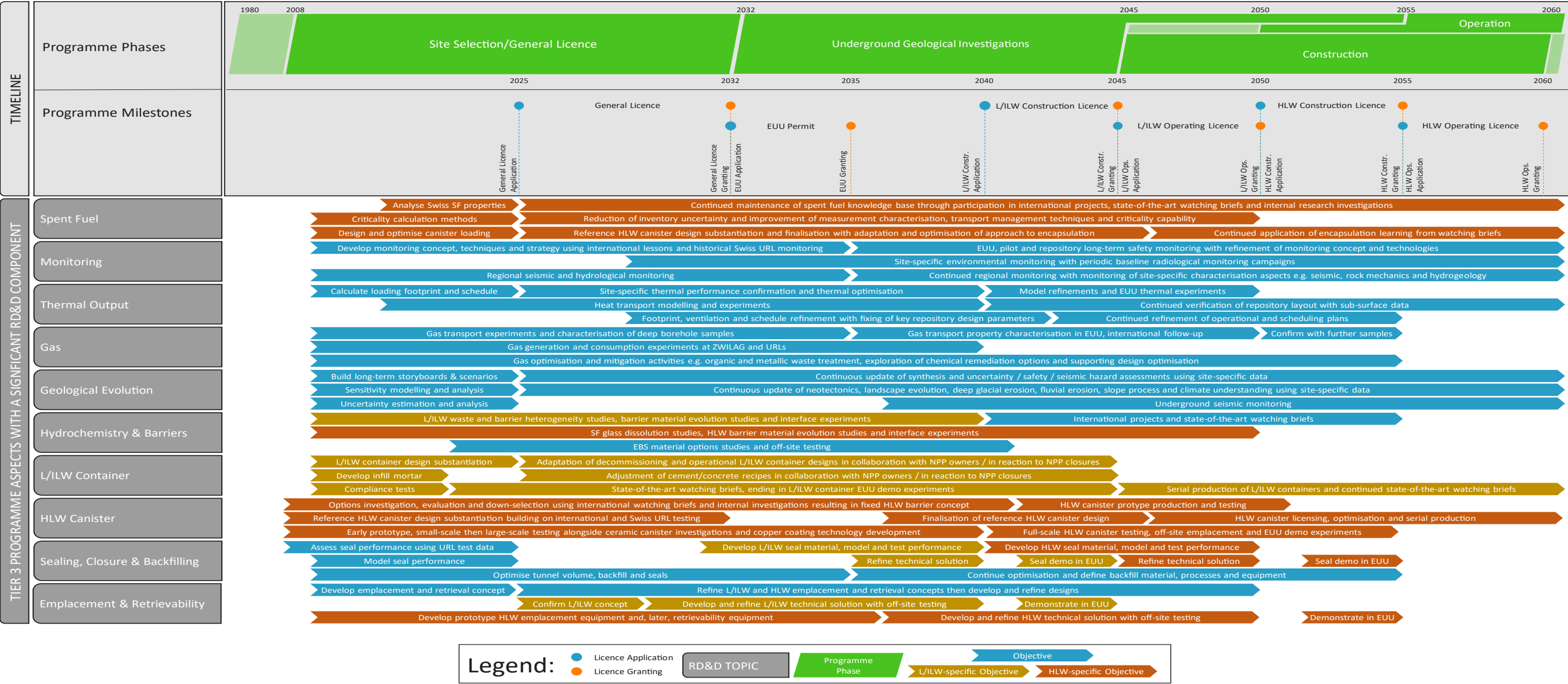


Fig. 7-1: Strategic summary of the ten Tier 3 roadmaps

7.1 Spent fuel

The Tier 3 Spent Fuel roadmap captures the work required to understand the spent fuel inventory and its properties, along with the manner in which spent fuel assemblies will be encapsulated in a dedicated facility, either on site or off. The current status of the topic, including the progress made during the last five years, is captured in more detail in Sections 8.3.1, 8.3.4 and 8.3.5. The corresponding roadmap graphics are included in Appendix A3, Fig. A3-4.

This roadmap covers the investigation and assessment of spent fuel (SF) assemblies that have undergone interim storage and the improvement of the methods used to assess the properties of spent fuel assemblies. An important aspect to be addressed is the potential degradation undergone by spent fuel assemblies during their operating lifetime and the subsequent period of interim storage. This roadmap includes the development of methods for managing degraded and/or damaged spent fuel assemblies. The outcome of these investigations will be used to underpin the post-closure safety case submitted with each licence application (including criticality assessments).

This roadmap also communicates a major aspect of repository implementation: the development of a solution for loading the spent fuel inventory into HLW canisters in a future encapsulation plant. International operational experience is expected to be useful.

The majority of the analysis work is planned up to the submission of the general licence applications, and the focus of investigations after 2024 will depend on the findings up to that point. The overarching spent fuel disposal solution is paired closely with the schedule for closure and decommissioning of Swiss nuclear facilities, which will provide important input for reducing uncertainties relating to the inventory and an expansion of the spent fuel knowledge base.

The activities in the Spent Fuel roadmap are organised across three distinct workstreams:

- **Research investigations:** The aim of this workstream is to improve the understanding of SF assembly properties following their interim storage, increasing confidence in the characterisation and quantification of SF assembly evolution for optimised encapsulation and, ultimately, disposal.
- **Inventory management:** This workstream aims to ensure that the properties of the Swiss spent fuel inventory are sufficiently determined and understood in order to underpin, and ensure compliance with, the safety case assumptions and granted licences.
- **Spent fuel encapsulation:** The aim of this workstream is to ensure that Nagra develops a safe, feasible spent fuel encapsulation solution that is adapted to the Swiss spent fuel inventory and in line with international state of the art and best practice.

Present (2021) to general licence applications (2024)

Nagra will continue its long-standing involvement with research investigations in international projects. These will drive and support internal work on understanding the criticality and thermal limits associated with loading several SF assemblies together in the current disposal canister based on assumptions from the latest MIRAM. For the general licence applications, the canister loading strategy will be optimised with regard to the thermal output criterion, minimising the number of canisters needed while ensuring associated safety boundaries are respected.

Materials from Swiss SF assemblies will be analysed to understand the degree to which the properties of the spent fuel inventory can be expected to evolve throughout the lifecycle of the Nagra programme, especially with regard to long-term dry interim storage.

For inventory management, projects will continue with national and international partners to quantify uncertainties regarding spent fuel properties (nuclide inventory, decay heat, etc.). Their results will be used for the refinement of the MIRAM document supporting the *RBG* in preparation of the safety case.

The continued review and evaluation of the current design for the spent fuel encapsulation plant will ensure a safe and feasible concept for the general licence applications.

Period from 2025 to granting of general licences and *EUU* licence application (2032)

Following the submission of the general licence applications, the continuation of much of the research investigations will depend on initial results. Nagra will continue its involvement with, and watching brief of, international spent fuel investigations.

As Swiss nuclear power plants cease operation over time, the characteristics of a greater volume of SF assemblies depending on actual lifecycle history will be known and available for analysis. A dedicated database will be developed to capture the relevant characteristics. This will allow Nagra to reduce inventory uncertainties and thereby optimise operations and design concepts. For that purpose, a dedicated database will be developed and maintained.

At this stage, the majority of spent fuel encapsulation work will focus on international experience and best practice, as no decisions with regard to an on- or off-site location of the encapsulation plant are expected to be made during this period.

Period from 2032 to granting of HLW operating licence (2060)

Following the submission of the *EUU* licence application, much of the previous work in spent fuel research will continue, further reducing uncertainties and refining and expanding the knowledge base. The latest understanding in these areas will be used to underpin the post-closure safety case and the operations concept associated with each licence application, up to and beyond the submission of the HLW operating licence application.

As the SF encapsulation plant (*BEVA*) moves into a phase of more detailed design development, the adaptation and optimisation of technologies relating to spent fuel become more important. This is also true of experience from international programmes on all associated techniques, technologies and equipment. In parallel to design development activities, *BEVA* operating concepts and associated systems and software will be advanced, leading to the submission of the HLW operating licence application.

Throughout the programme, the understanding of the Swiss inventory for disposal will be improved and associated uncertainties reduced, particularly as Swiss nuclear facilities undergo closure and decommissioning. Improved measurement and characterisation techniques will enable waste package measurement criteria to be developed, supporting the licence applications.

International collaboration will continue to be important from a spent fuel perspective up to and beyond the beginning of *BEVA* construction. The proposed Nagra solution will use all available relevant knowledge from other programmes and will be state of the art.

7.2 Monitoring

The Tier 3 Monitoring roadmap captures the work that underpins the development and implementation of the monitoring programmes, along with the associated technology and concept development needs up to and including the granting of the HLW operating licence. Monitoring related to EIAs and radiological emissions from the repository facilities is defined to be outside the scope of this roadmap. The Monitoring roadmap forms an important part of the Nagra disposal programme, as monitoring activities will start before underground investigations take place and will continue long after waste emplacement operations have ceased. The current status of the topic, including the progress made during the last five years, is captured in more detail in Section 8.7. The corresponding roadmap graphics are included in Appendix A3, Fig. A3-5.

In the near-term, the major focus of the monitoring programme is on developing and completing an overarching monitoring concept for the general licence applications. This will set out monitoring strategies, parameter selection and measurement techniques. The overarching monitoring concept will evolve as new information becomes available, and updates will be published periodically to communicate this.

In the intermediate term, site-specific surface and underground monitoring data will be acquired for baseline measurements, site characterisation, the assessment of performance targets and to support construction activities.

From 2045, the major focus will be on the pilot repositories, where data will be used to confirm the accuracy of predictions around the very early evolution of the repository. Throughout the programme, monitoring activities will support stakeholder communication efforts, ultimately contributing to increased stakeholder confidence.

The activities in the Monitoring roadmap are organised across four distinct workstreams:

- **Implementation:** This workstream aims to ensure that a feasible concept for monitoring is developed and carried out using the best and most suitable technologies available.
- **Monitoring supporting long-term safety:** This workstream aims to ensure that the right types of monitoring data are available in sufficient quality and quantity and in a timely manner to support the respective safety cases.
- **Monitoring supporting site characterisation:** This workstream aims to ensure that monitoring data are available to improve the understanding of the site to a suitable level of confidence. The purpose of these data is to provide evidence of the undisturbed system prior to any construction activity, as well as the basis for assessment of the performance targets.
- **Environmental monitoring:** This workstream aims to provide data for demonstrating that regulations and legal requirements are met by the evolving disposal system. Prior to any construction activity, an accurate picture of the undisturbed environment will be developed. Once construction starts, the environmental monitoring assesses potential differences between monitored data and the baseline. This workstream will also include the compulsory radiological monitoring of the surrounding environment before radioactive waste emplacement operations begin.

Present (2021) to general licence applications (2024)

Monitoring activities in the siting regions, which have been ongoing for many years, will continue to provide data for site selection and the general licence applications. In addition, work on evaluation and further development of monitoring technologies will continue through experiments in the underground research laboratories (URLs) within the framework of the RD&D programme and through projects such as the EURAD MODATS work package (Monitoring Equipment and Data Treatment for Safe Repository Operation and Staged Closure).

An overarching monitoring concept will be developed, outlining the holistic integration of the monitoring programmes and needs. This is key to the general licence applications, as monitoring is an activity that will be embedded into all phases of the disposal programme. The concept will define the technological needs for the entire monitoring programme, thus allowing the underpinning RD&D to be specified and carried out. As more data become available in subsequent programme phases, the concept will be updated and refined periodically.

Period from 2025 to Granting of general licences and *EUU* licence application (2032)

The preparations for the *EUU* licence application will be supported by the implementation of the site-specific atmosphere, groundwater and surface water monitoring programme and additional Global Navigation Satellite System (GNSS) and seismic stations. Prior to sinking of the first shaft, sources of underground data will be restricted to boreholes (and geophysics). Detailed planning and RD&D for other monitoring programmes, starting with monitoring to be carried out in the *EUU* facilities, will be conducted.

Period from 2032 to granting of *EUU* licence (2035)

Detailed surface-based monitoring of the site will take place. Geotechnical monitoring will begin, and the first radiological baseline measurements will be performed. Deep groundwater monitoring will be enhanced. Close interaction with the engineers leading the shaft and tunnel construction will ensure a comprehensive monitoring strategy and effective monitoring data once the *EUU* licence is granted.

Period from 2035 to L/ILW construction licence application (2040)

As construction of the *BEUU* access and the underground facilities begins, instrumentation will be set up to monitor site-specific underground parameters. This will be used to verify and/or update the models that underpin the repository design, safety case and construction.

Geotechnical parameters will be particularly important for ensuring operational safety and the feasibility of maintaining underground facilities for the duration of the repository operational period and the subsequent monitoring period.

The first experiments for L/ILW performance verification in the facilities for *EUU* will be started and monitored. In addition, RD&D work will begin on the refinement of the overarching monitoring concept.

Period from 2040 to L/ILW operating licence application and granting of L/ILW construction licence (2045)

Infrastructure will be established to monitor the *EUU* L/ILW performance confirmation investigations and in-situ demonstrations that will take place during this period, and similar HLW investigations and experiments that will take place beyond 2044.

The monitoring RD&D programme will continue to progress, driven by a period of monitoring technology review to ensure the use of the best available technologies. The project for the L/ILW pilot repository monitoring programme will be submitted.

Period from 2045 to granting of HLW operating licence (2060)

Much of the instrumentation used for monitoring the pilot repositories will continue to be used throughout the programme, up to and beyond the closure of the entire repository. However, where technological advances are found to be beneficial and implementable, the monitoring equipment and processes will be updated. The focus will be on attaining better quality and more accurate monitoring data throughout the duration of the programme.

Monitoring of the *EUU* HLW performance confirmation investigations will take place. In parallel, the second extensive baseline measurement campaign for radiological environmental monitoring will be performed.

Regular radiological environmental monitoring will be established and continued throughout the programme. Monitoring information will be periodically reported to the regulatory authorities along with the monitoring of radiological emissions from the repository facilities, although the latter is outside the scope of this roadmap.

RD&D for the selection, development and quality assurance of the measurement techniques, sensors and data management for monitoring the HLW pilot repository will be concluded. The project for the HLW pilot repository monitoring programme will be prepared, submitted and initiated.

7.3 Thermal output

The Tier 3 Thermal Output roadmap captures the work required to ensure that the impact of decay heat from SF and HLW does not affect the safety functions of the engineered and natural barriers and that the repository is optimised from an implementation point of view. This roadmap addresses the HLW repository only as the L/ILW inventory will not emit a significant amount of heat. The current status of the topic, including the progress made during the last five years, is captured in more detail in Sections 8.2.2.4, 8.5.2.1, 8.5.3.3 and 8.5.3.4. The corresponding roadmap graphics are included in Appendix A3, Fig. A3-6.

This roadmap concerns the in-depth understanding of thermal impacts of the heat-emitting wastes on the thermo-hydro-mechanical (THM) evolution of the repository near-field. This includes the compilation of THM-related databases, the execution of dedicated laboratory programmes and in-situ experiments in generic URLs during the early programme phases and a complementary experimental programme as part of the *EUU* for the verification of THM-related process and system understanding.

Validation exercises are ongoing to build confidence in heat transport models which will then undergo refinement in the future. Calibrations of thermal properties of the engineered and natural barriers are undertaken.

Thermal optimisation of repository components and of the entire repository will begin, driven by THM model benchmarks and thermal property calibrations. These will be continued and refined in the context of the *EUU* at the final repository site.

A reduction of the uncertainties associated with the thermal source term is expected in the longer term due to the refined estimates of the inventory and the increased insight into the selected site. Thermal optimisation of the repository design and waste emplacement procedures will be continued and integrated into the overall optimisation process (as described under Tier 2 of the Roadmap) until the HLW construction licence application.

The activities in the Thermal Output roadmap are organised across five distinct workstreams:

- **Thermal performance assessment:** Thermal safety criteria, site-specific storyboards and site-specific databases are formulated, revisited and tailored throughout each phase of the repository lifecycle, aimed at developing a robust and complete post-closure safety analysis.
- **Heat transport in the repository:** This workstream aims to develop understanding of heat transport in the HLW near-field and the surrounding host rock, the development and validation of modelling tools for thermal performance assessment and the development and international benchmarking of data and models.
- **Thermal source term optimisation:** Estimates of the thermal source term are derived from the inventory and, in particular, from the estimated amount of waste that will be produced until the final shutdown of the NPPs. Hence, with each revision of the inventory, the inherent uncertainties associated with the thermal source term will be further reduced in the course of the programme.

- **Repository engineering & design optimisation:** Thermal optimisation of individual repository components and the entire repository will be an ongoing process up to the submission of the HLW construction licence application as part of the overall optimisation in Tier 2. This workstream aims to convey the shift from generic to site-specific aspects of repository layout, capturing the necessary focus on feasibility from the near-term onwards.
- **Repository construction and waste emplacement schedule:** This workstream has been initiated at a generic level as part of the storyboard development in the context of site selection. The aim is to highlight the necessary thermal optimisation of the waste emplacement schedule in the late stage of the *EUU*, when the uncertainties regarding the source term and the site-specific repository design have decreased substantially.

Present (2021) to general licence applications (2024)

Previous RD&D has focused on building up a broad knowledge base on heat transport in clay-rich barriers and the development of a generic workflow for thermal design of the repository. This includes the compilation of THM-related databases, the execution of dedicated laboratory programmes and in-situ experiments in generic URLs. The current stage of the programme is dedicated to the development of a traceable methodology for thermal performance assessment and repository optimisation, which will be revisited in future stages of the programme.

Deterministic and probabilistic sensitivity analyses on the thermal evolution of the HLW repository have been conducted in order to design and optimise the repository layout at a generic level with respect to thermal impacts (e.g. footprint area and canister pitch). Site-specific optimisation in the context of the general licence applications and subsequent phases of the *EUU* will concentrate on robust design with regard to long-term safety and cost.

During the site selection process, site-specific storyboards and databases will continue to be developed and paired with thermal safety criteria. This will allow comparison of the repository projects from the perspective of thermal impact and delineation of the most suitable HLW repository location in each of the three siting regions.

Traceable workflows for thermal performance assessments have been developed and tested with site-specific information from geological findings from the deep borehole campaign (*TBO*) and from 3D seismic surveys. After successful site selection, a robust site-specific repository project will be elaborated for the general licence applications, which has been optimised with respect to thermal impacts.

Validation exercises have been launched on international platforms (Sections 8.2.2.4 and 8.5.2.1) to build confidence in heat transport models. This ties in with the ongoing calibrations of thermal properties of the engineered and natural barriers.

Period from 2025 to granting of *EUU* licence (2035)

Beyond the general licences, generic activities will gradually be replaced by site-specific thermal assessments. Conceptual and parametric uncertainties will be reduced by developing refined storyboards and updated geological databases.

New experiment data will feed into an updated thermal performance assessment, which involves sensitivity analyses, uncertainty assessment and robustness assessment. The performance assessment will be used to update the interim post-closure safety analysis prior to the HLW construction and operating licences.

Thermal optimisation of repository components and of the entire repository, THM model benchmarks and thermal property calibrations will be continued and refined in preparation for the *EUU*. Maximum benefit will be derived from international developments and collaborations to keep the knowledge base state of the art, thus providing further confidence in the predictive capability of the THM modelling tools.

Period from 2035 to granting of HLW operating licence (2060)

Once access to the underground is available, a significant increase in volume, specificity and quality of data is expected. Thermal *EUU* experiments aimed at verifying and consolidating the understanding of the THM evolution of the repository near-field will be of particular importance. The predictive capacity of the THM modelling tools will be improved using site-specific information in terms of THM rock properties and the associated site conditions.

Data from the *EUU* will feed into an updated thermal performance assessment, where the thermal safety criteria, site-specific storyboards and site-specific databases will be revisited again and used to update the post-closure safety assessment. This will then feed into the overall optimisation process and corresponding design for the construction licence, ultimately resulting in a robust and complete post-closure safety analysis of the repository project when submitting the construction licence application.

As also shown in the Tier 3 Spent Fuel roadmap (Section 7.1), throughout the programme, understanding of the Swiss inventory for disposal will be improved, associated uncertainties (affecting heat output) will be reduced and the knowledge base surrounding the inventory for disposal expanded, particularly as Swiss nuclear facilities undergo closure and decommissioning.

Following the submission of the HLW operating licence application, the thermal evolution of the repository near-field will be monitored in the pilot repository, providing further evidence for performance verification during the lifetime of the pilot repository.

7.4 Gas

The Tier 3 Gas roadmap captures the work aimed at ensuring that the impact of gas generated by the corrosion of metal components and the degradation of the organic waste does not affect the safety functions of the engineered and natural barriers. The current status of the topic, including the progress made during the last five years, is captured in more detail in Sections 8.2.2.2, 8.3.3.5, 8.5.2.2, 8.5.3.2 and 8.5.3.3 and 8.5.3.4. The corresponding roadmap graphics are included in Appendix A3, Fig. A3-7.

This roadmap covers refinement of the understanding and quantification of how gas is generated, how it is transported in the engineered and natural barriers, and how it finally dissipates. In the generic stage of the programme, this is based on laboratory, URL and desk-based studies aimed at the definition of a performance envelope. Gradually, the focus of the work will shift to the site-specific properties (based on geological information from the deep borehole campaign (*TBO*) and *EUU* activities) to provide input for the safety concept leading up to the detailed design for the construction licence applications. This roadmap addresses both the HLW and the L/ILW repositories; however, most gas generation occurs in the L/ILW repository and the topic is therefore of greater relevance to the L/ILW repository.

Before the submission of the general licence applications, a wide range of options are open to accommodate a broad range of site-specific conditions and mitigate larger uncertainties in the performance assessment. As the design becomes more detailed, decisions have to be taken as to which options to include so that they can be further developed and included in the construction licence applications.

The activities in the Gas roadmap are organised across four distinct workstreams:

- **Gas performance assessment:** Gas-related safety criteria are formulated as part of the post-closure safety analysis. The safety-relevant impact of the gas is reduced in the process and over the different programme stages. It is affected by the repository concept and layout, the final metal and organic content of the wastes as well as their condition and the geological properties of the site(s).
- **Gas transport:** Through large- and small-scale experiments and modelling, this workstream develops understanding of how gas transport occurs under repository-relevant conditions, both in the engineered and the natural barriers.
- **Gas generation and consumption:** This workstream describes how much gas is produced, from which part of the waste and how fast this occurs. Mechanisms that potentially consume gas are also assessed.
- **Gas optimisation and mitigation:** This workstream screens and develops measures to reduce gas pressure build-up with the aim of reducing the amount of gas generated, enhancing the consumption of the gas or increasing the subsurface gas storage volume in the design, as part of the overall optimisation in Tier 2. While these measures are already developed generically today, final decisions on which measures to include in the design will have to be taken prior to the construction licence applications.

The bulk of the work for the "Gas transport" and "Gas generation and consumption" workstreams has already been carried out and is being continued in the current stage of the programme, with verification and confirmation activities scheduled for a later stage.

Present (2021) to general licence applications (2024)

In the current stage of the programme, up to the general licence applications, a large degree of flexibility exists as to how to meet the safety criteria. Furthermore, because no underground access is currently available (although observations in the Mont Terri URL and during the deep borehole campaign are available), the in-situ gas-relevant properties of the host rock cannot be characterised in detail. For the general licences, it has to be demonstrated that several options exist and that these can be implemented to meet the safety criteria with a sufficient margin (similar to Diomidis et al. 2016). This ensures the existence of an adequate process understanding in terms of gas transport and gas generation and consumption for the performance assessments. An extensive RD&D programme is being completed to establish this knowledge base.

Experiments take place at small, intermediate and large scales regarding both gas generation and gas transport, and an analysis and model chain is in place to bridge the temporal and spatial scales (Sections 8.2.2.2 and 8.5.2).

For the general licence applications, the safety margin will be demonstrated for the selected repository project. At that point, underpinning performance assessments will be conducted based on a reliable model abstraction chain, which relies on 1:1 evidence that the Engineered Gas Transport System (EGTS – see insert in Section 8.5.2.2) is a valid option for mitigating gas pressures for the selected site(s) and their characteristics (a basis is given in Diomidis et al. 2016). A bandwidth of gas-relevant properties will be established for the selected site(s) based on the geological

information from the deep borehole campaign, and the proposed repository concept will be tailored to the wider site characteristics. At that point, no final decision will be taken regarding the barrier materials to be used, the conditioning of the waste or whether or not to include bioengineering.

Period from 2025 to granting of *EUU* licence (2035)

Beyond the general licence applications, several of these activities will be continued to broaden the knowledge base and reduce further uncertainties. These could include long-term corrosion tests or developing the knowledge base for microbial degradation of the gas. Maximum benefit will be derived from international developments and collaborations to keep the knowledge base state of the art.

In parallel, decommissioning plans for the remaining power plants will have progressed and the case for metal waste reduction (melting) will be investigated. In the unexpected case of additional findings that would aggravate gas pressure build-up, melting as a measure to reduce the gas source term can be evaluated to re-establish the required safety margin.

Period from 2035 to L/ILW construction licence application (2040)

Once access to the underground is available, a significant data gain is expected. The bandwidths of the gas-relevant properties will be reduced through in-situ characterisation of the host rock. In the *EUU*, gas properties will be characterised, and gas transport and self-sealing performance confirmation experiments are foreseen. Based on the geological information gained in the *EUU*, the repository design is expected to be further developed. This phase will be important for further optimisation of the gas safety margin. At that point in time, the different options will be tested and the materials for the engineered barriers will be pre-selected. The final layout of the EGTS will also be decided and a decision will be made on whether or not to actively pursue additional measures.

Through an intensive iteration process taking into account the state of the art at the time, the final repository layout will be moved forward. Technology development and surface-based testing will take place as necessary. Further experimental work will be conducted if bioengineering is pursued. Additional testing will be conducted for the barrier materials if these are different and more promising than those proposed for the general licence applications. If necessary, the surface-based construction of the EGTS components will be tested and the corresponding technology will be developed. With the submission of the construction licence application, the major decisions regarding the gas-related issues will be fixed. At that time, the safety margin for the gas-related safety criteria will be clarified accurately.

Period from 2040 to granting of HLW operating licence (2060)

The gas-related activities for the submission of the HLW construction licence application will follow a similar workflow as described above for L/ILW. However, the expected effort will be much lower, as much of the knowledge will already have been acquired for the L/ILW construction licence application, and gas generation does not have a similar impact in the case of the HLW repository.

The measurement of gas-related parameters (other than hydraulic pressure) in the pilot repository is not anticipated, as the gas-generation process is deemed too slow to provide relevant information for performance confirmation during the lifetime of the pilot repository. This will be re-evaluated in the context of the next licensing steps.

7.5 Geological evolution

The Tier 3 Geological Evolution roadmap gathers data with respect to neotectonics, climate evolution and erosion to determine the potential consequences for host rock properties and radionuclide transport and release pathways over the period of concern. The current status of the topic, including the progress made during the last five years, is captured in more detail in Section 8.2.1.5. The corresponding roadmap graphics are included in Appendix A3, Fig. A3-8.

This roadmap describes a part of the safety assessment and site characterisation that requires special attention given the location of the siting regions in the vicinity of the Alps. It comprises the assessment of the main relevant erosion processes that reduce the stratigraphic column above the host rock and the understanding of seismic activity (fault rupture and shaking) that could impact the engineered and natural barriers within the repository area. The programme builds on desk studies, field data collection and numerical modelling that feed into the development of scenarios and an evaluation of uncertainties. Both the HLW and L/ILW repositories are addressed but, due to the longer period of concern, the HLW repository is of greater relevance to safety. Focused data interpretation and localised gathering of additional data on important topics will allow the integration and development of storyboards and will provide evaluation constraints for safety analyses.

In the intermediate term, the focus will be on site-specific evaluation (e.g. remaining overburden, probabilities of glacial excavation, fault-slip tendency), ultimately providing input for the safety concept, including a contribution on the spatial optimisation of the containment-providing rock zone.

Following the submission of the general licence applications, the focus of the erosion programme will shift to the mitigation of larger uncertainties and to refining the updated safety analysis for the selected site(s). Long-term seismic and geodetic monitoring and the development of a concept and workflow for site characterisation and seismic hazard assessment will then form a significant part of the neotectonics research programme.

The activities in the Geological Evolution roadmap are organised across six distinct workstreams:

- **Storyboard & scenario building:** Development of simplified models and scenarios, including an estimated range of uncertainties. Definition of indicators to provide evaluation constraints for the erosion criterion.
- **Neotectonics:** Neotectonic characterisation of the main faults in Northern Switzerland, geodynamic modelling and the illustration of rupture and shaking hazards.
- **Quaternary landscape evolution of Northern Switzerland:** Development of a database for spatio-temporal landscape evolution with illustration of driving processes and rates. This workstream is about understanding the past one to two million years as a key to understanding the next one million years.
- **Fluvial erosion & slope processes:** Process understanding of fluvial incision including sensitivity analyses on the main drivers and the denudation of local topography.
- **Deep glacial erosion:** Process understanding of climatic, glacio-dynamic and subglacial conditions for deep glacial erosion, including a conceptual basis for the radiological consequences of repository excavation.
- **Climate:** Climatic conditions for landscape evolution in Northern Switzerland in the past and future. This workstream includes global and regional modelling as a basis for the evaluation of future glaciations, erosion potential and biosphere modelling.

Present (2021) to general licence applications (2024)

In the current stage up to the submission of the general licence applications, most efforts lead to the site-specific evaluation of erosion effects. The assessment of future deep glacial erosion is a particular challenge due to large uncertainties and limited process understanding. A range of state-of-the-art scientific methods (e.g. age control of past landscape evolution) will be employed and supported by an extensive RD&D programme. Nagra's long-term geological evolution project provides the storyboards and the evaluation of the related site-selection criteria on erosion and neotectonics (Section 8.2.1.5). For the selected site(s), this project delivers the geological evolution knowledge base for the general licence applications.

Period from 2025 to granting of general licences and *EUU* licence application (2032)

Once the general licence applications are submitted, the erosion aspects of the programme will be reduced. During this period, international developments and collaborations will be used to broaden the knowledge base where possible and/or necessary. Tailored studies may investigate site-specific effects if necessary (e.g. ice, permafrost, or ice-fluvial interactions) or provide vegetation maps and future climate scenarios for biosphere evaluations. Monitoring of seismicity and geodetic measurements of deformation will continue.

Period from 2032 to granting of *EUU* licence (2035)

Before the *EUU* licence is granted, the storyboard will be updated and, if necessary, the methodologies revised based on state-of-the-art developments. During this period, a concept and workflow for site characterisation and seismic hazard assessment will be developed, and the surface seismic and geodetic monitoring programme will be intensified.

Storyboards and the knowledge base with respect to neotectonics and erosion will be updated for the safety analysis. Shallow subsurface investigations of potentially active faults and surface seismic monitoring activities are closely linked to these.

Period from 2035 to L/ILW construction licence application (2040)

During this period, the focus is on supporting the seismic hazard assessment and analysis of long-term seismic monitoring that will now also start from the subsurface in the *BEUU*. International development and collaboration are again used to broaden the knowledge base with respect to erosion and to further reduce uncertainties.

Period from 2040 to granting of HLW operating licence (2060)

A concept and workflow for site characterisation and updated safety and seismic hazard assessments for HLW will be in place by the end of 2049, allowing optimisation with respect to the development of the repository design. This will include updating the storyboards, methodologies and knowledge base for the safety analysis with respect to neotectonics and erosion. Long-term seismic monitoring is closely linked to this work.

7.6 Hydrochemistry & barriers

The Tier 3 Hydrochemistry and Barriers roadmap captures the work aiming to ensure that the impact of the hydrochemical evolution of the near-field does not affect the safety functions of the engineered and natural barriers. The current status of the topic, including the progress made during the last five years, is captured in more detail in Sections 8.3.3 and 8.5.3. The corresponding roadmap graphics are included in Appendix A3, Fig. A3-9.

This roadmap covers the refinement of the understanding and the quantification of processes and phenomena related to the chemical evolution, interaction and degradation of the waste inventory, repository components and engineered barriers. In the generic stage of the programme, this is based on laboratory, URL and desk studies aimed at narrowing down the relevant processes and phenomena. In the longer term, the work focuses on a well-characterised inventory of materials and ultimately provides input for the safety concept leading up to the detailed design for the construction licence applications. This roadmap addresses both the HLW and the L/ILW repositories. However, spent fuel dissolution is only looked at in the context of a HLW repository, while the heterogeneity aspect of the waste is only relevant for the L/ILW repository.

During the early stages, the waste inventory (especially the L/ILW inventory) is partially based on modelling assumptions, but uncertainties will gradually be reduced towards the submission of the construction licence applications, as power plants shut down and decommissioning takes place.

The activities in the Hydrochemistry and Barriers roadmap are organised across four distinct workstreams:

- **Performance assessment:** This workstream focuses on the impact of the chemical evolution in the near-field in the context of PA-relevant aspects, e.g. the lifetime of an HLW canister that will be determined based on corrosion rates that are, in turn, affected by the porewater composition.
- **Hydrochemical impacts:** This workstream illustrates how modelling, small- and large-scale experiments will be used to develop the understanding of how the different materials involved (including the wastes itself) will interact, from a chemical and microbial point of view, throughout the evolution of the repository.
- **Design:** This workstream describes how the different material options in the near-field will gradually be narrowed down in future licensing steps.
- **Off-site testing and demonstration:** This workstream describes the experiments demonstrating safety that are initially conducted in a generic environment and will ultimately be demonstrated off site for specific issues once the final materials are selected.

Present (2021) to general licence applications (2024)

In the current stage of the programme, up to the submission of the general licence applications, flexibility exists to meet the safety criteria, e.g. by considering different recipes for the cementitious backfill. The Nagra barrier concept will be submitted with the general licence applications, but several options that can be implemented with today's technology and meet the safety criteria with a sufficient margin will remain open, e.g. canister materials, cement recipes or emplacement strategies for L/ILW packages. It will thus be ensured that process understanding in terms of chemical evolution exists so that the barrier performance can be assessed. An extensive RD&D programme is being completed to establish this basis.

The safety margin for the selected concept will be demonstrated and included in the site-specific post-closure safety case. At this stage, international projects and URL testing of sealing materials will underpin PA activities.

It will be shown that the chemical evolution of the HLW near-field is well understood and that remaining uncertainties are not relevant to long-term safety, e.g. corrosion rates will be documented for the different environments to be used in the PA for the prediction of canister lifetime and gas pressure evolution. Understanding of the chemical evolution at material interfaces such as sealing elements and backfill will allow for a spectrum of potential material choices. The assessment of the heterogeneity in an L/ILW repository will allow an estimation of how the chemical interactions in L/ILW could impact the performance of the repository.

Period from 2025 to granting of *EUU* licence (2035)

Several ongoing activities will continue beyond the submission of the general licence applications, broadening the knowledge base and reducing uncertainties. Alternative concepts, potentially using alternative materials, will be assessed in the context of optimisation. Supporting this optimisation will be a number of long-term experiments, e.g. the investigation of material corrosion and degradation rates, which will improve confidence and further reduce uncertainties through additional data collection. A sufficiently wide choice of materials for the barrier system exists so that, if findings during this period affect the current material choice, these findings may be considered and addressed through studies of the material options.

International developments will be followed closely and opportunities for collaboration will be fully utilised. This will support the development and maintenance of in-house competences and ensure that the Nagra knowledge base remains state of the art. In parallel, decommissioning plans for the remaining power plants will progress, further reducing uncertainties with respect to the waste inventory.

Geochemical aspects, such as the chemical interactions between repository materials, are part of the off-site testing and will be assessed in detail to support overall repository design decisions and material choices.

Period from 2035 to HLW construction licence application (2050)

Focused studies on hydrochemical aspects will continue, and maximum benefit will be taken from international collaboration, especially for issues related to the HLW repository. These will further refine the storyboards that feed into the hydrochemical performance assessment.

Off-site testing at various scales will allow the definition and later the performance verification of most of the materials and designs that must undergo a PA, leading to the submission of the L/ILW construction licence application and later the HLW construction licence application.

7.7 L/ILW container

The Tier 3 L/ILW Container roadmap captures the work necessary to ensure that the current container designs for packaging L/ILW waste remain suitably state of the art for disposal of all decommissioning and operational wastes generated during the remainder of the operational lifetime of the Swiss nuclear power plants. The current status of the topic, including the progress made during the last five years, is captured in more detail in Sections 8.4.6, 8.4.7, 8.5.3.2 and 8.5.3.5. The corresponding roadmap graphics are included in Appendix A3, Fig. A3-10.

In the near term, the focus is on the final design substantiation and testing of the current designs. This transitions into a longer period of updates and adaptations to account for the international state of the art and any changing needs of nuclear power providers in the coming decades.

The activities in the L/ILW Container roadmap are organised across three distinct workstreams:

- **Performance assessment:** The aim of this workstream is to ensure that the container and its constituent materials are suitably durable for handling operations throughout the operational phase and for long-term safety performance targets following repository closure.
- **Design optimisation:** The aim of this workstream is to communicate the potential adaptations to the current, mature container designs that may be necessary in order to meet new requirements as the Swiss nuclear power plants close in the coming decades.
- **Off-site testing and demonstration:** The aim of this workstream is to communicate the testing that may be undertaken both outside the repository infrastructure and in situ, once the *EUU*, pilot repository and L/ILW repository are constructed and available for use.

Present (2021) to general licence applications (2024)

With the current container design for decommissioning waste in place, the design for operational waste will undergo further development. Leading into the general licence applications, a design for both types of containers and tested container infill mortar will be in place.

Investigations and international watching briefs on metal corrosion and cement properties will take place and continue up until the granting of the L/ILW operating licence.

Period from 2025 to L/ILW construction licence application (2040)

Much of the design work around the L/ILW containers is expected to have been completed by 2024 and the primary focus of this period will be on adaptations and adjustments, if necessary, resulting from NPP closure and decommissioning.

The focus here will be on developing equipment and procedures for emplacing and retrieving the L/ILW containers in the emplacement caverns, which will be constructed from 2044 onwards, with a technical solution in place for the L/ILW construction licence application.

Period from 2040 to granting of HLW operating licence (2060)

Final refinements will be made based on regulatory discussions, following the submission of the L/ILW construction licence application and in-situ demonstrations in the *EUU*, where prototype containers will be handled, emplaced and retrieved in conditions replicating the L/ILW repository caverns. Having been proven to be feasible in situ, this refined design will form part of the L/ILW operating licence application.

Once the operating licence application is submitted, final container optimisation will be carried out from a manufacturing perspective. This will ensure that serial production may begin in time for a store of containers to be ready for emplacement once the L/ILW operating licence is granted. Following this, operations will continue until 2065.

7.8 HLW canister

The Tier 3 HLW Canister roadmap captures the work necessary to develop an appropriate packaging concept for HLW disposal, develop a detailed design for the HLW package (referred to as a canister), licence the canister and manufacture the as-licensed design. The roadmap includes the underpinning research needed to optimise the design and to verify its performance in line with relevant safety criteria through a robust assessment process. The current status of the topic, including the progress made during the last five years, is captured in more detail in Sections 8.4.5 and 8.5.3.1. The corresponding roadmap graphics are included in Appendix A3, Fig. A3-11.

In the near term, a canister concept will be advanced primarily through internal design development activities. Collaborative investigations with, and learning from the experience of, international research and waste management organisations will contribute to the PA and development of alternative canister options.

The majority of the HLW canister design development will take place over the intermediate term of the Nagra programme as significant decisions to fix design elements will be made around 2040. As more site-specific information (e.g. detailed stress conditions) becomes available at this time, and the canister testing programme ramps up, verification of the canister performance within the relevant safety margins will take place and the canister design will be adapted appropriately.

Beyond 2045, the majority of the canister design work will be complete, and the programme will focus primarily on the industrial ramp-up: licensing, manufacturing optimisation and serial production. Industrial optimisation, which will primarily take the form of technology development and adaptation to improve efficiency, will continue throughout the operational phase during which canister production will take place.

The activities in the HLW Canister roadmap are organised across six distinct workstreams:

- **Performance assessment:** The aim of this workstream is to analyse the long-term performance of the canister, including an evaluation of the processes which will occur after emplacement, and provide evidence in support of the canister lifetime predictions. Activities here will be carried out in collaboration with external organisations.
- **Options evaluation:** This workstream investigates the feasible options for HLW disposal and aims to ensure that sufficient consideration has been given to alternatives. These evaluations will build on Nagra investigations, but will primarily look towards external collaboration, international understanding and international experience as a method of determining feasible alternatives to the current Nagra canister design.

- **Design:** The aim of this workstream is to communicate the staged process for the entirety of the canister design and its maturity in the context of improved understanding of the site(s) and the overarching repository system over time. The activities in this workstream focus on advancing the current canister design primarily through internal design development work.
- **Off-site testing:** The aim of this workstream is to communicate the testing that may be undertaken outside the repository infrastructure to ensure that in-situ testing and demonstration can be carried out once the *EUU*, pilot repository and HLW repository are constructed.
- **Technology development:** This workstream outlines the necessary supporting technologies that must be available to manufacture and emplace a licenced HLW canister.
- **Demonstration & optimisation:** The aim of this workstream is to illustrate the activities that will be necessary for licensing and manufacturing the final canister design as part of the overall optimisation in Tier 2.

Present (2021) to granting of *EUU* licence (2035)

The current canister concept (carbon-steel-based canister) will continue to undergo small-scale testing in dedicated facilities (e.g. the Swiss URLs), which will support design confirmation activities. The current investigation into copper-coating technologies will continue, substantiated by research activities into corrosion rates and canister lifetime modelling.

Prior to the submission of the general licence applications, the latest understanding will be captured in a specific canister design report, along with a PA of the canister design contained therein. A second report, presenting the progress of the copper-coated canister concept, will also be produced.

Leading up to the submission of the *EUU* licence application, the canister design substantiation will move towards its final stages, paired with the start of larger-scale canister testing activities.

Period from 2035 to L/ILW construction licence application (2040)

Once the *EUU* licence has been granted, subsurface data will be used to finalise the canister options and evaluation analyses, mature the canister design and accelerate the development of the canister emplacement and backfilling equipment. As these aspects progress, a long period of full-scale testing will begin and run until the submission of the HLW construction licence application. This will build up to the emplacement and retrieval demonstrations using non-nuclear HLW canisters true to size and weight in the same confined conditions that will be found in the repository itself, verifying the safety and feasibility of processes and procedures that will be used in the operational phase. The latest canister design information will be published in a dedicated report around 2040.

Period from 2040 to granting of HLW operating licence (2060)

Around 2040, certain elements of the HLW canister and repository design will be fixed or options substantially narrowed down to allow design adjustments to take place and the testing programme to continue, using equipment and conditions that are identical or very close to those that will be experienced in repository operation. The mature canister design will undergo a process of performance evaluation in the context of a continually improving understanding of the site-specific geology.

In parallel, a process of canister prototyping will be carried out, allowing Nagra's industrial capability to accelerate towards operational capacity. In-situ demonstration experiments will be carried out in the *EUU* HLW area and the pilot repository, verifying the engineering performance of the as-produced canister, thereby confirming the safety of the design and manufacturing process to support canister licensing, leading into the submission of the HLW operating licence application. From 2055 onwards, only regulator-agreed optimisations to the canister and its production process will take place, leading to the serial production of HLW canisters to allow initial HLW waste emplacement after the granting of the HLW operating licence in 2060.

7.9 Sealing, backfilling & closure

The Tier 3 Sealing, Backfilling and Closure roadmap captures the work required to deliver a solution for sealing the L/ILW and HLW repositories, backfilling the access routes and closing the entire repository in line with the overarching safety performance criteria for the deep geological repository. The current status of the topic, including the progress made during the last five years, is captured in more detail in Sections 8.4.8 and 8.5.3.3. The corresponding roadmap graphics are included in Appendix A3, Fig. A3-12.

This roadmap covers the development and refinement of sealing and closure-related engineered barrier design. This involves understanding and meeting the related safety requirements, developing the final seal designs, defining the backfill material specifications and establishing the final closure concept.

In the near term, the major focus is on the assessment of the current concept for the closure of the repository, ensuring that the required level of performance can be met through both the selected concept and/or any viable alternatives. The assessment is based on surface laboratory, URL and desk-based studies aiming at the definition of a performance envelope. The work gradually focuses on the site-specific properties and, ultimately, ensures the suitability of the safety concept leading up to the detailed design for the construction licence applications.

Before the submission of the general licence applications, a range of closure options is open to accommodate a broad range of site-specific conditions and mitigate larger uncertainties in the PA. Beyond the granting of the general licence applications, the closure concept is refined in parallel with the development of the L/ILW and HLW sealing solutions. Repository sealing, backfilling and closure solutions will undergo a stepwise process of development, from component modelling to the demonstration and refinement of the integrated technical solutions.

The activities in the Sealing, Backfilling and Closure roadmap are organised across five distinct workstreams:

- **Performance assessment:** This workstream outlines how the performance of the repository seals will be assessed against the required criteria, using the seal designs and site conditions as more specific geological data become available over time. Closure-related safety criteria (including sealing and backfilling) are formulated as part of the post-closure safety assessment. The safety margin is optimised in the process and over the different programme phases. It is affected by the repository concept and layout, the final content and condition of the waste and other materials in the repository and the geological properties of the site(s).
- **Design:** This workstream illustrates the underpinning design work on specific aspects and components that supports the design of the overarching repository sealing and backfilling sub-systems, including the incorporation of the PA results.

- **Off-site testing:** The aim of this workstream is to communicate the relevant historical and collaborative testing that underpins the current Nagra repository concept as well as future testing that is expected to be necessary outside the repository area, before in-situ demonstrations in the *BEUU* can take place.
- **Technology development:** This workstream sets out the activities for integrating and refining the sealing, backfilling and closure sub-systems and developing the necessary supporting equipment and procedures for implementing the closure concept, including the installation of the seals.
- **Demonstration & optimisation:** The aim of this workstream is to drive the demonstration activities for a mature sealing, backfilling and closure solution in order to optimise the system as far as feasibility and, primarily, operational safety is concerned, thereby contributing to the overall optimisation in Tier 2.

Present (2021) to general licence applications (2024)

In the current phase of the programme, up to the submission of the general licence applications, flexibility exists with regard to how the safety criteria and requirements can be fulfilled. Therefore, during this period, a number of alternatives/variants for closing the repository will be considered (Nagra 2021g). The existing designs and assumptions will be assessed to ensure that the performance criteria can be met. Substantiating this PA will be valuable experience from collaborative, international testing projects along with historical research on sealing materials that has taken place in URLs over the past two decades (Section 8.4.8). This off-site testing will be supported by the site-specific geological data that will be gathered through the deep borehole campaign (*TBO*) in each of the three siting regions. No final decision regarding the barrier materials or the final design of the individual seals will be taken during this period.

Period from 2025 to L/ILW construction licence application (2040)

The detailed design of the L/ILW seals will start in the lead-up to the *EUU* licence applications and continue until the submission of the L/ILW construction licence application. Supporting this design work, modelling, material development and PA of the L/ILW seals will take place, using the latest geological information to ensure that the seals meet the site-specific criteria for the closure of the L/ILW repository. As the design development matures, the focus will shift towards testing the seals in dedicated off-site facilities, in accordance with an outline for the testing implementation plan. These off-site testing activities will further support the design of the L/ILW seals and the related equipment and procedures. A mature L/ILW seal design and full plan for demonstrating its feasibility in the dedicated *EUU* facilities will be submitted with the L/ILW construction licence application.

Throughout this period, the design of the L/ILW seals will also support the refinement of the overall closure concept and the detailed design of the tunnel backfill material, processes and necessary equipment.

Period from 2040 to granting of HLW operating licence (2060)

Following the submission of the L/ILW construction licence application, the technical solution for the L/ILW seals, which includes the design and materials of the seals, all emplacement equipment and operational procedures, will undergo a period of refinement. The performance of this refined technical solution will then be finalised. The technical solution will then be demonstrated in the *EUU* facilities.

In parallel, the HLW seal design will undergo the same stepwise, iterative design process as the L/ILW seals, from modelling, development and off-site testing to technical solution integration, PA and demonstration.

The first industrial application of the technical solution will come with the construction of the L/ILW emplacement cavern and HLW emplacement drift sealing solutions as part of the pilot repository operations. This will take place during the operational phases of the L/ILW and HLW repositories, respectively.

7.10 Emplacement & retrievability

The Tier 3 Emplacement and Retrievability roadmap captures the work required to develop a feasible technical solution for emplacing and retrieving waste packages under the conditions in the deep geological repository. This needs to be developed for both the L/ILW and the HLW repositories. The current status of the topic is included in Section 8.4.1. The corresponding roadmap graphics are included in Appendix A3, Fig. A3-13.

In the near term, the overarching concepts for emplacement and retrievability of L/ILW containers and HLW canisters are developed and refined. The key near-term objective is to ensure the ability to retrieve waste packages without significant effort as this is a regulatory requirement.

Beyond the granting of the *EUU* licence, the L/ILW and HLW technical solutions are matured separately, but in a similar stepwise process. Testing and design work leads into the development of technologies to ensure the feasibility of the integrated technical solutions. Appropriate adaptations to systems, processes and tools will then be made as a result of off-site testing before emplacement and retrieval are demonstrated in the *EUU* facilities. These *EUU* demonstrations provide important input for the L/ILW and HLW operating licence applications.

The activities in the Emplacement and Retrievability roadmap are organised across four distinct workstreams:

- **Design:** This workstream illustrates the stepwise design development process for the emplacement and retrievability solutions, as a part of the overarching underground facilities system design.
- **Off-site testing:** The aim of this workstream is to communicate the relevant historical and collaborative testing that underpins the current Nagra repository concept and future testing, which is expected to be necessary off-site in surface laboratories, before in-situ demonstrations can take place.
- **Technology development:** This workstream sets out the activities required to establish technologies that ensure the feasibility of the emplacement and retrievability design.
- **Demonstration & optimisation:** The aim of this workstream is to drive the demonstration activities for a mature emplacement and retrievability solution in order to optimise the system as far as feasibility and, primarily, operational safety are concerned contributing to the overall optimisation in Tier 2.

Present (2021) to Granting of general licences and *EUU* licence application (2032)

International collaboration and historical URL research projects as well as Nagra feasibility demonstrations (Sections 8.4.4 and 8.4.7) will be used to develop the existing emplacement and retrievability concepts, which will be published along with the outline for an implementation plan for testing, prior to the submission of the general licence applications.

The refinement of the L/ILW emplacement and retrievability concept will accelerate following the submission of the general licence applications through the development of backfilling technologies and procedures to demonstrate the feasibility of the L/ILW backfilling concept, including meeting safety criteria through the specification of a backfill material. The development of the L/ILW emplacement and retrievability solution design will begin prior to the submission of the *EUU* licence application.

During this time, international lessons learned and state-of-the-art technologies will be used to further develop the existing prototype HLW backfill emplacement equipment and refine the HLW emplacement and retrievability concept.

Period from 2032 to L/ILW construction licence application (2040)

Once the general licence applications have been granted, L/ILW backfilling tests will be conducted in tailored off-site facilities, highlighting necessary adaptations to the emplacement and retrievability design and associated equipment and technologies. An L/ILW emplacement and retrievability solution will be established shortly before the submission of the L/ILW construction licence application, when the L/ILW repository construction method will be fixed. During this period, off-site testing of the L/ILW integrated technical solution will be completed and a plan for demonstrating the feasibility of the solution in the *EUU* will be finalised.

During this period, similar activities will be started for the HLW emplacement and retrievability design and technical solution. These are expected to be more complex as remote handling is required.

Period from 2040 to granting of HLW operating licence (2060)

In-situ L/ILW demonstration experiments will be carried out to verify every aspect of the emplacement and retrievability solution leading into the submission of the L/ILW operating licence application, thus concluding the RD&D for emplacement and retrievability of L/ILW.

The HLW design will continue to be developed in parallel with the supporting technologies through internal work and international collaboration. Similarly to the L/ILW process, an HLW emplacement and retrievability solution will be established shortly before the submission of the HLW construction licence application, the HLW construction method will be fixed, and the plan for *EUU* demonstration experiments will be finalised.

In-situ HLW emplacement and retrievability demonstration experiments will be carried out to verify every aspect of the emplacement and retrievability solution leading into the submission of the HLW operating licence application, thus concluding the RD&D for emplacement and retrievability of HLW.

8 Detailed technical programme: progress and outlook

8.1 Introduction and structure of the work programme

This chapter describes the status and the progress made since the 2016 RD&D report for each aspect of the RD&D programme. The most significant progress was made in the geological understanding of the siting regions, specific aspects of the inventory, the description of the expected repository evolution underpinning the safety case, and monitoring. Many outcomes of these activities will feed into the documentation of the general licence applications and are currently not yet available in open access documents. Where this is the case, reference is made to the key reports that will become part of the general licence applications.

Further, this chapter describes the objectives, scope and nature of the activities foreseen for the next five to ten years in more detail. As the general licence applications are currently planned to be submitted in 2024, this chapter covers not only the remaining RD&D activities supporting the licence applications, but also describes activities that will continue beyond them. RD&D then supports the following aspects of the Nagra disposal programme (Tier 2 of the Nagra Roadmap):

- safety optimisation, also addressing remaining uncertainties that are identified in the safety case supporting the licence applications
- implementation optimisation of the repository project as described in the licence applications

Both require a refined description of the geological understanding of the selected site(s). This includes further data acquisition and interpretation and planning for the *EUU* licence application submission.

The scope and volume of work performed specifically for the L/ILW programme is more limited compared to that for the HLW programme 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 HLW and L/ILW repositories (e.g. geology, safety assessment methodology, geochemical retention). In these areas, the scientific basis for the HLW programme thus provides much of the basis for the safety assessments required for the L/ILW repository.
- Performance requirements on most elements are less stringent and the level of understanding of the different processes that Nagra has to achieve is therefore less complex for the L/ILW repository than for the HLW repository.
- For the L/ILW repository, RD&D activities do not include significant thermal issues because of the low heat output of the wastes. However, gas-related RD&D is more relevant for the L/ILW repository.
- In general, the disposal of L/ILW is considered a mature technology, as evidenced by the licensing and operation of such repositories in other countries. Safety assessment of certain legacy wastes might need specific attention.
- The relationships between the major research themes addressed in this section are illustrated in Fig. 8-1. While Section 8.2 includes not only classical geological topics but also the safety-relevant processes in the undisturbed containment-providing rock zone (CRZ), the impact of the repositories on these safety-relevant processes is discussed in Section 8.5.

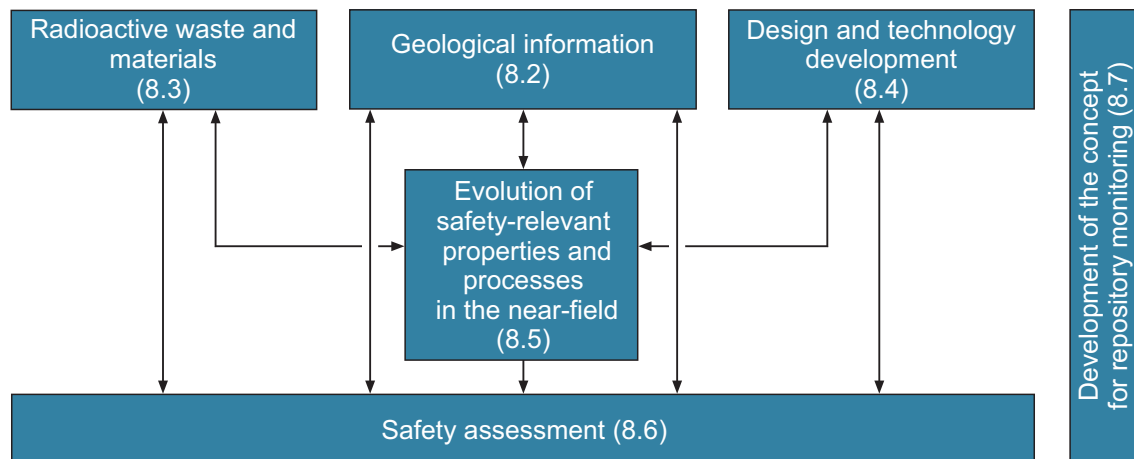


Fig. 8-1: Data and information flow between the major research themes described in the respective sections of Chapter 8

Many of the activities and their outcomes will be documented in Nagra NTB 24-03 (planned) and Nagra NTB 24-10 (planned) and their supporting documents as part of the general licence applications.

8.2 Geological information

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

- geometry of geological units, including the host rock, confining units and regional geological elements (e.g. regional faults, overdeepened valleys due to glacial erosion)
- properties and characteristic features of the host rock and low-permeability confining units (the so-called containment-providing rock zone). State parameters for key safety-relevant processes (e.g. hydraulic heads, hydrochemical composition of porewaters and groundwaters, stress)
- long-term geological evolution (e.g. neotectonics, erosion)

In the last decades, Nagra has developed a profound understanding of relevant aspects of the Swiss subsurface (see Appendix A2). During Stage 1 and Stage 2 of the Sectoral Plan, the focus was on using existing information through the development of state-of-the-art interpretation and modelling approaches.

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

With three siting regions remaining in *SGT* Stage 3, the focus of RD&D is on supporting the development of site-specific models for each of the sites (establishing local properties, geometries and state parameters), which will serve as the basis for selecting the final site(s) and developing

the safety case. Regional assessments remain highly important for certain aspects such as long-term geological evolution, including future hydrogeological conditions. During *SGT* Stage 3, substantial additional data based on field work from the surface (reflection seismic surveys, shallow and deep boreholes) have become available. For the safety assessment, the most important information relates to the geometry and quality of the host rock and confining units. The exploration programme is enhancing this information and will considerably reduce associated uncertainties. For the host rock, which is characterised by a high homogeneity and lateral continuity, the important parameters for the radionuclide transport (hydraulic parameters of the host rock, mineralogy of the host rock, etc.) could already be estimated relatively accurately in *SGT* Stage 2. Nevertheless, the site-specific information resulting from the exploration work for *SGT* Stage 3 will further strengthen the available knowledge of the properties of the host rock. This will allow further development of the conceptual models and parameter values used to date, taking into account site-specific differences where these are relevant.

After the general licences are granted, the construction of facilities for underground geological investigations (*BEUU*) is planned, allowing the underground investigations of the site(s) in the exploratory drifts (Chapter 6). The focus of the characterisation of the geosphere will be on developing a deeper understanding of the selected site(s). Regarding process understanding of the key safety-relevant phenomena in the host rock and confining units of the selected site(s), the state of the art will be further enhanced to support the updating of the safety case for the construction licences.

The structure of the following subsections is illustrated in Fig. 8-2. Geosphere characterisation and the long-term evolution of the selected sites is discussed in Section 8.2.1, while the focus of Section 8.2.2 is on the improved understanding of key safety-relevant phenomena. The impact of the repositories on these phenomena is discussed in Section 8.5.

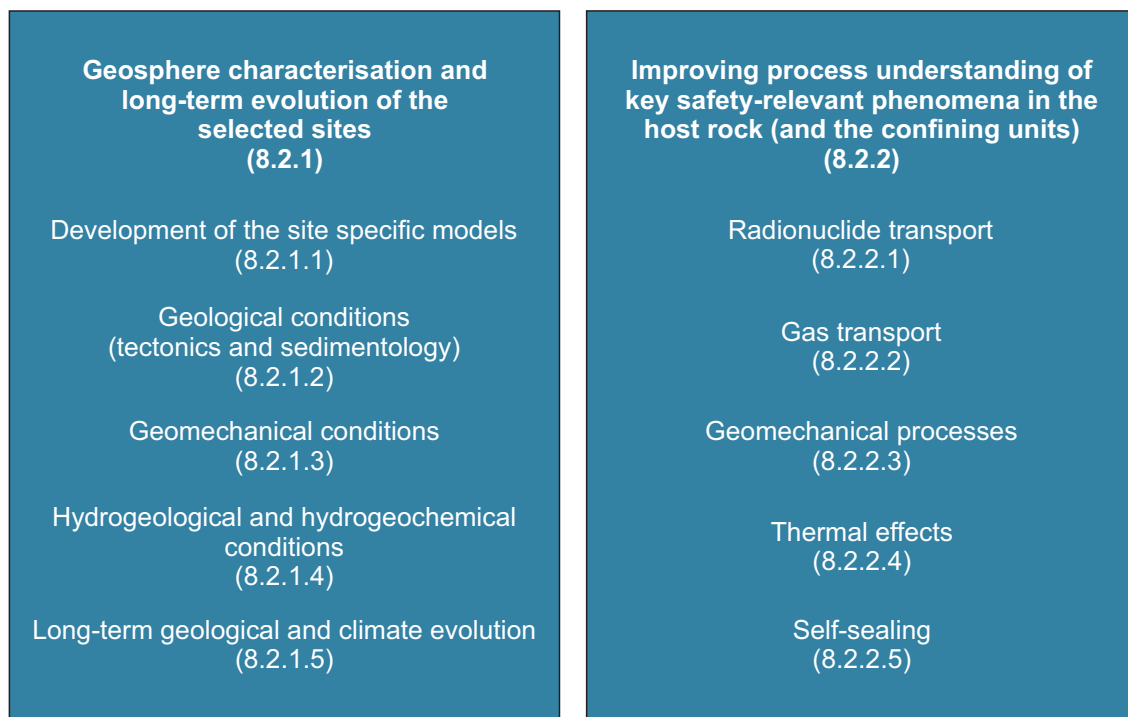


Fig. 8-2: Structuring of the RD&D activities relating to geological information and the understanding of key safety-relevant geological processes

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

The progress in the geosphere characterisation made in *SGT* Stage 3 will be continuously integrated into a series of site-specific models for the siting regions. The term site-specific model is used to describe a suite of conceptual models of the geological conditions at the proposed repository sites. These conceptual models include static models (lithostratigraphic layer models, fault models), property distributions (mineralogy, porosity, hydraulic conductivity, radionuclide retention, gas transport, stiffness and strength, seismic velocities) and dynamic models (defining and predicting in-situ conditions, e.g. pore pressure, water saturation, chemical composition of waters, temperature, stress state, strain/deformation).

Site-specific 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 needed for site-specific safety assessment and as input for engineering applications, including the evaluation of constructability. The development of the models is thus largely driven by the requirements derived from these applications. The final version of the site-specific models at the time of the general licence applications will incorporate the integrated understanding of the sites.

The following sections describe the RD&D activities in order of increasing model complexity, starting with activities related to the development of the site-specific models and followed by the development of the tectonic and sedimentological models. These are followed by geomechanical properties, hydraulic properties, state parameters and resulting models and, finally, dynamic hydrogeological and hydrogeochemical aspects.

Long-term geological evolution is discussed in a separate section. It affects the assumptions underpinning the post-closure safety assessment with regard to the description of both radionuclide transport pathways in the geosphere and in the biosphere.

8.2.1.1 Development of the site-specific models

Objectives

The objective is to develop and implement a suite of site-specific models that satisfy the need for a traceable and consistent description of the geological conditions at the proposed repository sites at the corresponding scales of interest. The development of the models is largely based on existing methodologies (e.g. Andersson 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 regarding the description of the properties on the site scale by 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 geoscientific domains
- developing robust calibration procedures for dynamic models (pore pressure/groundwater flow, groundwater/porewater 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-specific 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 2016 RD&D Plan

The site-specific models currently developed in *SGT* Stage 3 describe the geoscientific basis for both the site selection and the general licence applications. The workflows that have been developed are based on experience from previous site investigation programmes (Nagra 1997, 2002c) and from the reports of *SGT* Stage 2 (Nagra 2014c and references therein).

In the first phase of *SGT* Stage 3, the focus was on the following aspects:

- Increasing understanding and synthesising specific aspects of the regional geological situation as a basis for efficient integration of the new local field data that are currently being acquired in the siting regions. This work includes, for example, the consolidation of the lithostratigraphic and sedimentological framework of the host rock and confining units (Section 8.2.1.2), the tectonic history and deformation style (Section 8.2.1.3) and the petrography, mineralogy and porewater chemistry of the containment-providing rock zone (CRZ) (Section 8.2.1.4).
- Developing workflows to ensure consistent and quality-assured data acquisition and interpretation during the deep borehole campaign as a basis for a consistent and defensible description of the sites. In this context, manuals for the description of drill cores and for drill core sampling have been developed, as well as detailed laboratory measurement protocols (Ebert & Decker 2019, Jordan & Deplazes 2019, Naef et al. 2019, Minardi et al. 2019, Rufer 2019, Waber).
- Improving data interpretation, model building and modelling workflows (e.g. seismic interpretation workflows, hydrogeological models and stress models).

Planned RD&D in the next five to ten years

In the context of *SGT* Stage 3, a suite of site-specific models will be finalised for the siting regions, addressing the geological conditions (Section 8.2.1.2), geomechanical conditions (Section 8.2.1.3), hydrogeological/hydrogeochemical conditions (Section 8.2.1.4) and long-term geological evolution (Section 8.2.1.5) on the site scale.

Approaches for geometric up- and down-scaling of the sedimentary structures (layer models of lithostratigraphic units) and of the tectonic structures (fault models) will be investigated. As an example, an aspect currently being pursued concerns the deterministic and stochastic modelling of fracture systems observed in drill cores. The level of complexity of the static models will be determined in close cooperation with the end-users to ensure a robust, traceable and consistent abstraction of the geological conditions on the site scale. State-of-the-art visualisation will be developed to facilitate and illustrate the aspects of the site selection process.

Once the documents for site selection and for the general licence applications have been submitted, the focus of the site-specific models will shift towards a detailed characterisation of the geology around the access infrastructure (tunnels and shafts mainly tailored to the needs of the engineers) and to a detailed description of the host rock in and around the repository zone (basis for planning of *EUU* as well as concretising and optimising repository design).

Furthermore, the concepts and models included in the general licence applications will be refined and, if necessary, tailored RD&D projects will be initiated and existing site-specific models will be refined. The work will be summarised in the geosynthesis reports planned for future licensing steps.

8.2.1.2 Geological conditions (sedimentology and tectonics)

Objectives

Sedimentological³ and tectonic characteristics and features of the host rock and its confining units provide fundamental input for the understanding of their hydrogeological and geomechanical behaviour. These aspects thus contribute to demonstrating the barrier function of the host rock in the safety case, to the assessment of engineering feasibility and to the planning of repository construction and layout. In the course of activities carried out during *SGT* Stage 2, it became clear that the Jura Ost, Nördlich Lägern and Zürich Nordost siting regions have some significantly different tectonic and sedimentological characteristics that are potentially relevant to site selection. Knowledge of geological conditions gained through research activities in *SGT* Stage 3 will be used to further develop the tectonic and sedimentological models that will in turn serve as a basis for other static and dynamic models, such as hydrogeological models and stress/strain models (see Section 8.2.2.1).

Current state of the art and progress since the 2016 RD&D Plan

Since the publication of the 2016 RD&D Plan (Nagra 2016b), significant research and exploration activities (3D seismics, deep boreholes) have been carried out to further constrain the sedimentological and tectonic description of the siting regions and their respective host rocks. A summary related to sedimentological and tectonic characterisation is given below, focusing on the Opalinus Clay and its confining units in the investigated siting regions, as well as their surroundings.

Sedimentological facies analysis and models

A variety of approaches, such as litho-, bio-, chemo- and mineralostratigraphy were applied at the beginning of *SGT* Stage 3 to investigate and characterise the sedimentary facies, giving a more detailed view of sedimentological similarities and differences between the siting regions.

The petrological and geophysical parameters of the Opalinus Clay are, on a larger scale, substantially more homogeneous than many other Mesozoic formations in the wider area of the siting regions. However, facies changes do exist within this formation and new subfacies classification schemes have been developed based on detailed investigations in the Mont Terri Rock Laboratory and on drill cores obtained in Northern Switzerland (Lauper et al. 2018, Hostettler et al. 2017, Mazurek & Aschwanden 2020). New biostratigraphic studies of outcrops in Jura Ost have confirmed that the top of the Opalinus Clay is diachronous (Wohlwend et al. 2019b). Additionally, new chemostratigraphic approaches have been developed for a correlation of the Opalinus Clay between boreholes and outcrops (Wohlwend et al. 2019a).

³ Sedimentological properties include mineralogical and petrophysical properties.

The facies of the lower and especially of the upper confining units can vary considerably on a regional and local scale. A combined litho- and biostratigraphic study of outcrops allowed this variability to be better characterised in the case of the Passwang Formation, which directly overlies the Opalinus Clay in Jura Ost (Wohlwend et al. 2019b). The transition at the top of the Opalinus Clay to this formation, as well as its equivalents to the east, was investigated in detail using new approaches, such as high-resolution X-ray fluorescence (XRF) scanning (Laufer et al. 2020). These studies indicated differences between the siting regions, e.g. in the occurrence and extent of "hard beds" such as calcareous and/or quartz-rich beds, which will be considered in the safety analyses.

Tectonic regime

The analysis of tectonic structures in the subsurface of Northern Switzerland up to the end of SGT Stage 2 was largely based on 2D seismic data and on structural cross-sections specifically addressing the structural and kinematic evolution of regional fault zones (Madritsch et al. 2018, Malz et al. 2015, Malz et al. 2016, Malz et al.). In the period since then, 3D seismic data have been acquired for the three siting regions. The first horizon and structure interpretation of the 3D seismic data is already available (Nagra 2019c, 2019d, 2019e). While still regarded as preliminary, it appears to largely confirm previously identified differences regarding the tectonic setting of the three siting regions and will form the basis for further analyses.

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 tectonics. The sedimentary stack has been mildly detached and transported northwards (Jordan et al. 2015, Malz et al. 2015, Malz et al.). 3D seismic interpretations show clear evidence for contractional deformation of the Triassic evaporitic sequences underneath the containment-providing rock zone, but also some less clear indications for internal thrusting (Nagra 2019c). North-south striking and steeply dipping faults to the west of the site known from geological maps have been either confirmed, or additional ones have been identified for the first time.

In Nördlich Lägern, 3D seismic interpretations confirm that the northern part of the siting region, defined as "a tectonic zone to be avoided" (Nagra 2014d), is dissected by a strongly segmented ENE-WSW striking regional fault zone, showing evidence of strike-slip kinematics. The adjacent part of this siting region to the south, where Opalinus Clay is found at depths in excess of 700 m, appears to be largely devoid of seismic-scale structures, according to preliminary interpretations. The effect of Alpine shortening during the Miocene formation of the thin-skinned Jura fold-and-thrust belt was less strong.

The Zürich Nordost siting region is only weakly affected by compressional deformation related to Late Miocene Alpine collision tectonics. It lies immediately west of the extensional Hegau – Lake Constance Fault (Madritsch & Hammer 2012, Ibele 2015, Egli et al. 2017, Madritsch 2015). The referenced authors provide a regional overview of how Miocene formation of this tectonic zone was controlled by the reactivation of pre-existing structures rooted in the crystalline basement. The Neuhausen Fault, representing its western boundary, and the associated Wildensbuch Flexure reaching into the Zürich Nordost siting region (Birkhäuser et al. 2001) were more closely investigated by Roche et al. (2020). Based on newly available pre-stack depth-migrated 3D seismics, a quantitative analysis of these structures has been provided, indicating that the rheologically weak Opalinus Clay strongly influenced the evolution and present-day architecture, which is characterised by vertical and lateral fault zone segmentation.

Planned RD&D in the next five to ten years

The activities in *SGT* Stage 3 aim to support the three main steps necessary to establish suitable models for the siting regions (see Section 8.2.2.1): feature characterisation, feature distribution/variability and feature abstraction. In addition to the activities foreseen and partly completed within the exploration programme, the related RD&D activities aim to explore, develop and test less established qualitative and quantitative approaches. The primary goal of these activities is to provide input for the general licence applications. Beyond that, the knowledge acquired will be used in the framework of the underground geological investigations to develop approaches for the verification of the sedimentological and tectonic concepts that will eventually support the construction licence applications.

Regarding the advanced characterisation of sedimentological and tectonic features, the development of up-scaling and down-scaling techniques (seismic to outcrop to core to microscale) is of particular interest. New techniques will be tested for the integrative analysis of the extensive datasets compiled within *SGT* Stage 3 (e.g. a combination of new geochemical and petrophysical records with sedimentological logging) in order to better quantify different facies and especially lithologies. Additionally, in the Bülach-1-1 borehole, a new sedimentological facies, the coral-bearing «Herrenwis Unit» was found. This facies will be characterised using novel methodological approaches (e.g. CT scanner, microfacies, taphonomy).

Structural feature characterisation will initially focus on regional and local structures clearly imaged by 3D seismics. While the data interpreted so far have been processed in the time domain, the foreseen depth imaging will more properly account for lateral velocity variations and provide more accurate subsurface models. Regional fault zones around the sites will be analysed based on various conceptual approaches (e.g. thin-skinned vs. thick-skinned tectonic concepts). Concerning potentially layout-determining faults within the sites, multiple seismic vintages derived via different imaging techniques as well as seismic attributes will be considered to improve robustness of detection and to identify uncertainties (Eichkitz et al. 2020). Characterisation of smaller-scale structures will largely be based on drill core observations, which will be complemented by microstructural analyses. This will place the focus on veins that were repeatedly observed in drill cores of the host rock and its confining units. These structures represent rich archives that can be used to unravel the nature of past fluid flow in the context of the tectonic history of the siting regions. In this regard, advances in the dating of calcitic veins using uranium-lead (U-Pb) dating, in combination with isotope geochemistry, now allows the characterisation of fluid composition and temperature conditions during vein formation (Mazurek et al. 2018, Looser et al. 2021). The results of these investigations are expected to significantly improve the understanding of past tectonic processes.

A second RD&D 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 with the aim of tracing and correlating subtle sedimentological features and changes on different scales. Further approaches are expected to be developed to analyse and combine different records, such as geophysical, compositional, biostratigraphic and sedimentological data, to define the variability and distribution of lithofacial units (e.g. "hard beds") and investigate upscaling/downscaling effects. This will contribute to a better definition of the lithofacial units of the conceptual models. Accurately processed seismic and borehole petrophysical data could allow the application of seismic inversion techniques to estimate geological properties (e.g. Mari & Yven 2014). A special focus will be placed on the development of a conceptual depositional model of the newly identified «Herrenwis Unit» in the Nördlich Lägern siting region.

With respect to the distribution of structural features, it is of particular interest to bridge the observation gap between seismic imaging on the one hand and centimetre-scale borehole records on the other. Current efforts to model sub-seismic faults based on borehole records (Schneeberger et al. 2020) will be continued. The applicability of 3D balancing techniques of regional fault zones to gain indications about strain distribution and greater likelihood of sub-seismic faults within the repository area has to be critically assessed. As an alternative, novel seismic processing techniques such as diffraction imaging (Dell et al. 2019) theoretically also enable the direct imaging of smaller-scale faults and are expected to provide an effective improvement of subsurface characterisation. Finally, waveform inversion, possibly in combination with reverse time migration, could provide the prime technology for a refined subsurface model for future use after submission of the general licence applications.

Activities related to conceptualisation and abstraction of tectonic and sedimentological features aim to support the development of site-specific models for the proposed siting regions (see Section 8.2.2.1). The site-specific datasets obtained during the currently ongoing field investigations of *SGT* Stage 3 will allow high-quality geological models to be developed and consensus to be reached on the most appropriate conceptualisations for the selected site(s).

8.2.1.3 Geomechanical conditions

Objectives

Geomechanical conditions are described by rock properties in terms of specific state variables (notably the stress field, pore pressure and temperature distribution), including structural heterogeneities (faults and joints) at the rock-mass scale. They are an essential part of the site-specific models and are relevant not only to the site-specific evaluation of the engineering feasibility of a repository (e.g. constructability and operation), but also to the assessment of barrier performance and the optimisation of the repository projects in the context of the site selection process. Specifically, stress conditions are crucial for defining performance targets for acceptable thermally and gas-induced fluid overpressures (Papafotiou & Senger 2016a, 2016b, Marschall & Giger 2016, Nagra 2021c). These performance targets will be defined as part of the performance assessment and documented in Nagra NTB 24-10 (planned) and its supporting documents as part of the general licence applications.

Stresses and mechanical properties are scale-dependent due to the sedimentological, 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 on a centimetre to decimetre scale. Instrumented in-situ (mine-by) experiments in URLs (Mont Terri Rock Laboratory and elsewhere) contribute to reconciling laboratory test results and stress measurements with excavation response at the scale of underground structures.

Workflows for the upscaling of geomechanical conditions from core sample scale or borehole/cavern scale to the actual repository scale (Keller & Giger 2019) have largely already been developed and will be applied for the site selection. 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 8.2.2.3 (geomechanical processes in the host rock).

While significant effort will be undertaken to characterise the geomechanical conditions in the three siting regions based on the exploration programme in *SGT* Stage 3, it is recognised that underground access is required to fully characterise these conditions in anticipation of repository construction. This will take place in the *EUU* facilities.

Current state of the art and progress since the 2016 RD&D Plan

Stress field

The orientation of the principal horizontal stress 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 2007). A detailed analysis of such data for Northern Switzerland was performed by Heidbach & Reinecker (2013).

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. For site characterisation, only deep boreholes provide the access needed for active stress measurements in the rock mass (e.g. Zang & Stephansson 2010). Micro-hydraulic fracturing (MHF) is considered the most reliable method for constraining horizontal stress magnitudes in deep boreholes, since strain relief methods (e.g. overcoring) have not been demonstrated for greater depths (Intera 2011). For micro-hydraulic fracturing, only the determination of the minimum horizontal stress magnitude is well established, under the condition that the vertical stress due to the overburden is not the proportionally lowest of the three principal stress magnitudes. In sedimentary sequences with strongly contrasting rock properties, several studies have found that the minimum horizontal stress magnitudes vary significantly (e.g. (Warpinski 1989, Maerten et al. 2002, Yale D. P. 2003, Björkbacka et al. 2017, Roche et al. 2013, Gunzburger & Magnenet 2014). This highlights the importance of accounting for the spatial heterogeneity of the rock properties, especially across different formations, when extrapolating stress magnitudes from hydraulic fracturing.

Most difficult is the evaluation of the maximum horizontal stress magnitude. The only reliable method for bracketing this value by in-situ testing is considered to be a "sleeve reopening" or a "dry reopening" of a previously created fracture (Desroches & Kurkjian 1999). The theoretical basis of this method was formulated (Atkinson & Thiercelin 1993) and validated (Desroches et al. 1995) well over 20 years ago, and applied in the exploration campaign of Andra (France) to characterise the stress field at the Meuse/Haute Marne URL (Wileveau et al. 2007).

For the exploration programme in the three siting regions, Nagra has specified an MHF testing programme that includes both i) a high frequency of tests in each borehole (typically 10 to 20 measurements) to characterise the formation-specific heterogeneity of stress magnitudes, and ii) sleeve reopening measurements to bracket maximum horizontal stress magnitudes.

Numerical geomechanical modelling can assist in exploring the sensitivity of the stress field at the site or reservoir scale, and hence in estimating the far-field stress tensor (Fischer & Henk 2013). Such 3D geomechanical models were constructed for the three candidate sites in *SGT* Stage 2 (Heidbach et al. 2014, Hergert et al. 2015). The models will be revised based on the refined geological models from 3D seismics and results from the deep borehole campaign and documented in Nagra NTB 24-03 (planned) and its supporting documents.

Mechanical properties

The Opalinus Clay exhibits transitional deformation behaviour between hard soils and weak rocks, which makes geomechanical testing of the material challenging. Significant efforts have been undertaken in the past five years to develop advanced geomechanical testing procedures (Favero et al. 2018, Giger et al. 2018). These were validated in a benchmark study on Opalinus Clay drill cores recovered from the Mont Terri Rock Laboratory (Minardi et al. 2019, 2021).

Triaxial testing using these advanced test procedures is suitable for the characterisation of the properties of intact Opalinus Clay ("pre-peak" to "peak strength"), and also of tectonically fractured Opalinus Clay ("post-peak"). For the design of underground structures and for the evaluation of potential fault reactivation, it is also relevant to estimate the geomechanical properties of fault zones. This was investigated by crushing intact Opalinus Clay and shearing it to large displacements (Rosone et al. 2019).

The question of how representative laboratory tests are for rock mass properties in Opalinus Clay is addressed by performing larger-scale in-situ tests, specifically pressure-meter tests (Marsland & Powell 1990) or dilatometer tests (Zalesky et al. 2007). A detailed comparison of rock stiffness test results from laboratory plugs and from in-situ tests is currently underway at the Mont Terri Rock Laboratory as part of the Geomechanical Characterisation experiment (GC-A); it is also planned to perform the same analyses in one of Nagra's deep boreholes.

Laboratory testing of core samples and dilatometer or pressure-meter testing in boreholes focuses on constraining elastic (stiffness) and failure-strength parameters. As well as these "static" properties derived at the core scale, "dynamic" properties can be derived from geophysical exploration. Static and dynamic values can be significantly different, especially for shales (Tutuncu 2010). This difference was, however, reconciled in a recent case study on Opalinus Clay core material from the Mont Terri Rock Laboratory (Bauer & Lozovyi 2018). There are a number of factors that can impact the derivation of static and dynamic properties (Fjaer 2019) and, therefore, empirical correlations between (petro-)physical and geomechanical properties are widely used in the hydrocarbon industry (e.g. Ingram & Urai, Horsrud 2001, Chang et al. 2006), mainly to ensure 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 & Koehrer 2014). Andra (France) has also pursued this using 3D seismic data near the Meuse/Haute Marne URL, deriving a 3D cube of dynamic elastic properties (Mari & Yven 2014).

Research activities towards improved assessment of the structural heterogeneity of Opalinus Clay (fractures) are described in Section 8.2.1.2.

Planned RD&D in the next five to ten years

The advanced and validated geomechanical testing protocols for Opalinus Clay will be applied in all triaxial tests on core material from the deep boreholes. More than 70 triaxial tests from two different boreholes had already been completed by the end of 2020. By including recent tests on Opalinus Clay from the Mont Terri Rock Laboratory (Minardi et al. 2019, 2021) and the Lausen borehole (Giger et al. 2018), the database will grow to more than 200 triaxial tests. To Nagra's knowledge, this will be the largest such database of any shale or claystone in the world. This will allow material heterogeneity and site-specific and depth-dependent properties of Opalinus Clay to be assessed. In addition, the effect of elevated (in-situ) temperature on material properties will also be evaluated.

The advanced geomechanical laboratory testing protocols will also provide an independent assessment of the in-situ stress magnitudes, as one part of the procedure is specifically designed for this purpose. Based on the new geological models (seismic and borehole data, see Section 8.2.2.2), the site-specific 3D geomechanical stress models are to be revised and populated with empirically correlated mechanical properties. In-situ geophysical logging data and laboratory testing on core samples recovered from the deep boreholes are to be used for this purpose. The database of static and dynamic elastic properties of the Opalinus Clay will be further increased by dedicated field and laboratory testing programmes in the Mont Terri Rock Laboratory (Geomechanical Characterisation, GC-A) and in specialised laboratory tests using cores from the deep boreholes (Bauer & Lozovyi 2018).

Micro-hydraulic fracturing (MHF) measurements have been acquired in boreholes in the three siting regions. Therefore, in contrast to previous stress models in *SGT* Stage 2, MHF results from more than one borehole will be available for each siting region. These field measurements are used as calibration points for modelling purpose and significantly reduce the uncertainty in the evaluation of site-specific stress conditions. Finally, 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.

After the submission of the general licence applications, and in preparation for the application and construction of the *EUU* facilities, the focus will be on verifying the stress field and rock mass behaviour at the selected site(s).

8.2.1.4 Hydrogeological and hydrogeochemical conditions

Objectives

Various aspects are being refined within the framework of the field activities in *SGT* Stage 3. The additional data will allow for a higher level of detail in site-specific geosphere characterisation and a reduction in the remaining uncertainties. The activities will improve and develop the tools and methods needed to meet the objectives for the general licence applications, which are:

- State-of-the-art description and visualisation of hydrogeological conditions, focusing on the siting regions.
- Acquisition of state-of-the-art porewater data, including data for natural tracer profiles. Porewater chemistry data will provide the basis for the models used in radionuclide speciation modelling, which provides key input for safety assessment calculations. The natural tracer profiles provide information on transport processes (advection, diffusion) in the containment-providing rock zone and thereby also support the safety case, including radionuclide transport calculations.
- Development of a sound basis for assessing diffusion coefficients and diffusion-accessible porosities in the units of interest (containment-providing rock zone), including the estimation of anion-accessible porosities as input to radionuclide transport calculations and as a basis for the interpretation of natural tracer profiles.

Current state of the art and progress since the 2016 RD&D Plan

General hydrogeology and hydrogeochemistry

The acquisition and initial evaluation of hydrogeological and hydrogeochemical data in the framework of the deep borehole campaign of *SGT* Stage 3 forms the basis for a refined interpretation of site-specific hydrogeological and hydrogeochemical conditions.

Due to the significant developments in isotope analytics that have recently taken place, important progress is expected, especially in the determination of residence times for very old groundwaters based on ^{81}Kr , as has recently been successfully accomplished in the Southern German Molasse Basin (Heidinger et al. 2019).

The 3D seismic survey, the general geological record of the rock units that have been drilled and also the hydrogeological properties and state of these units together provide the basis for detailed numerical analyses of the flow systems. Recent evaluations of state-of-the-art modelling codes using unstructured grids as well as post-processing capabilities indicate the potential for substantially improving on the hydrogeological models developed in the framework of *SGT* Stage 2.

Porosity

Porosity is a fundamental input parameter for the modelling of all transport processes. In clay rocks, the diffusion-accessible porosity is known to be species-dependent (e.g. "anion-porosity" concept). Since some key safety-relevant radionuclides are present as anionic species (e.g. ^{129}I , ^{36}Cl , ^{79}Se), a qualified estimate of anion porosity is needed for the interpretation of profiles of naturally occurring anionic species as a proxy for these radionuclides.

The total pore space within clay rocks can be related to interlayer water and interparticle porewater (Fig. 8-3). Interlayer water is not accessible to anions. The interparticle porewater comprises the electric double-layer porewater and the free, uncharged porewater. The relative proportion of the latter depends, among other factors, on compaction. Anion diffusion takes place mainly in the free porewater.

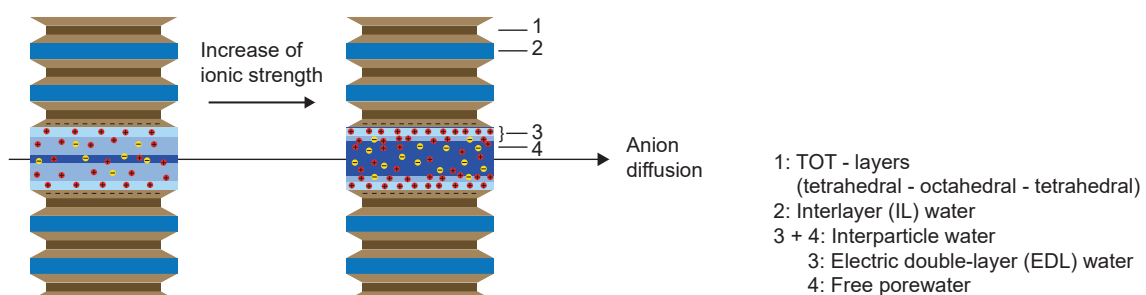


Fig. 8-3: Schematic illustration of the pore space within argillaceous rocks and the potential effect of ionic strength on the anion-accessible pore space

From Wigger & van Loon (2017).

The total pore space comprises interlayer water (2) and interparticle porewater (3 and 4). The interparticle porewater comprises the electric double-layer porewater (3) and the free uncharged porewater (4). Anion diffusion takes place mainly in the free porewater.

In addition, the anion-accessible pore space depends on the ionic strength of the porewater. Wigger (2017) and Wigger et al. (2018b) carried out through-diffusion experiments with Opalinus Clay and other rocks using synthetic porewaters with a range of ionic strengths covering several orders of magnitude. Overall, the anion-accessible porosity fraction decreases with decreasing ionic strength. For the conditions expected in the siting regions of Northern Switzerland, the impact of ionic strength on variation in anion accessibility along a borehole profile is expected to be small.

A variety of methods have been applied to the drill cores from the deep borehole campaign to obtain data on porosity. Through-diffusion experiments using well-characterised rock samples make up the main dataset on anion-accessible porosity. In addition, petrophysical logging provided a continuous record of porosity.

Within the ongoing CLAYWAT project, led by the University of Bern, novel and classic methods are being used to investigate the binding state of porewater in samples of clay rocks from various countries.

Porewater in the host rock and the confining units

Following an early phase during which methods for sampling and characterising porewater and rocks were developed (Pearson et al. 2003) and applied in the deep borehole in Benken (Nagra 2002c), as well as further development mainly in collaboration with the University of Bern and/or in the Mont Terri Rock Laboratory (notably the Analyses of Geochemical Data (GD) experiment), these methods and the resulting insight reached a stage where targeted projects could be carried out to resolve remaining questions.

Earlier results (Wersin et al. 2015) provided a guide for the topics that have been addressed and activities that have been undertaken:

- Comparison of methods and data among research groups within the deep borehole experiment at Mont Terri (Mazurek et al. 2017a).
- Measurement of natural tracer profiles across the Opalinus Clay and adjacent units in the Mont Terri deep borehole experiment (Rufer et al. 2018, Waber & Rufer 2017). Among other benefits, this also served as a test of workflows, including the feasibility of cutting a core axis-parallel segment ("strati-slab") for a continuous lithostratigraphic documentation.
- Intercomparison of cation exchange capacity (CEC) methods among different laboratories (Hadi et al. 2019).
- Refined host rock characterisation: chemistry of carbonate and sulphate minerals (Pekala et al. 2019b) and spectroscopic investigation of sulphur-containing minerals (Jenni et al. 2019a).
- Systematic evaluation of aqueous extraction laboratory protocols and their impact on solute concentrations, notably the sulphate contents (Debure & Gailhanou 2019, Aschwanden & Wersin 2020).
- High-pressure squeezing method: benchmarking with other porewater datasets and evaluation of the impact of sample preparation (Mazurek et al. 2016, Rufer & Mazurek 2018).
- Further development of the advective displacement method, including a dedicated effort to enable a large range of chemical analyses on small volumes of water samples (Mäder 2018).
- Modelling to assess the impact of a CO₂ disturbance of the porewater system (Wersin & Pekala 2018).

The results of these activities were integrated into the preparation of the deep borehole campaign, including most notably the guidelines for drill core sampling and conditioning (Rufer 2019), as well as into the laboratory workflows and the refinement of analytical methods (Waber).

Porewater characterisation relies on a combination of methods. Particularly regarding the measurements of sulphate in porewater, mobilisation of relevant amounts of solid-bound sulphate during aqueous extraction is currently not taken into account. The dependence on the method may be due to the amounts of sulphate in the more mobile porewater fraction being different to bulk porewater.

Further development of the porewater model will continue based on the datasets from the deep borehole campaign, and further methodological development for small water sample analyses (including pH and alkalinity) is expected to allow the porewater carbonate equilibrium to be better constrained.

Long-term hydrogeological evolution of the containment-providing rock zone

The long-term geological and climatological evolution of a site can potentially impact the host rock and surrounding units. This includes possible changes to hydraulic conductivity and other properties during (un-)loading of the Opalinus Clay and the surrounding rocks. The potential impact of host rock decompaction due to future erosion was investigated in the Lausen borehole case study. In this shallow borehole, the Opalinus Clay was penetrated below around six metres of Quaternary sediments (Vogt et al. 2016). In the uppermost section, a hydraulic conductivity of up to 10^{-4} m s^{-1} was measured based on packer testing, and water samples could be pumped (Vogt et al. 2017). However, below a depth of 28 metres, hydraulic conductivity was found to be in the order of $10^{-13} \text{ m s}^{-1}$, similar to that observed at the Mont Terri Rock Laboratory. Various degrees of rock alteration can be observed as a function of depth, e.g. pyrite was found to be depleted in the rock matrix only down to a depth of nine metres, i.e. three metres into the Opalinus Clay, illustrating its low hydraulic conductivity. A detailed description of rock alteration is found in (Mazurek et al. 2017b). The impact of weathering and decompaction at this shallow depth was also evident in porewater investigations. For example, the chloride content was found to be strongly depleted in the uppermost section. From a depth of around 20 to 40 metres, a sharp increase in the chloride content of up to $\sim 3 \text{ g/L}$ was observed (Mazurek et al. 2017b). Overall, the findings from Lausen suggest that the Opalinus Clay is a good aquitard even with an overburden of only a few decimetres. An earlier study showed that the degree of weathering and decompaction also depends on the morphological situation (Hekel 1994).

Planned RD&D in the next five to ten years

In the first phase, the planned work will focus on the interpretation of the data from the deep borehole campaign to support the documentation needed for site selection and the general licence applications. In the second phase, the priority will be on resolving specific questions that could arise when compiling the documentation, on refining the description of the evolution of the host rock and of the hydrogeological system and on advancing the state of the art through exchange and collaboration with other waste management organisations and collaboration with Nagra's competence centres at the University of Bern and the Paul Scherrer Institute (PSI).

The hydrogeological and hydrogeochemical models elaborated in *SGT* Stage 3 and advanced descriptions of potential long-term geological evolution will form the basis for framing the impacts of these evolutions on the hydrogeological cycle and on the natural barrier system, including potential radionuclide release pathways. The models can also contribute to the planning of access tunnels and/or shafts. Particular effort will be placed on developing a consistent hydrodynamic and hydrogeochemical system description, including uncertainty analyses.

The porewater models are expected to be further developed, incorporating state-of-the-art understanding of porosity in clay rocks to better explain observed phenomena. Incorporation of such models into, for example, 2D reactive transport models will allow more realistic process evaluation.

Exchange with other waste management organisations is expected to continue, mainly in the framework of the Analyses of Geochemical Data (GD) experiment at Mont Terri. Scientific competence will be maintained for future licensing steps as part of the collaboration with the University of Bern.

8.2.1.5 Long-term geological and climate evolution

Objectives

Active tectonics, climate evolution and erosion have the potential to change host rock properties and radionuclide transport and release pathways over the period of concern (100 ka for L/ILW and 1 Ma for HAA)⁴. For both site selection and the general licence applications, these aspects will be addressed by developing and evaluating long-term evolution scenarios.

Erosion will lead to a decreasing overburden thickness and ultimately, if sufficiently extensive, to an increase in host rock permeability (decompaction, see Section 8.2.1.4) or even to the partial or total exhumation of the repository. The most important factors in landscape evolution scenarios are hydrological base level changes, the evolution of local topography and the formation of glacial overdeepenings. Climate evolution will strongly influence the future landscape, biosphere and hydrosphere and is therefore relevant for safety assessments (Näslund et al. 2013, Becker et al. 2014, SKB 2020). The first results of site exploration using 3D seismic analysis confirmed that it is possible to reliably identify major faults with vertical offsets of more than 15 metres (a threshold which is being confirmed) (Ebert & Decker 2019, Nagra 2019c, 2019d, 2019e) and to avoid these. Nevertheless, future tectonic activity, possibly involving the formation of new faults around or within the repository, cannot be fully excluded. Consequently, an enhanced understanding of active tectonics and its relevance is being developed.

The activities described below aim at improving confidence in these erosion, climate and tectonic scenarios by providing additional constraints for the reconstruction of the geological, climatic and geomorphic past and by investigating the key factors and processes guiding future evolution.

Current state of the art and progress since the 2016 RD&D Plan

A wide variety of research activities aimed at attaining a better understanding of Northern Switzerland's long-term geological evolution have been carried out. A brief summary of the key topics of active tectonics, climate evolution and erosion is given below.

Active tectonics

For the siting regions, the results of 3D seismic exploration allow a better definition of potentially active tectonic structures and regional faults. Regionally, results of previous geomorphic reconnaissance studies (Hammer et al. 2019, Nagra 2014c) helped to identify locations for more detailed investigations of selected faults using shallow geophysical investigations, e.g. the Neuhausen

⁴ ENSI-G03 (ENSI 2020) requires an assessment for repository exhumation beyond a time period of 1 Ma.

Fault (Madritsch, H., Hammer, P., Ibele, T. Hauvette, L., Fiebig, B., Hölker, A. & Spillmann, T. 2019). Nagra also participated in geophysical investigations of Lake Constance, a high-potential archive for neotectonic movements (Fabbri et al. 2021). Geodetic measurements indicate that recent crustal movements in Northern Switzerland are < 0.5 mm/y (Nagra 2014c). During *SGT* Stage 2, the density of the global positioning system (GPS) network was densified with 11 additional permanent stations to further consolidate these results (Studer & Zanini 2013). These stations now show high accuracy and reliability with continuously decreasing measurement error and increasing signal-to-noise ratio. Collaboration with geodesists from the Swiss Federal Office of Topography, swisstopo, and the Karlsruhe Institute of Technology (KIT) aimed at incorporating the data into a regional framework and potentially synthesising them with Interferometric Synthetic Aperture Radar (InSAR) time series. Vertical movements, constrained along regional profiles of precision-levelling measurements, yield rates of < 0.25 mm/y (Fuhrmann & Zippelt 2013, Schlatter 2013). Selected profiles indicate a slight differential uplift across the Jura Mountains. Northern Switzerland is characterised by comparatively low seismic activity, mainly occurring at depths $> 5 - 10$ km (Nagra 2014c). Inversion of focal mechanisms and other stress indicators yields a recent regime of strike-slip to extensional tectonics (at greater depths), with the maximum horizontal stress axis being oriented roughly NNW-SSE. The existing microseismic network in Northern Switzerland and Southern Germany was expanded with ten further stations, including three borehole seismometers (Plenkens 2014) to increase the detection capability and localisation accuracy of seismic events. The pattern of low-level seismicity provides a significant contribution to the seismotectonic model of Northern Switzerland (Diehl et al.), including localised activity within the Hegau – Lake Constance Graben system, including the Neuhausen Fault and the area around Eglisau in the north-eastern corner of the Nördlich Lägern siting region. During 2019, the density of the weak-motion network was further increased by the addition of mobile stations near these activity clusters. Sophisticated probabilistic methods have been developed for seismic safety assessment (shaking hazard) and for the design of critical surface infrastructure (e.g. nuclear power plants) with the support of Nagra (Abrahamson et al. 2004, Swissnuclear 2013, 2013-2015). To improve the characterisation of seismic hazard at repository depth, borehole seismometer measurements from the site of the Gösgen NPP have been analysed and empirical transfer functions have been determined.

Climate evolution

Proxy data reviews summarise paleoclimatic studies of lake and peat sediments, speleothems, glacier records and loess-paleosol sequences. During the last glacial period, an ice lobe probably reached the internal Alpine foreland at least once (Marine Isotope Stage, or MIS 4) before the last glacial maximum (MIS 2) (Ivy-Ochs et al. 2008). At least two major glacial advances reached into the Alpine foreland during MIS 6 (Buechi et al. 2018). Within the IAEA project MODARIA (Modelling and Data for Radiological Impact Assessments), a common understanding to bracket uncertainty in long-term climate modelling and to downscale the models to an appropriate scale as input for biosphere and landscape evolution modelling was developed and will be applied (IAEA 2020). Nagra has initiated a programme of climate modelling into the far future (up to 10^6 years from now). One approach involves studying past and future climate evolution on a global scale, particularly the effects of future orbital forcing and different anthropogenic CO_2 scenarios. This project is conducted in collaboration with the Potsdam Institute for Climate Impact Research (PIK, *Potsdam-Institut für Klimafolgenforschung*). Preliminary results indicate that, depending on (anthropogenic) CO_2 emission scenarios, the next severe future glaciation will not take place within 50,000 years from now. The second approach (in collaboration with the Oeschger Centre for Climate Change Research (OCCR, *Oeschger-Zentrum für Klimaforschung*) aims at improving the understanding of the influence of the global climate system on local climate in the central Alps and their northern foreland. Such models better constrain local temperatures and precipitation patterns, e.g. as input to ice flow and erosion modelling.

Erosion

The regional (erosional) base level in Northern Switzerland, which is relevant for the siting regions, is set by the Aare – Rhine river system. Deep (sub-)glacial erosion, however, can reach as far as several hundred metres below this regional base level (as has been seen in prior glacial advances from the Alps). The timing of the formation of such overdeepenings and thus their effects on the long-term safety of a deep geological repository depends on the future climatic evolution and on the potential for new incised breach channels at the sites. These processes have complex links, feedbacks and uncertainties that must be addressed to evaluate potential future evolutions. During the past five years, research investigations have addressed the Quaternary erosion history of Northern Switzerland, the understanding of fluvial and related slope processes and glacial erosion.

Quaternary erosion history of Northern Switzerland

The Quaternary erosion history allows the evaluation of past processes and rates at timescales similar to the future observation period. It is thus the most important archive for scientific observations, understanding and argumentation. An important borehole campaign was launched, incorporating drilling and coring of 11 glacial overdeepenings or paleochannels. In collaborative research with the ETH Zürich, the shallow subsurface was geophysically imaged with ultra-high-resolution techniques (Schmelzbach et al. 2018). Scientific boreholes based on this imaging provided fundamental field data to constrain the reconstruction of the most recent geological evolution of Northern Switzerland (Ebert & Decker 2019, Nagra 2019f, 2019i, 2019h, 2019g, 2019j). This approach was accompanied by further 2D seismic subsurface investigations (Nagra 2018) and age determination of Quaternary sediments from drill cores and outcrops (Büchi 2011, Müller et al. 2020). Seismic lines and sediments are currently being further analysed. Age determination from outcrops of geomorphic marker horizons (the so-called Deckenschotter, i.e. "cover gravels") focused on the method of isochron burial dating using the cosmogenic nuclides ^{10}Be and ^{26}Al (Grischott et al. 2020). Initial results reveal younger than expected ages for the *Höhere Deckenschotter* (HDS, "Upper Cover Gravels") deposits of around one million years and a shorter than expected time interval between them and the next younger *Tiefere Deckenschotter* (TDS, "Lower Cover Gravels") (Grischott et al. 2020, Knudsen et al. 2020). These ages are in strong contrast to the previous age estimate of 1.8 – 2.7 million years, which was based on mammal teeth (Bolliger et al. 1996). To better understand this discrepancy and to provide an improved age control of the geomorphic markers, a multi-chronological approach is being applied, including cosmogenic nuclide dating, luminescence, magnetostratigraphy, palynology, uranium-thorium dating of cements and biostratigraphy on mammals, molluscs and amino acid racemisation.

Fluvial processes

The main parameters driving fluvial incision are uplift/subsidence rates and erodibility, with natural feedbacks between them. A compilation of global bedrock incision rates was conducted to support the arguments for future projection (Nativ & Turowski 2020). The main activities to better understand the fluvial processes within Northern Switzerland are a study on the response of lithological contrasts to base-level drop (Yanites et al. 2017), a detailed Aare-Rhine river system review, a knickpoint celerity⁵ study along the Wutach river, a sensitivity study on model parameters

⁵ Knickpoint celerity refers to the speed at which a transient disruption within a fluvial channel migrates upwards. This velocity might be related to external factors, such as erodibility of the underlying lithology.

and forward modelling of the *Hochrhein* (High Rhine) and Aare river profiles using the Stream Power Incision Model (SPIM), as well as abrasion mill experiments on rock types from Northern Switzerland.

Local topography

The nature of fluvial channel-hillslope coupling controls the degradation and denudation of topography. Jura Ost has more local topographic features and a larger ratio of overburden above local base level than the other siting regions. A detailed analysis of the slope processes in Jura Ost with respect to geomorphic process domains and incorporating different lithologies was reported by Ludwig (2018). A similar report is currently being prepared for the Wutach topography, which is assumed to be analogous to a landscape undergoing a rapid response to base-level drop. A simplified modelling approach ("geometric model") was incorporated to show the hillslope response within the siting regions after various fluvial incision scenarios, including Nagra's 3D geological model to account for different lithologies. A workflow was designed to couple this model to the SPIM output of future fluvial incision modelling and will be applied for the decision-making related to the site selection and the safety case for the selected site(s).

Glacial erosion

Future ice ages with their associated glacial erosion and sedimentation, formation of permafrost and significant transient hydraulic, mechanical, thermal and chemical changes, could influence groundwater flow and radionuclide mobility and hence represent important external perturbations to repository evolution (Fischer et al.,). Ice-flow modelling of the Rhine glacier during the last ice age indicates that the potential for glacial erosion exists even beneath the low-lying lobes that extended far into the Alpine foreland (Cohen 2015, 2017, Cohen et al. 2018, Cohen & Juvet 2017). Significantly, ice flow is routed along troughs, some of which coincide with glacially eroded overdeepenings (Fig. 8-4). In agreement with the notion that glacial erosion scales with basal sliding, the spatial pattern of the sliding distance (sliding velocity integrated over a full glacial cycle) points to locations of intensive erosion (Cohen & Juvet 2017). For the Alpine valleys, the corresponding model calculations realistically reproduce features of deep glacial erosion. However, in the Alpine foreland, the pronounced overdeepenings extend far beyond regions of large sliding distances and thus beyond areas of glacial erosion (Fig. 8-4). This suggests that subglacial meltwater erosion and evacuation of basal sediment played a role. Improved process understanding of the mechanisms of subglacial meltwater erosion is gained through a continuation of the Greenland Analogue Project (Claesson et al. 2016, Harper et al. 2016) with other waste management organisations (SKB (Sweden), Posiva (Finland) and NWMO (Canada)). Relevant topics investigated in this project include basal water pressure conditions, hydraulic gradients and subglacial water flow at the ice-sheet scale (Harper et al. 2019). Coupling of subglacial drainage and erosion processes with dynamic ice-flow models remains a scientific challenge. Hence, the capability of a numerical glacial landscape evolution model to capture the erosion of overdeepenings in a distal foreland setting was tested. Physics-based processes were included to look at subglacial water flow and sediment evacuation, in particular along occasionally steeply inclined adverse slopes of overdeepenings. Finally, an international expert workshop on subglacial-fluvial erosion, transport and deposition organised by Nagra emphasised the benefit of a geometric and morphological characterisation of existing overdeepenings in providing an empirical quantitative knowledge base of glacial landforms (Pietsch & Jordan 2014, Haeberli et al. 2015, Patton et al. 2015, Patton et al. 2016, Haeberli et al. 2016). Subsequently, this led to the initiation of a global analogue study to collect morphometric data and, based on fact sheets, to compile associated boundary conditions.

The results of many of these studies will be published in Nagra NTB 24-03 (planned) and Nagra NTB 24-10 (planned) and their supporting documents.

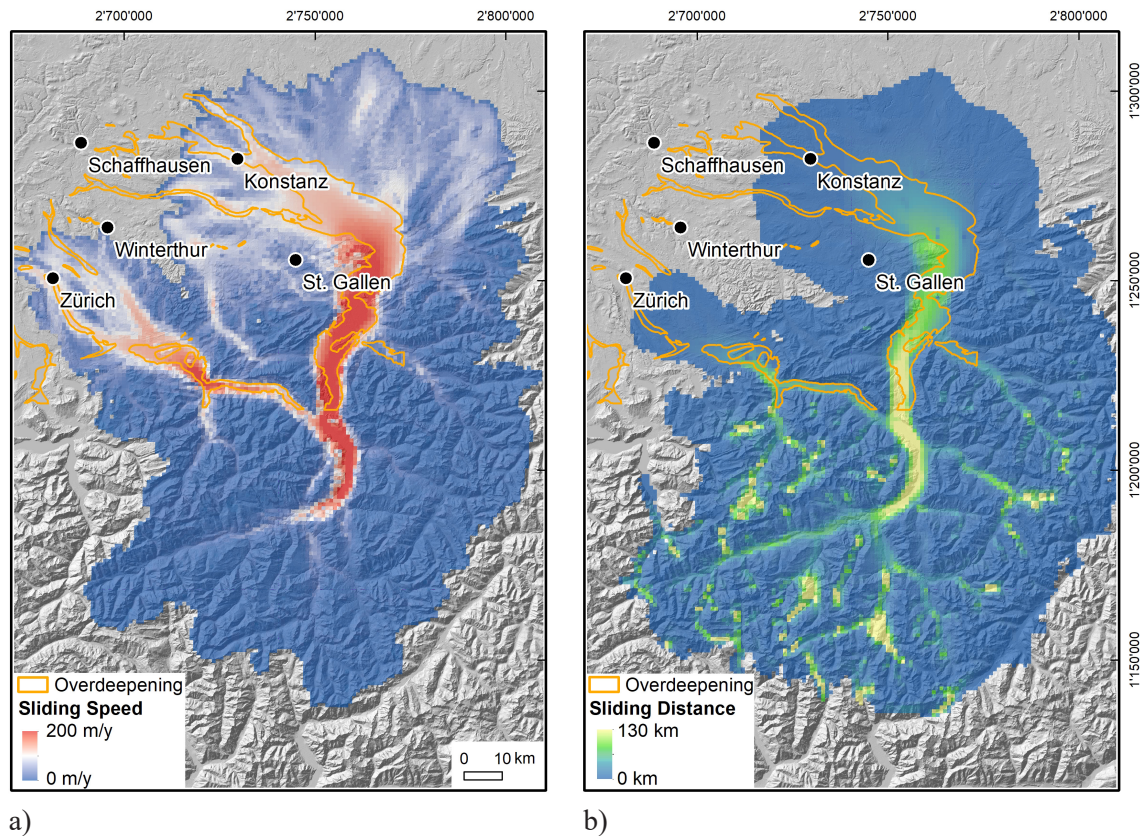


Fig. 8-4: Results of numerical simulations for the last ice-age Rhine glacier

Orange outlines indicate regions of glacially eroded troughs and overdeepened valleys:
 (a) ice sliding speed at the Last Glacial Maximum (LGM) (Cohen et al. 2018). (b) sliding distance (basal sliding velocity integrated over the last glacial cycle; Cohen & Jouvet 2017).

Planned RD&D in the next five to ten years

Data interpretation and additional localised data collection focusing on critical topics will allow the integration and development of the storyboards describing the long-term evolution as required for safety assessment. After the submission of the general licence applications, data collection of longer time-series and periodic refinement of the storyboards will continue for updated safety assessments. Long-term seismic monitoring and the development of a concept and workflow for site characterisation and seismic hazard assessment will be part of the research programme following the submission of the general licence applications and will feed into the *EUU* licence applications.

Active tectonics

The long-term effect of geodynamically driven uplift across the northern Alpine foreland is an important driver of fluvial incision (Schlunegger & Mosar 2011, Hagke et al. 2012). A recently launched project on detrital low-temperature thermochronology on samples from Nagra's deep boreholes will provide a direct marker of basin inversion in Northern Switzerland to constrain Late Miocene to recent erosion rates. The continuing collaboration with the Swiss Seismological Service (*SED, Schweizerischer Erdbebendienst*) will result in a seismotectonic model for Northern Switzerland, including detailed studies of areas of particular interest (e.g. Hegau – Lake Constance Graben, Eglisau). Efforts to reconstruct fault activity during the Quaternary will be further pursued. This includes the interpretation of specifically acquired seismic sections. Given that future tectonic activity within the repository area, possibly involving the formation of new faults, cannot be fully excluded over the period of concern, another set of activities will explore the potential effects of fault movements and seismicity on the various elements of a repository, including the geological and engineered barriers. Nagra plans to refine the regional stress model and perform numerical simulations of fault-slip tendencies. This should make it possible to identify which faults are particularly likely to slip in the current tectonic regime, but also what the potential effects of such slip events on the adjacent repository sites may be (e.g. stress deviations). Investigations on active tectonics are expected to be further pursued beyond site selection and the general licence applications and will feed into the *EUU* licence application. These investigations are likely to include more in-depth analyses of selected faults in the vicinity of the final repository site. The instrumental record of recent crustal movements (low-level seismicity, geodesy and potentially integrating InSAR) will be extended into the monitoring period for *EUU* licensing to enable detection of very low deformation rates. A geodetic strain analysis and a comparison of stress and strain using seismicity and geodetic data are planned. To characterise the seismic hazard for the subsurface infrastructure, a borehole seismometer will be installed in a deep borehole in Northern Switzerland. The empirical transfer functions (surface to repository depth) will be determined and a procedure for seismic hazard assessment at depth will be developed.

Climate evolution

Nagra will coordinate its activities related to climate evolution with other waste management organisations and has started a network/project within the IGD-TP focusing on climate change and its integration into the safety case. Global and regional climate modelling continues, global modelling simulations of the last glacial cycles are planned with high-resolution snapshots for MIS 2, 3, 4, 5e and 6, as well as a probabilistic assessment of future glacial cycles for one million years. A set of representative past key glacial cycles will then be downscaled to provide regional distributions of temperature and precipitation. While these future datasets provide inception times for future glaciations and indications of their expected severity, the simulations of past glacial cycles are used as input for ice-flow modelling.

Erosion

The focus will be on further analysing the drilled sediment samples and synthesising the results in interpretive profiles and maps across the Quaternary landscape of Northern Switzerland. Ultimately, this will add to the understanding of glacial erosion prior to the Last Glacial Maximum (LGM), thus associated with larger glacial extent. Age determination for deposits older than MIS 6 is still challenging, and further efforts are required to reach conclusive answers. To some extent, this will involve testing novel approaches, such as porewater dating or thermoluminescence in sediment cores from overdeepenings. The multi-chronological approach for outcrop dating will be continued with a subset of methods that showed promising first results (cosmogenic nuclide isochron burial, biostratigraphy, amino acid racemisation and luminescence).

Fluvial incision modelling using a Stream Power Incision Model (SPIM) will be coupled with analysis of sediment transfer models and will provide scenarios, arguments and rates of future evolutions of the Rhine and Aare rivers. These outputs will provide data for further analysis of the local topography. Synthesised results of ongoing studies on the erodibility of rock units in Northern Switzerland will provide input for the models and support the calibration of their parameters. Ultimately, the remaining overburden in the siting regions at different times will be estimated, and uncertainties will be addressed. Because future landscapes in Northern Switzerland will also be sculpted into limestone, another focus will be on karst processes and limestone denudation.

A series of studies is being considered to improve the overall process understanding of deep glacial erosion. The behaviour and extent of ice-flow systems, such as the Rhine, Aare and Rhone glaciers, will be investigated by means of ice-flow modelling under different climatic conditions. Sensitivity studies using ice flow and glacial landscape evolution models will allow the identification of controlling parameters for deep glacial erosion and sediment transfer in distal foreland settings. Important Quaternary glaciations that left an imprint in the northern Swiss landscape (LGM, Beringen, Möhlin) are classified as key glacials for comparison between their respective ice extent and ice-flow modelling results, as well as between climate proxy data and climate modelling results. The patterns of precipitation and temperature distribution derived from regional climate modelling of past key glaciations will provide input for ice-flow modelling. Potentially, past climatic and glaciological boundary conditions might be compared to expected future climate patterns to evaluate the impact of future glaciations on the siting regions. The information gained from global morphometric analyses will be evaluated to assess the lithological control on overdeepening formation (including the influence of limestone bedrock) and additional boundary conditions. A toolbox will be developed to (generically) simulate overdeepenings in order to assess the potential/probability of a future glacial overdeepening affecting a portion of the repository.

A Tier 3 roadmap describing planned activities regarding the geological evolution of the site(s) in the more distant future is described in Section 7.5.

8.2.2 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 natural subsurface processes that would also occur without the presence of a repository and are important for safety assessment. As these processes are independent of the repository concept at hand, they are included here as part of the geological understanding.

First, 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 natural phenomena are described that take place in the host rock and strongly influence the impact of the repository-induced effects. The repository-induced effects themselves are described in detail in Section 8.5. Repository-induced phenomena, such as gas and heat transport and geomechanical (and biochemical) processes, are triggered by conditions that deviate significantly from the initial natural conditions 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 to assess their impacts.

The improved process understanding thus contributes to:

- confidence that the repository-induced effects are correctly described at the conceptual and parametric levels
- assurance that the requirements on expected performance and associated performance targets formulated for assessing the impact of repository-induced effects are well-founded and complete
- assurance that these requirements and performance targets can be met in most reasonably foreseeable circumstances

Based on the current state of the art, the safety-relevant impact of repository-induced effects on the host rock for the SF/HLW and L/ILW repositories will be re-assessed as part of the documentation for *SGT* Stage 3 and for the general licence applications.

The phenomena are described here independently of each other for the sake of clarity, although it is acknowledged that a strong coupling exists between them. The joint impact of all the phenomena and the link to the requirements on expected performance and associated performance targets are incorporated and described as part of the evaluation of the near-field in Section 8.5.

Beyond the submission of the general licence applications, the state of the art will be maintained and, where necessary, further developed by Nagra for the selected site(s). Subsurface data will be acquired as part of the *EUU* activities.

8.2.2.1 Radionuclide transport

Objectives

Post-closure safety assessment requires a sound knowledge of radionuclide migration in geological media, particularly in the host rock and confining units. Suitable modelling approaches and robust datasets of transport and retention properties with uncertainty bands are needed to reliably describe radionuclide migration. In the Opalinus Clay and its confining units, diffusion and/or advection/dispersion with radionuclide-specific sorption govern the transport of radionuclides. It has been demonstrated that the transport of dissolved species is dominated by diffusion, as illustrated also by natural tracer profiles (Section 8.2.1.4). The confining units with lower clay mineral content, in contrast, contain discrete transmissive features where advective/ dispersive flow govern transport.

To assess the uncertainty of the retention properties of the containment-providing rock zone under in-situ conditions, a thorough understanding of transport and reaction processes is required. This has largely been achieved in the last 20 years by developing and refining concepts for radionuclide transport in sedimentary rocks, and the knowledge base can be considered mature, especially for the Opalinus Clay. Nonetheless, in addition to, and based on, the site-specific data that will be collected in *SGT* Stage 3, understanding is expected to be further advanced and remaining uncertainties to be further reduced.

Current state of the art and progress since the 2016 RD&D Plan

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

The status of knowledge on transport in the host rock and the confining units was compiled at the end of *SGT* Stage 2 (Nagra 2014c). The in-situ testing in the deep boreholes and the laboratory investigations within the framework of the siting activities of *SGT* Stage 3 will provide an extensive new dataset. This will allow a refined conceptualisation and parametrisation of the formations of interest with regard to radionuclide transport.

In the last 20 years, the radionuclide transport properties of the Opalinus Clay and its confining units have been studied in detail. Particular knowledge advances were made on diffusion anisotropy (van Loon et al. 2004a), confining pressure effects (van Loon et al. 2003a, 2003b, Xiang et al. 2016), pore-size effects (Appelo et al. 2010, Houben et al. 2013), anion exclusion (Wigger & van Loon 2017, 2018, Wigger et al. 2018a, 2018b, 2018c), surface diffusion (Appelo et al. 2010, Gimmi & Kosakowski 2011, Glaus et al. 2015, 2020) and temperature effects (van Loon et al. 2005b, Savoye et al. 2011, Joseph et al. 2013). The diffusion data can be upscaled from small laboratory samples via URL experiments (Tevissen et al. 2004, van Loon et al. 2004b, Leupin et al. 2017b) to the formation scale (Gimmi & Waber 2004, Gimmi et al. 2007, van Loon et al. 2012). The upscaling of diffusion processes for iodide is currently being studied in the Hydrogeochemistry and Transport Mechanisms (DR-B) experiment at the Mont Terri Rock Laboratory, which was started in 2016 and will continue over the next few years.

The implementation and parametrisation of surface diffusion and anion exclusion models for various types of cations and anions in the pore space of negatively charged clay minerals play a crucial role in the transfer of sorption data for strongly sorbing tracers obtained from dispersed systems to those of an intact rock system. In *SGT* Stage 2, an empirical approach was used to develop diffusion databases for the safety analysis (van Loon 2014, van Loon & Mibus 2015). The approach was established using non- or weakly sorbing tracers (e.g. Na^+ , Sr^{2+} , U^{6+}), with

experiments and modelling studies supporting the transferability of sorption data to the compact rock system (van Loon et al. 2005a, 2009, Joseph et al. 2013). The approach, however, had not been validated for strongly sorbing tracers (e.g. Cs^+ , Co^{2+} , Zn^{2+} , Eu^{3+}). Over the last few years, research efforts have provided a better understanding of the transferability of sorption data for strongly sorbing tracers (Glaus et al. 2015, 2020, Montoya et al. 2018, Savoye et al. 2015, Maes et al. 2017a, 2017b). Ongoing work at PSI over the next few years focuses on the influence of competing ions and aims to evaluate the impact of sorption competition on transferability. The currently available data indicate that it is feasible to predict the diffusive transport properties of a variety of elements for which no diffusion data are available, based on the diffusive transport behaviour of selected elements.

Sorption of radionuclides onto clay surfaces

The methodology developed by PSI for deriving sorption databases for argillaceous rocks has advanced over the last two decades (Baeyens & Bradbury 2017, Bradbury & Baeyens 2017, Bradbury et al. 2017, Bradbury & Baeyens 2003, 1997, 2011, Bradbury et al. 2008, 2010, Fernandes et al. 2015). The latest approach, used in *SGT* Stage 2, is based on sorption isotherms measured on pure clay minerals (Baeyens et al. 2014b). The method is adapted to 2:1 clay minerals (e.g. illite and montmorillonite), which are the clay minerals dominating sorption in the Opalinus Clay, in most of the confining units and in the bentonite buffer. In recent years, other waste management organisations have published sorption databases for sedimentary rocks, for example NWMO (Canada) (Vilks & Yang 2018), JAEA (Japan) (Sugiura et al. 2018) and COVRA (The Netherlands) (Schröder & Meeussen 2017a, 2017b).

The so-called "bottom-up" approach based on a mechanistic understanding of sorption processes on pure clay minerals (Fernandes et al. 2015, Bradbury & Baeyens 2011, Baeyens & Bradbury 2017) will be used to derive sorption data for the safety analysis in *SGT* Stage 3. To further develop the "bottom-up" approach so that it can be applied to redox-sensitive radionuclides for which the sorption behaviour is still subject to some uncertainty (Ma et al. 2019), sorption experiments on redox-sensitive radionuclides such as U, Np, Tc and Se are currently being conducted at PSI. Sorption measurements on samples from the Opalinus Clay and the confining units, obtained in Nagra's deep borehole campaign in the three potential siting regions, will provide data for the further validation of the "bottom-up" approach.

Prior to *SGT* Stage 3, the competition of radionuclides and stable elements for sorption sites was considered in the safety analysis in a simplified way. PSI has recently conducted studies on competitive sorption between elements with different valence states on illite and montmorillonite (Baeyens & Bradbury 2017, Bradbury et al. 2017, Fernandes & Baeyens 2019, Nagra 2020a) (Fig. 8-5). Chemically similar elements (valence state, hydrolysis behaviour) have been shown to sorb on the same set of strong sites and exhibit sorption competition, whereas chemically dissimilar metals sorb on different strong site sets and either do not compete or can only partially compete with one another.

The behaviour of low molecular weight organic compounds in the host rock was studied to assess their impact on ^{14}C transport in the geosphere and the implications for dose calculations (Chen et al. 2018b, 2018c). A weak retardation of the organic compounds was observed.

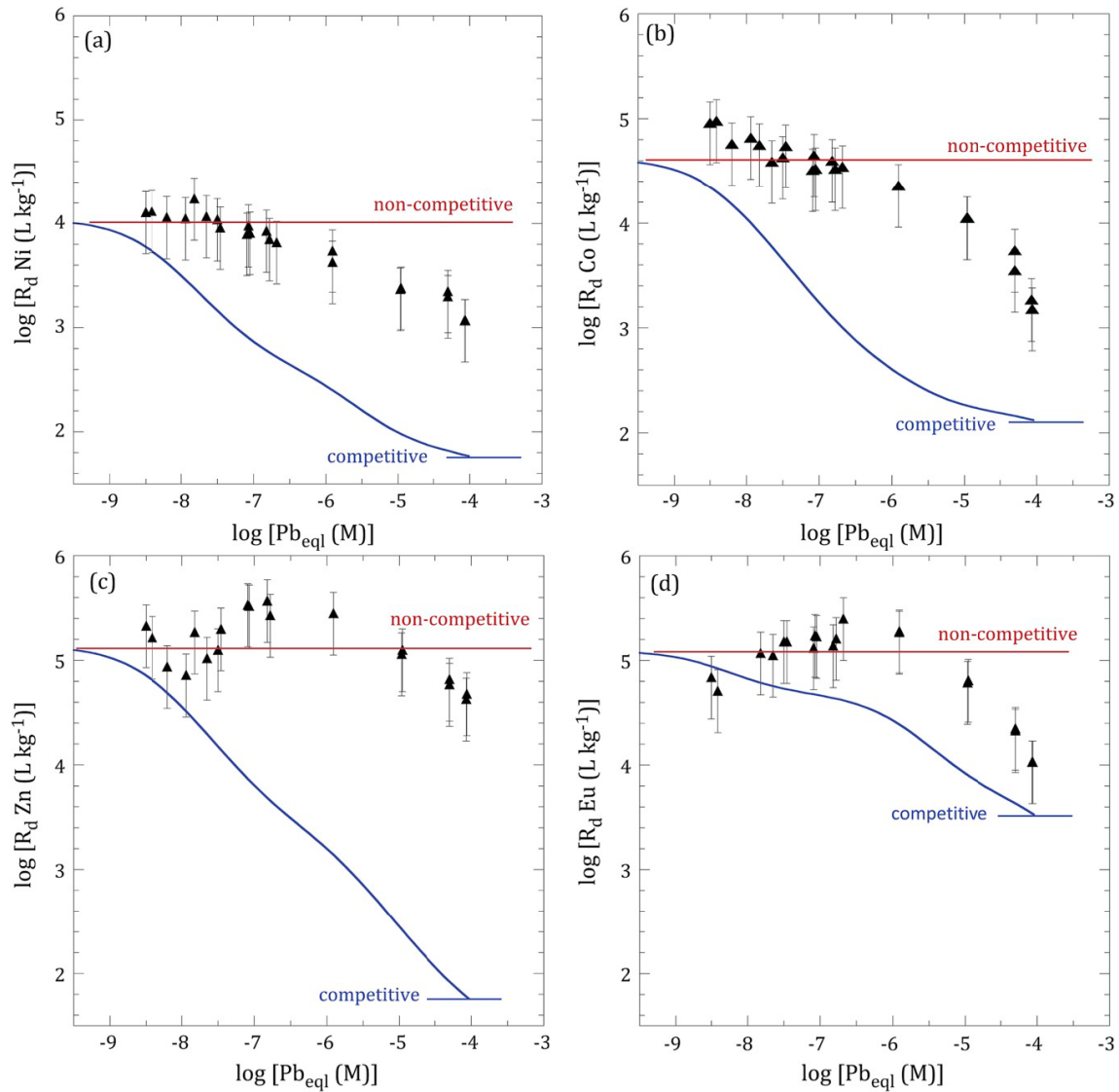


Fig. 8-5: Competitive sorption on illite with Pb^{2+} as blocking element in the presence of a) Ni^{2+} , b) Co^{2+} , c) Zn^{2+} and d) Eu^{3+}

From Fernandes & Baeyens (2019).

Black triangles indicate experimental data, while the red and blue lines indicate modelling results for non-competitive or mutually competitive situations, respectively. For the cases where partial competition is experimentally observed (e.g. (a), (b) and (d)), the data can be modelled by assuming that a given fraction of the strong sites is accessible only to the trace element, and that both trace and blocking element adsorb on the remaining fraction.

Concepts for radionuclide transport in safety analysis

Within the framework of *SGT* Stage 2, concepts for radionuclide transport were developed for the provisional safety analyses (Nagra 2014c, 2014b). Nagra's deep borehole campaign will provide the site-specific validation of these concepts for the safety assessment in *SGT* Stage 3.

Planned RD&D in the next five to ten years

Diffusive radionuclide transport in the containment-providing rock zone of similar high quality

Major laboratory work at PSI on diffusion processes in the geosphere, with a focus on the containment-providing rock zone to support the general licence applications, will be finalised in 2023 with the end of the EURAD GAS work package (2019 – 2023). In this work package, PSI studies the diffusion processes of gases, such as methane or hydrogen, in fully and partially saturated conditions in various materials. Methane is the most relevant gas phase containing ^{14}C , a dose-dominating radionuclide for the L/ILW repository (see Section 8.3.3.4). The results from this study will contribute to the treatment of volatile radionuclide transport in the safety assessment.

Sorption of radionuclides onto clay surfaces

With the conclusion of the EURAD FUTuRE (Fundamental Understanding of Radionuclide Retention) work package (2019 – 2023), major laboratory work at PSI on sorption processes in the geosphere will be finalised in 2023. In this work package, PSI studies adsorption reversibility and the nature of mechanisms controlling radionuclide retention over long time periods, e.g. adsorption versus incorporation, in more detail.

For the two topics above, the maturity of the understanding in the Opalinus Clay and the confining units will be fit-for-purpose to be integrated in the safety analysis by around 2023.

Concepts for radionuclide transport in safety analysis

In *SGT* Stage 2, concepts for radionuclide transport were developed for the provisional safety analyses (Nagra 2014c, 2014b). The concepts considered transport dominated by diffusion in the Opalinus Clay matrix, assuming the absence of relevant advective flow along fractures, and a variety of conceptual models for diffusive and advective-dispersive transport in the confining units that are characterised by a more heterogeneous lithology.

Nagra's deep borehole campaign in *SGT* Stage 3 will provide site-specific information for updating, as necessary, the concepts developed in *SGT* Stage 2 for radionuclide transport in the containment-providing rock zone. Nagra will apply these concepts in the safety assessment for *SGT* Stage 3.

PSI will finalise the measurements of diffusion and sorption on samples from the deep borehole campaign. The diffusion coefficients derived for three selected tracers (HTO, Cl^- , Na^+) and diffusion-accessible porosities will provide important additional information on the radionuclide transport processes in the containment-providing rock zone, and potential differences between the three siting regions.

Nagra and PSI will continue integrating and participating in international research on this topic in anticipation of the updates of the safety cases for the construction licences.

8.2.2.2 Gas transport

Objectives

In a deep geological repository, gases are generated as a result of the anaerobic corrosion of metals (which produces H_2), microbial and chemical degradation of organic matter (which may produce gaseous compounds, CO_2 , CH_4 , that may incorporate ^{14}C and other volatile radionuclides; see Section 8.3.3.5) and radiolysis of water (which principally produces H_2). Other gas sources such as helium generated through alpha decay are minor in comparison.

If the production rate of gas is higher than can be taken up through dissolution and diffusion, a free gas phase will form and accumulate, with increasing gas pressures, that will eventually be released along the backfilled underground structures or through the host rock.

The principal impact of gas is expected to be increased pore pressures, leading to changes in effective stress in the surrounding host rock and potentially affecting its mechanical integrity (reactivation of faults, creation of gas fractures). These effects, if they were to occur, could compromise requirements placed on the expected performance of the host rock, and performance targets for gas overpressure have been set accordingly. Adherence to these targets then has to be assessed.

In this section, emphasis is placed on the phenomenological understanding and conceptualisation of gas transport processes in the Opalinus Clay and on the associated mechanical impact on the rock. The simulation of the associated gas transport and deformation mechanisms uses thermo-hydro-mechanical (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 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 described in Sections 8.5.2.1 (HLW) and 8.5.2.2 (L/ILW). Gas generation, including the possibilities for its reduction, are discussed in Section 8.3.3.5.

Current state of the art and progress since the 2016 RD&D Plan

Gas transport through low-permeability rock formations is controlled by the hydraulic and mechanical properties of the intact rock mass (intrinsic permeability, porosity, rock stiffness and strength), by the tectonic overprint of the rock in the siting area (fracture patterns and properties, residual stiffness and strength of the fractured rock mass), 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 of gas transport since gas was identified as a potentially safety-relevant issue in the late 1990s (Nagra 1997, 2004, Marschall et al. 2005, Nagra 2008a, Romero et al. 2012, Senger et al. 2014b, Ferrari et al. 2014).

Confirmation of the phenomenological understanding of gas transport in disturbed and undisturbed Opalinus Clay and similar host rock types has been obtained through the Euratom Near-field Processes (NF-PRO) and especially the Fate of Repository Gases (FORGE) projects (Marschall et al. 2013, Harrington 2013). In the FORGE project, the focus was on the interpretation of gas-related laboratory and in-situ experiments, previously conducted at the Mont Terri Rock Laboratory (HG-A (gas paths through host rock and along seals) and HG-D (reactive gas transport in argillaceous formations) experiments, 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. The phenomenological and conceptual description of flow and transport processes in the Opalinus Clay was complemented by microstructural conceptualisations, revealing that, in ultra-low-permeability rock such as the Opalinus Clay, a network of connected pores in the micro- to nanometre size range defines the space where flow of immiscible fluids can occur (Keller et al. 2013).

Since the 2016 RD&D Plan, major efforts have been dedicated to the experimental investigation of gas transport processes in triaxial cells and model-based analyses of the test results (Romero & González-Blanco 2015, Minardi 2018, Senger et al. 2018). Furthermore, Nagra takes a leading role in the EURAD GAS work package (2019 – 2023) aimed at (i) improving the mechanistic understanding of gas transport processes in natural and engineered clay materials and (ii) evaluating the gas transport regimes that can be active at the scale of a geological disposal system and their potential impact on barrier integrity and repository performance. In this context, Nagra coordinates Task 3 ("barrier integrity"), associated with the gas-induced failure of clay barriers and the effectiveness of self-sealing processes along gas-induced pathways in the clay barriers. The evaluation will be accomplished using model-supported data analyses, predictive modelling and the application of new modelling tools to in-situ experiments. On the experimental side, Nagra supports three research teams in the EURAD GAS work package (EPFL, ZHAW, UPC). The laboratory experiments comprise gas-induced fracture initiation and propagation experiments on Opalinus Clay core samples from the deep borehole campaign and experiments on mechanistic understanding of self-sealing mechanisms along gas-induced fractures. Special focus is on the characterisation of gas transport properties of remoulded and reconstituted Opalinus Clay samples, aimed at mimicking gas transport in fault gouge material.

In *SGT* Stage 3, further in-situ gas threshold pressure tests have been conducted in the siting regions, and a criteria-based indicator workflow has been developed to ensure a traceable site selection process ("Model-based assessment of repository-induced effects" – MARIE). Repository-induced effects are one of the 13 criteria specified by the regulatory authority for site evaluation, and gas-related impacts have been formulated as a key aspect to be assessed. Nagra has set out a model-supported performance assessment approach for a balanced quantitative evaluation of the impacts of gas release in the three siting regions. The documentation will be published as part of the general licence applications.

Planned RD&D in the next five to ten years

The MARIE modelling framework will be applied for the quantitative evaluation of gas-related impacts in the three siting regions. The potential for activating steeply dipping faults and the potential for fault leakage will be addressed for each site. The performance of the sites with respect to the gas-related performance indicator will feed into the overall evaluation of the sites. After completion of the site selection process, further analyses of gas release are envisaged, aimed at safety-related repository optimisation and performance assessment, contributing to the safety case for the general licence applications. This includes a detailed evaluation 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

- modelling tools for site-specific analyses of gas transfer through the host rock (matrix flow and fracture flow, respectively) and for design optimisation
- evidence from in-situ (validation) experiments, demonstrating the transferability of gas transport mechanisms and the corresponding properties from the laboratory scale (centimetre scale) to the tunnel scale (decimetre to metre scale)

The focus of the activities in the next years will be on refining and completing the elements above, and more specifically on:

- Completion of the EURAD GAS work package contributing to the extension of the existing experimental database on relevant gas transport mechanisms and the corresponding gas-related properties of the Opalinus Clay. Special focus will be on the phenomena and processes related to gas-induced damage initiation and propagation and on self-sealing of gas-induced fractures. Representative core samples for laboratory experiments will be recovered as part of the deep borehole campaign. Dedicated gas threshold pressure tests in the investigation boreholes in the siting regions will provide complementary information about gas transport in tectonic features.
- Development and benchmarking of upscaling techniques for modelling gas transport in heterogeneous media (porous media, fractured media) within the framework of existing international collaborations (SKB's Modelling Task Force on Engineered Barrier Systems) 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 (parametric models and effective model parameters, respectively).
- Development and benchmarking of assessment workflows aimed at evaluating the risk of gas-induced fracture re-activation at the candidate sites. This includes the development and testing of new hydromechanical coupled models for gas-induced damage initiation and propagation. Furthermore, nested workflows will be elaborated, which allow the transfer of available site- and regional-scale information on in-situ stress, pore pressure and temperature to the scale of the repository near-field.
- Ongoing survey of the state of the art through literature studies on specific topics (gas sorption, saturation-dependent diffusion coefficients, natural gas seeps). This includes analogue studies of subsurface applications that generate increased pressurisation (natural gas storage systems, CO₂ storage studies, hydrocarbon industry findings, etc.).

8.2.2.3 Geomechanical processes

Objectives

Geomechanical processes control rock mass behaviour and the hydraulic properties of the host rock. They are therefore relevant to various functional requirements such as excavation support design and maintaining the barrier function after emplacement. Extensive experience has been 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 boreholes. Transfer of these empirical data from laboratory tests to the scale of underground structures and from the Mont Terri Rock Laboratory to the siting regions, taking into account the different geomechanical conditions (Section 8.2.2.3), has to be undertaken as far as this can be justified by the data available. This essentially requires a quantitative understanding of the material behaviour (i.e. a constitutive model).

Given the very low conductivity of the intact host rock, open connected fractures would have to be present before significant advective flow could occur. From a safety perspective, the critical geomechanical process with the potential to impair barrier integrity is therefore fracturing associated with fracture dilation. Mechanical properties, pore pressure and the stress field (Section 8.2.1.3) provide constraints on the conditions under which dilatancy could occur, either by fracture initiation or fault reactivation for a given orientation of the dominant fault plane.

Fluid pressure will be affected by, e.g., gas pressure buildup (Section 8.2.2.2) or thermal effects associated with heat-generating SF/HLW (Section 8.2.2.4) and maintaining the fluid pressure well below the levels needed for fault reactivation is a crucial aspect of repository design. A suitable construction depth is also chosen to minimise the risk that the host rock will, in the long term, be brought into the extensive fracture domain by uplift and erosion.

Hence, robust geomechanical process understanding is mainly used for design purposes, especially avoiding the occurrence of dilatant fault reactivation. However, the most relevant geomechanical processes that could occur in the Opalinus Clay as a host rock are related to its volumetric behaviour following the generation of fractures or reactivation of existing fractures. This is covered in more detail in the section on self-sealing (Section 8.2.2.5).

Current state of the art and progress since the 2016 RD&D Plan

Opalinus Clay exhibits a strong hydromechanical coupling due to 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 (Monfared et al. 2011, Ferrari et al. 2016, Giger et al., Belmokhtar & Delage 2018, Minardi et al. 2021) and also in instrumented fault reactivation (e.g. Guglielmi et al. 2020) and mine-by tests at Mont Terri (Lanyon et al. 2014b, Giger et al. 2015, Marschall et al. 2017, Lanyon 2019).

Hydromechanical coupling is expressed in the following three key categories characterising the geomechanical behaviour of the Opalinus Clay:

- *Volumetric behaviour*: Change in mean stress leads to a reduction (consolidation) or increase (swelling, see self-sealing in Section 8.2.2.5) of pore space under drained conditions. Mechanical properties such as stiffness and strength are directly related to the consolidation state of the Opalinus Clay (Marschall & Giger 2016). It is noteworthy that porewater drainage or uptake is time-dependent and controlled by the low permeability of the Opalinus Clay.
- *Shear behaviour*: Shear deformation is related to a change in the deviatoric stress. The pore pressure coupling during shear deformation is a function of the stress path and the loading direction with respect to the bedding plane (Giger et al., Minardi et al. 2021, Wild & Amann 2018a, 2018b). This is also corroborated by theoretical analyses of anisotropic (transversely isotropic) materials such as the Opalinus Clay (Graham & Houlsby 1983). Failure in the Opalinus Clay is characterised by strain localisation (development of rather discrete shear planes) and observed 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. 2014, Wild et al. 2015). It was also demonstrated at the Mont Terri Rock Laboratory 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. the niche of the Fracture Generation experiment (EZ-B); Möri et al. 2010). Control of relative humidity (ventilation) is therefore recognised as a key aspect to be considered during the construction and operation of underground structures.

Quantifying the underlying physical processes controlling the geomechanical behaviour of the Opalinus Clay requires reliable testing in the laboratory. As emphasised in Section 8.2.1.3, Nagra has developed advanced triaxial testing procedures in recent years and validated them in a benchmark study on Opalinus Clay cores from the Mont Terri Rock Laboratory (Minardi et al. 2019). This is a major advance since the 2016 RD&D Plan, and the test results have allowed more detailed quantification of the geomechanical behaviour and of hydromechanical coupling.

The constitutive law used for Opalinus Clay depends on the geomechanical application (Nagra 2014c), but generally comprises an elasto-plastic material law combining critical state soil mechanics (volumetric behaviour) and a Hvorslev limit state (shear behaviour). It accounts for stress-dependent properties as a function of the consolidation state, but it is widely recognised that there are limits to the extent to which post-failure behaviour, anisotropy and time-dependent behaviour can be captured. In recent years, the constitutive models have been improved by incorporating aspects such as stiffness degradation (Parisio & Laloui 2017) and anisotropy of both stiffness and strength (Mánica et al. 2016, Mezger 2019).

There is evidence that mineralogical and structural variability within the Opalinus Clay can strongly impact its geomechanical behaviour. This has been observed in laboratory testing (e.g. Bossart & Thury 2008, Ferrari et al. 2010) and in deep boreholes (Matter et al. 1987, 1988, Nagra 2001, Ebert 2014). At the Mont Terri Rock Laboratory, excavation rate and convergence data indicate strong differences between the shaly facies and sandy facies of the Opalinus Clay (Lanyon et al. 2014b), as well as across fault zones within the same facies (Thöny 2014). The relevance of such mineralogical variability lies mainly in the relative proportions of clay minerals versus larger grains, which can be expressed as a range with its end-members being either framework-supported or matrix-supported structures (Bourg 2015). However, even considering such variability, based on experience from the hydrocarbon industry it can be demonstrated that the Opalinus Clay has mechanical properties that are comparable to many of the shales that have acted as effective top seals in hydrocarbon reservoirs, even when they are extensively faulted (Fisher et al. 2013).

In their literature survey, Fisher et al. (2013) also concluded that one key requirement for reservoir top seals to act as fluid pathways over significant timescales is the maintenance of high fluid pressures. This is consistent with in-situ tests at the Mont Terri Rock Laboratory, where a significant increase in fluid flow in faults was only achieved (or fracture closure impeded) if the effective stress was very low (Nagra 2002c).

Additional evidence for the restriction of fracture dilation to situations of low effective stress comes from shallow boreholes. A detailed analysis of the Opalinus Clay directly underlying Quaternary sediments has shown that the occurrence of fractures and meteoric water signatures are limited to the uppermost 20 to 30 metres (Vogt et al. 2017, Crisci et al. 2019) in a weakly disturbed tectonic situation (Tabular Jura) with moderate topography. This is consistent with previous observations in the Swabian Alb (Tabular Jura), indicating that fracture-controlled flow in the Opalinus Clay is restricted to the uppermost 50 metres (Hekel 1994). In a tectonically disturbed environment (Jura Fold and Thrust Belt) with well-pronounced topography, occasional minor advective flow along fractures or so-called 'wet spots' have been observed down to a depth of 300 metres (Gautschi 2017).

In summary, Opalinus Clay exhibits brittle behaviour under repository-relevant conditions (both during excavation and during long-term evolution) characterised by the generation of fractures. Fractures may control fluid flow if dilation occurs, but this requires the maintenance of high pore pressures or low effective stresses (1 to 2 MPa). Otherwise, mechanical closure and self-sealing processes (Section 8.2.2.5) determine the hydraulic properties of fractures.

Planned RD&D in the next five to ten years

The geomechanical database is currently being extended by carrying out a large number of laboratory tests on cores from the deep borehole campaign (Section 8.2.1.3). These tests will document material heterogeneity and the effect of different stress paths and will also provide a more complete picture of hydromechanical coupling. Particular attention will be given to linking the results of deformation tests to basic properties (such as mineralogy), and an attempt will be made to establish a facies-specific database. Fault material from Mont Terri and Nagra's deep boreholes will also be further characterised by various imaging techniques and laboratory tests. Active in-situ testing (hydraulic and geomechanical) in the deep boreholes will further complement Nagra's qualitative and quantitative understanding of self-sealing in the Opalinus Clay. In agreement with recommendations⁶ by the Expert Group on Nuclear Waste Disposal (EGT), the deviated Rheinau borehole is specifically dedicated to this aspect, targeting an anticipated fault zone for characterisation of barrier integrity in the region of a future repository.

Constitutive models will be further developed (including numerical implementation) and calibrated against these new test results. The constitutive models will be validated by comparing their results with excavation data, notably the new data from the recently completed extension of the Mont Terri Rock Laboratory. Scaling of rock properties to rock mass properties in the Opalinus Clay will be further explored by performing active and passive measurements at different scales, from laboratory core specimens to boreholes (dilatometer/pressure meter and sonic logging), and to the tunnel scale.

The literature survey (Fisher et al. 2013) will be updated, taking account of the vast experience gained over the past ten years from both unconventional reservoirs (resource shales) and caprocks used for plugging and abandonment of wells.

8.2.2.4 Thermal effects

Objectives

SF/HLW emits heat immediately after emplacement and for many decades thereafter. In the early phase, due to differential thermal expansion of water and minerals, the Opalinus Clay reacts to a temperature increase with a rise in the porewater pressures and associated mechanical effects on the solid skeleton, potentially leading to fracture initiation in the intact rock mass or fault reactivation in a tectonically overprinted rock mass. The thermo-hydro-mechanical (THM) response of the Opalinus Clay and the upper confining units has to be sufficiently understood to assess the consequences with respect to their role as a transport barrier for dissolved radionuclides and to assess the impact on the overburden (surface heave) and potential neighbouring faults. Pore pressures have to remain below a specified threshold to ensure that the natural barrier is not subject to potential sub-seismic damage (creep) or induced seismicity. This threshold defines a performance target relevant to the repository-induced effects of 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 8.2.2.3.

⁶ Gas SGT E3 (Recommendations for Supplementary Investigations related to Repository Gas Transport in the Opalinus Clay – EGT (egt-schweiz.ch), 10th July 2020.

The objective of the following 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 a particular focus on:

- extension of the experimental THM database, providing new insights into the long-term deformation behaviour of the Opalinus Clay and the upper confining units in response to thermal perturbations (thermal consolidation, thermally induced loss of strength, enhanced creep, thermal fracturing)
- 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)
- assessment of expected overpressure development and the risk of fault (re-)activation at the repository scale for the selected sites. These model-supported assessments contribute significantly to the definition of requirements with respect to the optimisation of the thermal loading of the canisters as well as the minimum required spacing between the waste packages and between the emplacement drifts and thus to the optimisation of the overall layout and footprint of the HLW repository.

Although increased temperatures can potentially also influence chemical processes, these are not a main concern as the temperature increase is limited to below the paleotemperature of the Opalinus Clay and is of short duration (in the order of a few decades), so the impact on chemical processes is assumed to be minimal.

Current state of the art and progress since the 2016 RD&D Plan

The impact of heat 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. More moderate but nonetheless significant 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 stiffness of the clay, these are smaller than the thermally induced deformations. Other couplings are likely to have a smaller impact.

Since the 2016 RD&D Plan (Nagra 2016b), significant progress has been made in assessing the thermal impact on repository performance, comprising THM characterisations in the laboratory, interpretation of experiments at the URL scale and the development of model-supported assessment workflows in support of the site selection process.

A series of heater tests of increasing complexity has been carried out at the Mont Terri Rock Laboratory to better understand heat transfer through the engineered and natural barriers of a HLW repository and related processes. After the first heater tests in direct contact with the Opalinus Clay (Wileveau & Rothfuchs 2007), HE-E experiment, a 1:2 scale heater test, showed that measured results were in good agreement with state-of-the-art THM models (Gaus et al. 2014). These observations and the corresponding modelling framework are now being confirmed based on the monitoring data from the FE experiment, the 1:1 scale heater test at the Mont Terri Rock Laboratory initiated in early 2015 (Müller et al. 2017), as described in Nagra (2019a). The international Modelling Task Force, as part of the FE experiment, was launched in 2019 to confirm the completeness and technical readiness of the conceptual THM framework needed to assess the

impact of repository-induced effects on the long-term performance of the HLW near-field (covering the full spectrum of relevant phenomena and processes). Specific aims are the calibration and validation of THM models (Alcolea in prep.).

At the laboratory scale, THM tests were conducted on Opalinus Clay samples from the Mont Terri Rock Laboratory and the Schlattingen-1 borehole, including suction measurements, oedometer tests and triaxial tests on core specimens in the temperature range 20 – 80 °C (Favero 2017). In the context of *SGT* Stage 3, Opalinus Clay core samples from the deep borehole campaign in the three siting regions have been subjected to a comprehensive THM characterisation in the temperature range 80 – 120 °C (Seiphoori 2021).

A methodology for an indicator-based assessment of heat- and gas-induced effects in an SF/HLW repository in the Opalinus Clay has been developed, which integrates a probabilistic treatment of parametric uncertainty (Papafotiou et al. 2016, 2019a). A prediction-evaluation exercise was launched in the context of the FE experiment at Mont Terri, aimed at building confidence in Nagra's thermo-hydraulic modelling approaches (Papafotiou et al. 2019b).

Nagra participates in the EURAD HITEC (Influence of TEMperature on Clay-based material behaviour) work package (2019 – 2023), which aims (i) to improve understanding of the THM behaviour of clay rock and engineered clay material (buffer) under high temperatures and to provide suitable THM models for both clay host rock and clay buffer, (ii) to better assess the effects of overpressures caused by the heat produced by radioactive waste on the THM behaviour and properties of the clay host rock, and (iii) to identify processes occurring at high temperatures and the impact of high temperatures on the THM properties of the buffer material.

Large 1:1-scale experiments have also been conducted in other programmes, and full-scale demonstrations are being analysed at the Meuse/Haute Marne URL (France) and at the HADES URL (Belgium), where the large-scale in-situ PRACLAY Heater and Seal Tests were initiated in early 2015 (Dizier et al. 2021).

Planned RD&D in the next five to ten years

Repository-induced effects are one of the 13 criteria in the Sectoral Plan that must be taken into account to ensure a traceable site selection process. Thermal impacts in particular have been identified as a key aspect to be assessed in the context of the HLW programme. A model-supported performance assessment approach will be applied for quantitative evaluation of thermal impacts in the three siting regions. After successful completion of the site selection process, further analyses of thermal impacts will be dedicated to safety-related repository optimisation and performance assessment, contributing to the safety case for the general licence applications. The focus of the RD&D activities in the next five to ten years will be on the refinement and completion of the THM-related performance assessment workflows and, more specifically, on:

- Extension of the existing THM-related database, comprising thermal conductivity at various temperatures and bedding anisotropy, mechanical response to thermal loading in triaxial configurations (e.g. thermal expansion/thermal consolidation along relevant stress paths). Empirical correlations between THM properties and other petrophysical properties of the Opalinus Clay will be derived as a prerequisite for site-specific assessments of repository-induced effects in the context of the site selection process.
- Development and benchmarking of probabilistic assessment workflows, aimed at evaluating the likelihood of thermally induced fracture re-activation at the potential repository sites in Northern Switzerland.

- Development and benchmarking of workflows for repository optimisation from the thermal perspective. Repository optimisation will already be undertaken in the context of the general licence applications (e.g. combined disposal: minimum distance between L/ILW and SF/HLW repositories) and will gain further importance during future licensing steps.
- The HE-E and FE experiments at the Mont Terri Rock Laboratory will be continued for several years. The increasingly extensive dataset will allow significant model validation and refinement in the context of the FE Modelling Task Force, in the EURAD HITEC work package and as part of the DECOVALEX programme (DEvelopment of COupled Models and their VALidation against EXperiments).
- 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 to the thermal pulse in different types of clay rocks.
- Developments in related geodomains (e.g. applications for hydrocarbon and geothermal purposes) will be monitored.

8.2.2.5 Self-sealing

Objectives

Self-sealing is a favourable feature of the Opalinus Clay and other clay-rich host rocks: upon re-saturation, it ensures the recovery of the barrier function when the rock is fractured. The capacity of the rock to self-seal is of special significance in the context of repository-induced effects (damage to the host rock due to excavation processes, gas- and thermally induced porewater overpressures) and long-term geological evolution (fault (re-)activation in response to neotectonic processes, erosion and glaciation).

Data on the Opalinus Clay indicate that the transmissivity of fractures is restricted provided the rock is saturated and there is sufficient mechanical confinement (typically $T_f < 1 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$ when mean effective stress is $> 3 \text{ MPa}$, corresponding to an overburden of $> 200 \text{ m}$).

The objective of the work described below is to further confirm confidence in the processes associated with self-sealing and to further constrain the range of conditions and properties under which this occurs. A particular focus is on:

- collection of further phenomenological and experimental evidence, confirming the self-sealing capacity of clay-rich rocks for a wide range of THM conditions and host rock mineralogy
- refinement of mechanistic (conceptual) models of self-sealing and their implementation in application-oriented numerical simulation tools
- further confidence-building through advanced in-situ validation experiments (e.g. in the Mont Terri URL)

Current state of the art and progress since the 2016 RD&D Plan

The state of the art with respect to self-sealing, especially in the Opalinus Clay, is mature. Based on earlier phenomenological evidence, the following self-sealing mechanisms were identified as important:

- compaction of the solid framework (consolidation)
- mechanical closure of fractures (increased normal stress, contraction by shear, creep)

- physico-chemical interaction between porewater and clay platelets (swelling)
- sedimentation (colloidal phases) and precipitation (solutes) on fracture walls

The current understanding of self-sealing processes has been refined since 2016, the principles identified remain valid and the current concepts are still similar to those developed by Fang et al. (2017), based on laboratory studies on cores from a range of mudrocks, including the Opalinus Clay.

Also, empirical evidence for the efficient self-sealing capacity is provided by the compilation of all available hydraulic packer test in boreholes in the Opalinus Clay – many of them containing faults – showing very low hydraulic conductivities $< 10^{-12} \text{ m s}^{-1}$ at depths below 300 m (data until 2017; Gautschi 2017).

In the Swiss HLW disposal concept, thermal impacts on the self-sealing capacity of the Opalinus Clay are of limited relevance, as the Opalinus Clay has experienced elevated temperatures in the past while still maintaining its self-sealing capacity. The thermal transient in the host rock around the HLW emplacement tunnels is not expected to exceed these paleotemperatures⁷. A synopsis of studies on thermal consolidation and irreversible hydromechanical processes in the Opalinus Clay is given in Nagra (2014c).

Bock (2015) estimated a clay mineral content threshold below which self-sealing might be ineffective. He conservatively assumed this threshold value to be about 40% depending on the type of clay minerals, with a lower threshold in the presence of swelling clays (smectites). Similar values have been derived by recent studies by Bourg (2015) and Bourg & Ajo-Franklin (2017), building on previous work by Crawford et al. (2008).

Seiphoori (2019a) performed a detailed characterisation of Opalinus Clay mineralogy, micro-fabric and pore structure, together with a series of triaxial tests on artificially fractured samples, to investigate different self-sealing mechanisms. The opening and closure of the fractures under normal load were characterised using X-ray micro-computed tomography. A rapid permeability reduction was observed upon wetting due to hydration and swelling of the clay minerals on the fracture surfaces. The results provide supporting evidence for Nagra's conceptual framework of fracture closure and self-sealing. The impact of diagenesis on pore structure and mechanical properties was investigated in a related study (Seiphoori 2019b).

Recent studies on Callovo-Oxfordian Clay samples showed a similar behaviour: rapid self-sealing of artificial flow channels at the core scale (Giot et al. 2019, Di Donna et al. 2019) and the influence of mineralogy on self-sealing processes. Further phenomenological evidence of self-sealing and of the importance of wetting and swelling is provided by the recent studies of Laurich et al. (2019) and Voltolini & Ajo-Franklin (2020).

The sealing of reactivated faults is being investigated as part of the FS-B/C (Fault Slip) experiments at the Mont Terri Rock Laboratory, where fault rupture zones induced during the Fault Slip experiment (Guglielmi et al. 2020) are being characterised.

⁷ The paleotemperature represents the maximum temperature of the Opalinus Clay during burial history.

Planned RD&D in the next five to ten years

Through its participation in the EURAD GAS work package (see Section 8.2.2.2), Nagra will benefit from a comprehensive experimental programme dedicated to the effectiveness of self-sealing processes along gas-induced pathways in the clay barriers. Nagra's geotechnical competence centres (EPFL, UPC) will gain further insights into the associated phenomena and processes that will support the development of advanced mechanistic models of self-sealing in clay-rich media. As part of a collaborative initiative between the EURAD GAS and HITEC work packages, the project partners agreed to perform self-sealing tests on claystones at elevated temperatures.

A laboratory programme on core samples from the deep borehole campaign as part of *SGT* Stage 3 aims at characterising the THM properties of the Opalinus Clay in the siting regions. The test programme foresees measurements of thermal conductivity, thermal expansion, swelling indices and hydraulic conductivity at temperatures between 20 and 80 °C (Seiphoori 2021).

The continuation of in-situ experiments in the Mont Terri Rock Laboratory to further characterise fracturing and self-sealing is foreseen. The possibility exists to acquire long-term data (10+ years) from the excavation damaged zone (EDZ) where re-saturation has occurred and self-sealing is expected to occur, such as in the FE tunnel, where natural re-saturation occurs and repeat hydraulic testing in the EDZ is possible.

Through international collaboration, the results of ongoing large-scale experiments in other URLs will be integrated, leading to a more comprehensive understanding of the hydromechanical and hydrogeochemical processes that control the self-sealing capacity of clay-rich rocks. Furthermore, the state of the art in fault permeability investigations carried out by related industries (geothermal, hydrocarbon) will be surveyed.

This state of the art will be maintained beyond the submission of the general licence applications. The next major step in the site-specific description of self-sealing processes will occur as part of construction of the *EUU* facilities, supporting the update of the safety case for the construction licences.

Summary of Section 8.2 – Geological information

The main drivers for the work are (1) the site selection process, (2) the safety case to be developed for the selected site(s) including provision of the basis for assessing repository-induced effects and (3) the engineering of the subsurface infrastructure.

- The bulk of the RD&D activities foreseen support the geosphere characterisation in the siting regions and the development of the site-specific models. These are strongly supported by the results of the 3D seismic campaigns and the deep borehole campaign in the siting regions.
 - Characterisation methods for the sedimentary facies have made significant progress, while the tectonic picture for the three siting regions has become clear. Based on seismic interpretation, the advanced characterisation of sedimentological and tectonic features will continue to refine this.
 - Major progress was achieved through benchmarking of geomechanical properties, while novel techniques for characterising the stress field in the siting regions are being applied and interpreted.
 - Hydrogeological and hydrogeochemical characterisation techniques, already fairly mature, have been further refined, providing increased insight into the expected long-term evolution of the porewater and groundwater systems.
 - Activities providing an understanding of the long-term geological and climate evolution have made a significant leap forward and are also supported by an extensive Quaternary sediment characterisation programme. This unique assessment methodology is based on the evaluation of fluvial processes, the evolution of local topography and glacial erosion dynamics. It will provide strong support for site selection and for the subsequent description of the long-term evolution of the selected site(s).
- Process understanding for the key safety-relevant phenomena in the containment-providing rock zone was further refined to provide the basis for the description of repository-induced effects and for the safety assessment.
 - In the area of radionuclide transport, where understanding was already highly advanced, concluding syntheses of various aspects (e.g. competitive sorption) are being compiled to underpin the safety assessment.
 - Gas transport characterisation receives considerable attention, also internationally, and has focused most recently on characterisation of gas-induced fractures. To accommodate the remaining uncertainties, a framework was developed to assess gas-related impacts in the siting regions.
 - A more robust geomechanical understanding provides strong support for repository design and is now based on more advanced constitutive models. The impact of material heterogeneity is being further assessed.
 - Understanding of thermal properties and behaviour is key for the thermal dimensioning of the repository, and efforts are focused on extensive characterisation, benchmarking of URL experiments and development of probabilistic workflows to support site selection and thermal optimisation.
 - While the state of the art regarding understanding of self-sealing processes in the host rock is mature, novel small-scale visualisation experiments convincingly demonstrate the rapid self-sealing of artificial fractures.

Given the mature status of the knowledge base (also based on decades of activities in the Mont Terri URL) and the advanced status of exploration programme, from a geological viewpoint, no major risks are anticipated that would affect the licence application development.

8.3 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 knowledge of the radiological and material properties of all waste streams destined for disposal.

To this end, the ISRAM database (Information System for Radioactive Materials) has been established and is maintained and operated by the producers/managers of radioactive waste (except CERN), as well as by Nagra. ISRAM contains radiological information (e.g. nuclide inventory, dose rates), material information (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 to account for wastes that are expected to arise 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 MIRAM (Model Inventory for Radioactive Materials) database forms the basis for safety and design studies of 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 2014a) is periodically updated to include the latest ISRAM, accounting for existing wastes, developments and results from RD&D efforts, and to reflect changes in regulations (e.g. the Radiological Protection Ordinance, RPO 2017) or other boundary conditions affecting the future production of wastes (e.g. NPP operating lifetime). The next major update is expected in 2022 in preparation for the general licence applications.

The scope of RD&D for radioactive wastes and materials also extends beyond 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 the 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 by 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 has to be followed up with the waste producers and may require additional RD&D.

Moreover, ongoing activities will continue in order to refine the understanding of safety-relevant characteristics of wastes, such as radionuclide release mechanisms, criticality safety and gas generation.

Additional activities are ongoing to further understand the impact of dry storage, transport and handling of spent fuel assemblies. Finally, research efforts will be devoted to optimising the loading of spent fuel assemblies into the final disposal canisters. An overview of the structure of the subsections that deal with these topics is given in Fig. 8-6.

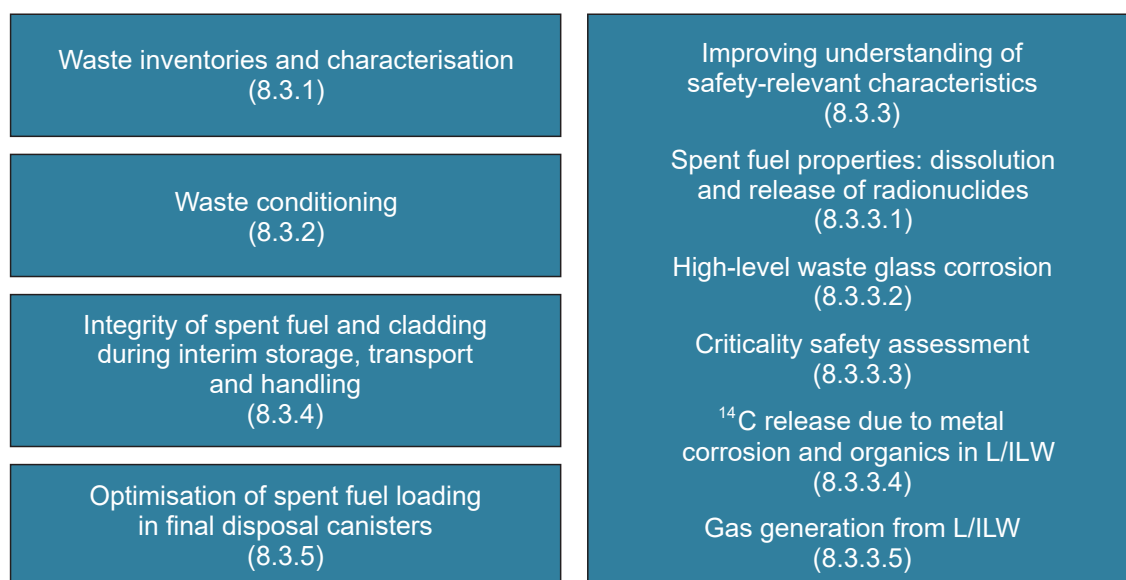


Fig. 8-6: Structuring of the RD&D activities related to radioactive wastes and materials

Many of the activities and their outcomes will be documented as part of the general licence applications in the MIRAM database supporting the *RBG* (Nagra NTB 24-10 planned) and the supporting reports.

8.3.1 Waste inventories and characterisation

Objectives

The objectives of inventorying and characterisation are to fine-tune methods and tools used to improve the technical data included in the Swiss radioactive waste database. More specifically, efforts are aimed at further consolidating data for all wastes that have been produced or are expected to be produced in Switzerland. These 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 2016 RD&D Plan

The MIRAM 14 database (Nagra 2014a) still constitutes a comprehensive database containing all relevant technical data for repository safety analyses. As part of the 2021 Waste Management Programme (Nagra 2021h), the estimation of the volumes of radioactive waste is being revised by including updates of the amount of waste arising from all waste streams. This updated volume estimation will be expanded to include updated inventory data (nuclides, masses, materials, etc.) to form the MIRAM database for *RBG*, the inventory basis for the safety case of the upcoming general licence applications.

RD&D efforts in the context of the future revision of the MIRAM database for *RBG* and beyond (e.g. in relation to operational safety and logistics), undertaken since the last RD&D Plan 2016, have been devoted to refining the characterisation of low-level waste, as well as of spent fuel and waste from reprocessing. These efforts include the following:

Low-level waste (LLW)

- Regarding NPP decommissioning waste, the Nagra "Advanced Methodology for Activation Characterisation" (AMAC) has been further developed and optimised. The NPP Monte Carlo simulations are significantly accelerated by using the hybrid variance reduction code ADVANTG (Mosher et al. 2013). Post-processing data analysis and waste packaging strategy are supported by in-house developments (Bykov 2019). Nagra's AMAC has become an internationally acknowledged, state-of-the-art methodology and has been successfully applied for NPP decommissioning projects in Germany (Scolaro 2016) and South Korea (Vollmert et al. 2020). The former rotational-symmetric 3D models of the Swiss NPPs, i.e. Beznau (*KKB*) (Pisano 2018), Gösgen (*KKG*), Leibstadt (*KKL*) and Mühleberg (*KKM*) (Bykov 2014) have been transformed into real 3D configurations, including all relevant neutron streaming paths (e.g. all openings for the cooling pipes of the biological shield). The validation of AMAC results for all Swiss NPPs by in-situ full-cycle sample irradiation campaigns is well underway, i.e. *KKM* and *KKB* are close to finalisation, *KKL* and *KKG* are awaiting the sample analysis.
- For operational wastes, all data for waste packages that have been produced since the release of MIRAM 14 have been continually integrated. Revised waste stream treatments (e.g. resins, sludge) were incorporated as needed, and the international development of best practices was monitored and analysed for their potential impact on Nagra procedures.
- Regarding new methods for waste characterisation, particularly characterisation of research waste, Nagra supported different research projects, e.g. at PSI. A proof-of-principle for using high-energy neutron spectra for validation of the methodology for calculating the inventory of radioactive waste in accelerator facilities was achieved (Galeev 2021).

Spent fuel and wastes from reprocessing

- Spent fuel assembly inventory calculations have been further refined. The first, more detailed 2D/3D light water reactor fuel models have been developed. The basis for assessing the quality of the spent fuel inventory has been developed (Bureš & Caruso 2018). Inventories of assembly components are determined separately. A state-of-the-art assessment of uncertainties in nuclear data, nuclear codes, models, etc. was also undertaken (Shama et al. 2019) in collaboration with EPFL and PSI. Since 2019, Nagra has participated in the EURAD SFC (Spent Fuel Characterisation and Evolution until Disposal) work package. Its aim is to increase the quality of spent fuel inventory calculations, as well as the quantification of related uncertainties.
- With regard to reprocessing wastes, international collaboration with waste management organisations has continued with the aim of monitoring international developments and ensuring that the Swiss reprocessing waste is inventoried and characterised according to international standards and state-of-the-art findings (Caruso et al. 2017).

Planned RD&D in the next five to ten years

The short-term focus lies on the conclusion of current research and integration for the update of the MIRAM database for *RBG*, especially with regard to LLW. In this area, the medium-term focus of research activities will shift towards the development of powerful planning tools. With regard to spent fuel and reprocessing waste, intermediate-term research will focus on detailed inventory calculations and uncertainty assessments to build up the data basis for future licensing steps.

Low-level waste (LLW):

- The overall validation process for all four Swiss NPP 3D AMAC models based on in-situ campaigns is expected to be completed in 2022, allowing the update of activation-induced activity prognoses. These data will include corresponding full nuclide inventories (activation, contamination) and surface characterisation information for all relevant decommissioning waste streams.
- For material characterisation validation, chemical and radiochemical sampling of NPP components and building structures will be incorporated. In particular, the existing close collaboration with *KKM* during its dismantling will provide an important opportunity and source for extended material sampling, which will also be used for updating the current assumptions made for the other Swiss NPPs still in operation. This will be supplemented further by selected sampling at those NPPs and by final analysis of the measurements taken for the decommissioning of the AGN (Aerojet General Nucleonics) research reactor to be completed soon (Vlassopoulos et al. 2016).
- The post-processing codes (DASHBOARD, ALGOPACK) will be further optimised and released for external use (e.g. by utilities preparing for decommissioning).
- New tools will be developed to support efficient planning of logistics and operational variants. For this purpose, new interfaces have to be programmed to link package-wise information from ISRAM, model inventories of MIRAM, detailed prognosis plans and different sets of relevant boundary conditions.

Spent fuel and wastes from reprocessing:

- Although generally well understood for SF, further inventory refinement to include not only the SF but also SF assembly components (e.g. cladding and structural component parts) will be undertaken, and heat production data will be obtained by the ongoing development and validation of 2D/3D light water reactor fuel models.
- Ongoing activities in this context include the continuing collaboration with EPFL/PSI regarding the assessment of uncertainties in nuclear data, nuclear codes and models.
- With the shutdown of *KKM*, the transfer of data and know-how concerning the detailed operational history of the SF, measurements and assessments will be planned and implemented within the next years.
- In the context of the reprocessing wastes, the international collaboration for the further verification of the radionuclide inventories in reprocessing wastes will be continued within the framework of an established working group consisting of Andra (France), GRS (Germany), ONDRAF/NIRAS (Belgium) and Nagra.

Beyond the submission of the general licence applications, the international state of the art will be monitored, and the methods described above will be further enhanced.

8.3.2 Waste conditioning

Objectives

The objective is to ensure, where required and justified, the development of methods that might be required for the future conditioning of waste streams, in coordination with PSI and the NPPs and through international collaboration.

Current state of the art and progress since the 2016 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 guidelines of the regulatory authority (ENSI 2015, 2018b). 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 specified waste packages. Approval of a waste package type means permission for the operator to undertake autonomous conditioning of future waste.

Best available techniques for the conditioning of radioactive waste are continuously screened and evaluated both nationally and internationally. In this context, Nagra participated as an end-user in the Euratom Thermal Treatment for Radioactive Waste Minimization and Hazard Reduction (THERAMIN) project (Euratom, available online at <http://www.theramin-h2020.eu/>).

Since the generation and impact of gases from metallic and organic L/ILW is an important aspect of assessing post-closure safety, alternative waste conditioning methods for the reduction of the gas production potential of L/ILW have been evaluated (Rüdebusch 2008, Ferrière & Kluth 2013). The potential to reduce gas production through reconditioning or new/different waste conditioning procedures has been assessed (Diomidis et al. 2016).

- In principle, metallic decommissioning wastes can be conditioned by melting. This can minimise the gas generation peaks by reducing the surface-to-volume ratio of the conditioned waste. However, due to acceptance criteria of the available industry facilities, the contribution of melting will not be significant regarding the overall mass reduction of contaminated wastes. While for the non-activated wastes, part of the nuclide inventory is concentrated in the sludge and melting can thus be effective, the largest amount of metallic decommissioning waste is activated, and no significant waste mass reduction can be achieved. Advantages of potential surface-to-volume reductions by melting the activated metallic decommissioning wastes currently do not outweigh the effort needed or do not justify the additional operational waste created by such a facility.
- Regarding organic wastes, a change in the treatment procedures is not being actively considered as only a low percentage of the total gas generated in the repository originates from organic waste (< 10%).

Based on the current assessment of gas generation (Diomidis et al. 2016), which will be updated for the general licence applications, the total gas impacts are estimated to be acceptable with respect to performance targets, and the melting option is kept open for future licensing steps in case it is needed. The need for RD&D aimed at waste treatment procedures that reduce gas generation will be reassessed as part of this.

Planned RD&D in the next five to ten years

Even though adequate waste conditioning practices are established, over the coming years best available techniques for the conditioning of radioactive waste will be continuously screened and evaluated both nationally and internationally. In this context, Nagra participates as an end-user in the Euratom Pre-disposal Management of Radioactive Waste (PREDIS) project (Euratom, available online at <https://predis-h2020.eu/>) that runs from 2020 to 2024. PREDIS aims to produce tools guiding decision-making on the added value of the technologies that have been developed and their impact on the design, safety, environmental aspects and economics of pre-disposal waste management.

Additionally, the decommissioning of *KKM* will be closely followed, with a focus not only on the characterisation and documentation of materials, but also on geometric information for the assessment of corrosion rates and gas generation from the actual waste inventories.

Further development of waste conditioning procedures, especially with regard to gas generation issues, will be continuously assessed, also beyond the submission of the general licence applications. These procedures, when contributing to further optimisation (either for objectives related to safety or implementation), will then support future licensing steps.

8.3.3 Improving understanding of safety-relevant waste characteristics

Activities for characterising the various waste types are required to provide data for operational and post-closure safety assessments. The properties of greatest importance in safety assessment are the release rate of radionuclides and the gas generation rate under disposal conditions, as well as the confirmation that wastes will neither exceed criticality requirements in waste handling operations nor under long-term disposal conditions. In relation to radionuclide release, experience from previous safety analyses (Nagra 2002a, 2014b) 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 greatest importance. In contrast, while uncertainties associated with long-term HLW glass dissolution remain, the significance of these uncertainties for the post-closure safety assessment has been shown to be low (Nagra 2002a). Even if radionuclides other than ^{14}C are released 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.

8.3.3.1 Spent fuel properties: dissolution and release of radionuclides

Objectives

The objective of studies on the release of radionuclides from UO_2 and MOX spent fuel assemblies is to improve the radionuclide release model used in safety assessment. Areas of specific interest include:

- release of radionuclides from Zircaloy cladding and structural materials of the fuel assemblies as a result of corrosion processes
- comparison of the dissolution behaviour of UO_2 and MOX as well as doped fuel

- changes in solid-state properties arising from radioactive decay and, in particular, changes that may affect subsequent radionuclide release
- mechanisms controlling the release of radionuclides from spent fuel under repository conditions under a hydrogen atmosphere, including matrix dissolution and rapid release of a fraction of the inventory of some fission products (instant release fraction (IRF)).

RD&D on the integrity of spent fuel during interim storage, which is also relevant to radionuclide release, is discussed in Section 8.3.4.

Current state of the art and progress since the 2016 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 ^{14}C inventory along with some other activation products associated with the oxide film on Zircaloy, followed by the slow release of the remaining activation products as a result of corrosion.
2. *Release of the IRF* from the spent fuel assemblies, which mainly represents the fraction of the total inventory of certain radionuclides (e.g. ^{135}Cs , ^{129}I and ^{36}Cl) in the fuel that is released from the gap (the interconnected void space in the fuel rod). Release from this 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, the IRF can be in the order of 10% for ^{135}Cs , ^{129}I and ^{36}Cl , which are highly soluble elements, and is assumed to dissolve instantaneously when a canister is eventually breached and water penetrates into it. Some other long-lived fission products that are commonly found at grain boundaries in the fuel (e.g. ^{99}Tc) are often included in the IRF, but are insoluble under the reducing conditions of repository groundwater.
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 and for a long period subsequently. Many of these radionuclides precipitate upon their release as a result of low solubility.

The release of ^{14}C due to corrosion of Zircaloy under geological disposal conditions was studied in the Euratom CAST (CArbon-14 Source Term) project, which ended in 2018. In the summary (Necib et al. 2018), it was demonstrated that the uniform corrosion rates of zirconium alloys are very low, i.e. for irradiated Zircaloys the corrosion rates seem to be around 1 – 2 nm/y in the longer term (the duration of the experiment was 6.5 years), although they were higher during the first year (up to 100 nm/y). In bicarbonate groundwater at concentrations $< 10^{-2}$ M, the solubility of zirconium oxide films remains very low. It was also shown that, during the corrosion of Zircaloy, there is a possibility of a mechanism in which ^{14}C is not released immediately by corrosion, but is incorporated into the oxide film and then released by diffusion or during the zirconium dissolution (Necib et al. 2018). Further information is provided in Section 8.3.3.4.

Spent fuel will be placed in disposal canisters that will prevent access of water to the fuel for at least 1,000 years. Under these conditions, only solid-state mechanisms could lead to changes in properties. It has been suggested that these processes might enhance the IRF. The principal solid-state processes relevant to long-term spent fuel behaviour are related to actinide decay, which will lead to helium accumulation within the fuel grains and could in principle influence the diffusion

of fission products in the UO_2 lattice. Helium from alpha decay will gradually accumulate, eventually forming nano-scale bubbles in the UO_2 grains after many thousands of years. However, as shown by the study by Wiss et al. (2014), this process is of low relevance for UO_2 fuel, although it may have some relevance to MOX fuel behaviour, possibly leading to microcracking after thousands of years. Alpha-decay-enhanced solid-state diffusion of fission products has been shown by Ferry et al. (2008) to be irrelevant for fuel behaviour over the safety assessment timeframe.

Fission gas release from spent fuel is known to correlate with the IRF of some radionuclides (Johnson et al. 2012). Therefore, the fission gas releases for full core loads of the Swiss reactors have been calculated in order to obtain reliable average fission gas release data (Areva 2010, 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).

Nagra participates in the end-user group of the Euratom DISCO project (Modern Spent Fuel Dissolution in Spent Container Conditions), where the IRF is determined for MOX fuel under an $\text{Ar} - \text{H}_2$ atmosphere. Furthermore, PSI and Nagra have continued a collaboration through this project, where, in the scope of a theoretical study, oxygen potentials for conventional and Cr-doped UO_2 fuels are determined based on solid-solution thermodynamics. A major conclusion from this modelling study by Curti & Kulik (2020) is that Cr-doping should have no significant effect on the oxidation state for UO_2 fuels irradiated in light water reactors. Therefore, undesired effects such as increased fission gas release and enhanced diffusivity of radionuclides or a reduction in thermal conductivity during neutron irradiation are unlikely. As a result, enhanced segregation of volatile fission products (Cs, I) or oxidation of redox-sensitive radionuclides to water-soluble species is not expected to occur due to Cr-doping.

Studies of the effect of reducing agents (H_2 , Fe(II)) present in a repository on spent fuel matrix dissolution continue to support the finding that H_2 greatly inhibits matrix dissolution (Carbol et al. 2009, Liu et al., Puranen et al. 2020). The pressure of H_2 required to essentially prevent matrix dissolution is about 0.1 MPa (Puranen et al. 2020, Liu et al.). This is far below the pressure expected to arise in a repository as a result of iron and Zircaloy corrosion. Recent findings of Puranen et al. (2020) illustrate that magnetite by itself does not inhibit matrix dissolution of spent fuel.

Planned RD&D in the next five to ten years

The outcome of the Euratom DISCO project will be integrated into the synthesis of the chemical evolution of the HLW near-field for the general licence applications. IRFs determined in the context of hot-cell experiments (if appropriate) will be integrated into the database for the safety analysis, which is currently based on the reference data for IRF and fuel dissolution from Johnson (2014). In addition, the Zircaloy corrosion rates, as assessed within the scope of the Euratom CAST project, will be revised and reference values defined for safety analysis.

In the future, Nagra will continue its analysis of spent fuel dissolution, mainly through international initiatives, and will maintain a watching brief on the international state of the art.

8.3.3.2 High-level waste glass corrosion

Objectives

Vitrified HLW contributes about one third of the activity of the waste that has to be disposed of in the Swiss HLW/SF repository. The remaining two thirds come from spent nuclear fuel. Vitrified HLW results from the reprocessing of spent fuel and has been produced industrially since the 1970s by COGEMA (subsequently AREVA and now ORANO) in France and by British Nuclear Fuels Ltd. (BNFL) in the UK. The objective is to improve mechanistic understanding of the behaviour of HLW glass in the repository environment so 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 2016 RD&D Plan

A large body of data on the dissolution kinetics of HLW glass is available from dedicated Euratom projects carried out over the past decades (SOURCE-TERM, GLASTAB, NF-PRO) and from experiments performed at PSI (Werme et al. 1990, Curti 2003, Curti et al. 2006) and at other laboratories (e.g. Gin et al. 2013, McGrail et al. 2001). Many studies focused on the effects of specific factors, such as glass/leachant composition (e.g. Strachan & Croak 2000, Frugier et al. 2005, Thien et al. 2012), radioactivity (Burns 1981, Feng & Bates 1992, Peugeot et al. 2014) and engineered barrier materials such as clay, steel and cement (Lemmens 2001, Gin et al. 2001, Michelin et al. 2013, Ferrand et al. 2013). From these data, long-term vitrified waste dissolution rates have been implemented and regularly updated in Nagra's safety assessments. Complementary evidence from suitable natural and archaeological analogues (e.g. Wolff-Boenisch et al. 2004, Verney-Carron et al. 2010) was also used in support of developing a better understanding of long-term dissolution behaviour. A comprehensive summary of these studies has been reported by Bradbury et al. (2014). PSI recently compiled a comprehensive database on glass corrosion rates arising from the reports of the joint Japanese – Swiss – Swedish (JSS) project. The data produced at PSI and Studsvik can be selected according to specific criteria (e.g. temperature, solid/ liquid ratio, solution type, environmental materials added to the glass such as Fe corrosion products and bentonite). An update of the available data is foreseen in anticipation of the general licence applications (Nagra NTB 24-10 planned) and its supporting documents.

The aqueous corrosion data for SON68 and MW glasses (inactive ORANO and BNFL simulants for glass types to be disposed of in the Swiss repository) clearly show the same pattern as observed for many other silicate glasses (Curti 2003). After an initial fast dissolution rate in the order of $1 \text{ g m}^{-2} \text{ day}^{-1}$, the corrosion rate of both types of glass decreases within a few months by 3 to 4 orders of magnitude, i.e. from about 1 to about $0.0001 - 0.001 \text{ g m}^{-2} \text{ day}^{-1}$. The most likely explanation is the formation of a protective amorphous gel layer on top of the pristine glass (Gin et al. 2001). The passivating effect was found to depend on the chemical composition of the layer. Some incorporated elements (e.g. Zn, Ca, Mg, Fe or Zr) have an impact on the nano-porosity and thus diffusivity of solute species through the gel (e.g. Thien et al. 2012, Aréna et al. 2016). The formation of this passivation layer has been further investigated (Dillmann et al. 2016, Fournier et al. 2014) with a special focus on the impact of Fe on glass dissolution at the macro, micro and nano scales (Carriere et al. 2017).

The initial fast dissolution of silica from the glass is thought to be sufficient to both quickly saturate the sorption sites on the nearby clay and to raise the dissolved Si concentrations sufficiently for the silica released through glass corrosion to condense and build a protective gel layer. The net effect is a reduced glass dissolution rate relative to the case of glass dissolving in a solution either

without clay or with only uncompacted clay. In addition, studies of glass dissolution in the presence of Fe oxides (Bart et al. 1987, Grambow 1987, Werme et al. 1990, Zwicky et al. 1989, Godon et al. 2013) indicate that the addition of Fe oxides leads to an increased glass dissolution rate and that the total amount of dissolved 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/precipitation drives the glass dissolution kinetics. A study by Guo et al. (2020) claimed that accelerated dissolution may occur at localised spots between the stainless steel and the modelled nuclear waste glasses. However, the latest experimental percolation tests performed at 50 °C and 90 °C for the alteration of ²⁹Si-doped SON68 borosilicate glasses exposed to Callovo-Oxfordian pore-water in the presence of stainless steel and Callovo-Oxfordian argillite showed that the presence of steel did not increase the dissolution rate of the glass (Carriere et al. 2017, Bouakkaz et al. 2019). This contrast with other studies is related to the fact that a lower water/solid ratio was employed, which better approximates conditions in a radioactive waste repository (Bouakkaz et al. 2019).

In summary, the dissolution kinetics of the HLW glass used for the safety assessment of the repository can be estimated within reasonable bounds. Furthermore, safety assessment studies (Nagra 2002a) show that the HLW glass makes a relatively small contribution to radionuclide release from a repository.

Planned RD&D in the next five to ten years

The EURAD ACED (Assessment of Chemical Evolution of ILW and HLW Disposal Cells) work package that will finish in 2023 aims at developing an enhanced understanding of the interactions occurring at interfaces between waste packages and different barriers and places some emphasis on the degradation of the HLW glass. Studies on glass dissolution performed in France and Belgium will be followed by Nagra, with a view to integrating them into the estimates of the glass dissolution rate for the dose calculations and as part of the description of the chemical evolution of the HLW near-field for the general licence applications.

The state of the art regarding glass dissolution will continue to be followed in the future, potentially as part of international collaborations to support the next licensing steps.

8.3.3.3 Criticality safety assessment

Objectives

The objective is to assess the potential for criticality in a repository for spent fuel and HLW and to ensure that design measures comply with the requirement for subcriticality in a repository (ENSI 2020).

Current state of the art and progress since the 2016 RD&D Plan

The proposed approach for dealing with criticality assessment for spent fuel disposal is to use burnup credit (i.e. taking credit for the fact that the reactivity of spent fuel has decreased according to the burnup of fissile nuclides and build-up of neutron-absorbing nuclides) to assess acceptable loadings of spent fuel canisters.

A methodology for criticality evaluations based on burnup credit (BUC) was developed by PSI and Nagra to ensure that this method could be applied to all spent fuel assemblies discharged from Swiss reactors. The work resulted in a review of BUC approaches in other countries as well as of existing BUC calculation methodologies and associated RD&D needs (Herrero 2015).

The methodology and tested codes were applied to reference configurations relevant to disposal, i.e. to nominal disposal canister designs and fuel assembly loadings (Gutiérrez et al. 2018). In particular, the application of burnup credit to criticality safety evaluations of geological repositories for disposal of spent nuclear fuel has to be taken into account for the case of Swiss pressurised water reactors, and possibly also for the planned spent fuel canister loadings from boiling water reactors.

Loading curves were obtained for nominal canisters loaded with pressurised water reactor UO₂ spent fuel assemblies (Herrero et al. 2017), showing what minimum average fuel assembly burnup is required to ensure subcriticality for the given initial fuel enrichment of fresh fuel assemblies. It was shown that only taking credit for the neutron absorption of non-fissile actinides would not be sufficient to meet the criticality safety criteria for all Swiss spent fuel assemblies. However, the AC+FP approach, where the credit for neutron absorbers includes both non-fissile actinides (AC) and fission products (FP), provides evidence for the safety of the nominal canister design for spent nuclear fuel with all existing realistic Swiss enrichments, assuming the required minimum burnups. These loading curves can be considered preliminary since a large scope for improvement was identified, particularly regarding the treatment of uncertainties.

The methodology and results are discussed continuously within the scientific community and are compared with the approaches adopted by other waste management organisations in bilateral projects and international workshops.

Planned RD&D in the next five to ten years

A follow-up project was already started in 2019 within the PSI – Nagra framework to address areas identified for improvement of the BUC methodology and to perform calculations for degraded configurations, such as may occur in the long term in the repository after extensive corrosion and structural degradation of the canister and fuel assemblies. These configurations also take account of the expected evolution of the repository and canisters, including water ingress. Additionally, work is foreseen to expand the preliminary reference loading curves and, if needed, to assess certain loading configurations separately.

The international state of the art will continue to be monitored after the submission of the general licence applications to prepare the necessary foundations for future licensing steps.

8.3.3.4 ¹⁴C release due to metal corrosion and organics degradation in L/ILW

Objectives

¹⁴C 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. In Swiss L/ILW, the ¹⁴C inventory is mainly associated with irradiated steel and, to a lesser degree, with Zircalloys and organic sources. ¹⁴C 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 either as dissolved species or in the gas phase in the form of volatile compounds. It is a safety-relevant radionuclide, especially for the L/ILW repository during the first few tens of thousands of years after repository closure. The broad aim is to develop a scientific understanding of the release mechanisms of ¹⁴C from organics, irradiated steels and other metallic components under conditions relevant to deep geological disposal. The rate of release of ¹⁴C, the speciation of ¹⁴C in the gas and liquid phases and how these relate to the ¹⁴C inventory and near-field conditions are of primary interest due to their importance in evaluating the retention, transport and finally the dose due to this radionuclide.

Current state of the art and progress since the 2016 RD&D Plan

The Euratom CAST project (CARbon-14 Source Term), which aimed to study ^{14}C release mechanisms, rates and speciation in the context of geological disposal, was completed in 2018. Both PSI and Nagra participated, and Nagra led the activities dealing with irradiated steel and contributed to the activities on the applicability of the CAST outcomes in safety assessments for deep geological disposal.

The CAST project showed that, in the case of ^{14}C released due to corrosion of irradiated steel, both organic and inorganic compounds are present in the liquid phase, while methane dominates the gas phase (Guillemot et al. 2020a, Mibus et al. 2018). Zircalloys show a similar behaviour: inorganic and low molecular weight oxygenated organic compounds are present in the liquid phase, while mainly methane was detected in the gas phase. In the context of the long-term release of ^{14}C under repository-relevant conditions, ^{14}C speciation is expected to shift to reduced compounds, such as gaseous hydrocarbons like methane, as local conditions become reducing due to, e.g., the generation of H_2 from corrosion and the decrease in the generation of oxidant species by radiolysis. The proportion of carbon released in the initial phase of the leaching process for steel was estimated to be a maximum of 5% (Mibus et al. 2018); however, it should be mentioned that the durations of the experiments in the CAST project were relatively short (no longer than ~ 1 year). No reliable data on the instant release fraction based on long-term studies can be extracted from the CAST project. Steel corrosion rates in alkaline conditions are very low because of the presence of a passivating layer (Swanton et al. 2015, Mibus et al. 2018). Uniform carbon steel and stainless steel corrosion rates in anoxic, alkaline conditions are below 0.1 and 0.01 $\mu\text{m}/\text{year}$, respectively, with recent studies indicating values of less than 1 nm/year (Senior et al. 2020a). Corrosion studies of Zircalloys show maximum rates in the order of a few nm/year at low temperatures and in alkaline or neutral conditions (Gras 2014, Necib et al. 2018).

Within and since the CAST project, PSI has developed a methodology to reliably measure the speciation of ^{14}C in the liquid and gaseous phases at extremely low concentrations (Cvetkovic et al. 2018a, 2018b, Guillemot et al. 2020b). A long-term steel corrosion experiment at PSI began in 2016 in the framework of the CAST project and will continue until at least the end of 2021, due to the opportunity it provides to obtain information on the long-term evolution of ^{14}C release rates and changes in the speciation of ^{14}C released from irradiated steel. The results of this experiment will provide the most reliable experimentally derived ^{14}C speciation data to date for irradiated steel and will be incorporated into future safety assessments.

The release of ^{14}C from organics is assumed to occur congruently with the organic waste using a rather conservative rate for organic waste degradation to cover a large group of organic substances and degradation mechanisms. More accurate descriptions of the very heterogeneous organic wastes that actually contain ^{14}C can make the source term more realistic.

Safety assessments for clay disposal systems as part of the CAST project showed that these systems have an excellent performance regarding ^{14}C because transport times typically greatly exceed the half-life of ^{14}C , especially in the clay host rock (Henocq et al. 2018). The impact of organic ^{14}C could become more relevant if there were scenarios in which radionuclide transport through the geological barrier is relatively fast. In such scenarios, the impact of organic ^{14}C on the dose is highly dependent on the corrosion rates, amount of metals and their specific surfaces (Capouet et al. 2018).

Planned RD&D in the next five to ten years

Nagra will contribute further to the long-term corrosion experiment at PSI with irradiated steel and to the activities in the EURAD CORI (Cement-Organic-Radionuclide Interactions) work package (2019 – 2023) on degradation of organic carbon compounds in repository-relevant conditions, which will continue at PSI until at least 2023. The results of the Euratom CAST project, as well as other progress made internationally, will be reviewed in detail with a view to incorporating relevant information on ^{14}C behaviour, e.g. ^{14}C release rates, instant release fractions, ^{14}C speciation and retention (see Sections 8.2.2.1 and 8.5.4) over long timescales into future safety assessments.

In the "Carbon-14 and Iodine-129 Migration in Cement" (CIM) collaborative experiment (NUMO (Japan), RWM (U.K.), SURAO (Czech Republic) and Nagra) at the Grimsel Test Site, the transport of these two dose-dominating radionuclides through the aged cementitious backfill of an L/ILW repository, as well as their retardation, are studied to develop a method for upscaling the results obtained from extensive laboratory-based migration studies to the field scale. The first phase of the field experiment began in 2017 and will continue until end of 2022. Information on the results of the experiment is not expected prior to 2023.

Nagra will continue to follow international progress on ^{14}C release due to metal corrosion with a view to updating the treatment of ^{14}C in future safety assessments.

8.3.3.5 Gas generation from L/ILW

Objectives

The generation of gases in deep geological repositories can affect the evolution of the near-field and the performance of engineered (Section 8.5) and natural barriers (Section 8.2.2.2). The assessment of the impact of gas generation requires characterisation of the gas source term resulting from the corrosion of metals (H_2) and the decomposition of organic materials (CO_2 , CH_4 , H_2 , H_2S). Thus, the main objective of the work summarised below is to quantify the rate of gas generation from L/ILW and to gain a comprehensive understanding of its evolution with time as the near-field conditions in the repository evolve (gas generation in the HLW repository is discussed in Section 8.5.3.1). In this respect, substance- and condition-specific gas generation rates, as well as an understanding of relevant processes and how these relate to each other, are required.

Current state of the art and progress since the 2016 RD&D Plan

Metals

The experimental campaign aiming to measure the corrosion rate of steel in cementitious environments discussed in (Nagra 2016b) was completed with the publication of a final report (Newman et al. 2016). An important outcome was the observation that cement also generates H_2 under anoxic conditions, mainly due to the presence in cement of metallic debris originating from the grinding of clinker. This phenomenon is not expected to be relevant to the evolution of the repository with respect to the gas source term, but it does mean that corrosion rates reported in the literature are overestimates. Corrected corrosion rates, i.e. with the contribution from cement removed, were found to be $< 5 \text{ nm/y}$ for unsaturated conditions and $< 10 \text{ nm/y}$ in saturated grout. In addition, it was noted that an experimental duration of at least 150 days was needed for short-term changes to complete and long-term behaviour to start becoming evident (Senior et al. 2017).

In 2017, Nagra, together with NWMO (Canada) and ONDRAF/NIRAS (Belgium), initiated a collaborative research platform to address corrosion-related issues of common interest. A primary issue was the accurate and dependable measurement of the extremely low corrosion rates expected under certain conditions, and the concern that reported corrosion rates are often overestimates because the real values are lower than the detection limit of the techniques applied. To address this issue, a novel methodology was developed and validated that allows the measurement of corrosion rates as low as 0.01 nm/y (Senior et al. 2020b). Using this new methodology, the corrosion rate of steel in L/ILW repository-relevant conditions was seen to continuously decrease with exposure duration (Senior 2017, 2019, Senior et al. 2017), reaching values as low as 0.1 nm/y after 4.5 years, but even then a steady state was not yet reached (Senior et al. 2020a). These extremely low corrosion rates are a result of passivity under repository conditions (Lu et al. 2015); recent studies have explored the incorporation of elements from the cement into the passive layer (Pally et al. 2020). Additionally, the effects of cement ageing and the corrosion rate of stainless steel (Senior et al. 2020c) and other metals present in the waste are currently being studied. Preliminary results indicate a corrosion rate for stainless steel of 1 nm/y after 12 months and still decreasing in agreement with the literature (0.4 nm/y after 7 years) (Sakuragi et al. 2016).

Organics

Given the low proportion of organics in L/ILW, gas generation from the degradation of organics is significantly less important than the gas generation from the corrosion of metals (Diomidis et al. 2016). Recently, the long-term monitoring of a full-scale experiment and the modelling of its evolution were reported (Small et al. 2017). To gain more experimental data, a large-scale experiment for the measurement of gas generation rates from organic waste streams (ion-exchange resins and PVC), initiated in 2015, is ongoing at Zwiilag. The gas generation due to the degradation of organics is investigated in Opalinus Clay porewater under non-sterile conditions using gas sensors, while temperature and pressure are monitored, and gas samples are taken for offline analyses.

Planned RD&D in the next five to ten years

The long-term plan for RD&D in the field of gas generation is presented and discussed in the Gas Roadmap (see Section 7.4). Activities planned for the short and intermediate terms are discussed below.

Metals

Research conducted as part of the international collaboration discussed above will continue, aimed at measuring the corrosion rate of metals in conditions relevant to the L/ILW repository. Further objectives are to increase confidence in the reference corrosion rates and in the understanding of the influence of local conditions, such as pH changes due to cement degradation and the availability of water. In anticipation of the general licence applications, the experimental data produced, together with information from the literature, will be reassessed to derive and substantiate updated reference corrosion rates in line with the state of the art.

Organics

The large-scale gas monitoring experiment discussed above will continue to gather information on the behaviour of organic waste materials until the general licence applications and beyond, as shown in the Gas Roadmap (Section 7.4). In anticipation of the general licence applications, the experimental data produced, together with information from the literature, will be reassessed to derive and substantiate updated reference degradation rates in line with the state of the art.

8.3.4 Integrity of spent fuel and cladding during interim storage, transport and handling

Objectives

Spent fuel assembly unloading/loading operations will be carried out in hot cells in the surface encapsulation plant. Several docking stations dedicated to transport and storage casks as well as final disposal canisters are planned to operate simultaneously. Safe handling and encapsulation of the fuel assemblies has to be ensured.

In line with the decision by the Swiss Federal Council (see Appendix A1 – Condition 6.1), the main objective of this research is to assess the integrity of the spent fuel assemblies during unloading/ loading and handling operations in which they are transferred from the transport and storage casks to the final disposal canisters. While experience with fuel handling (e.g. at Zwiilag) and current knowledge of degradation mechanisms confirm that the integrity of spent fuel assemblies will be maintained, further data and analyses will help to build on the understanding of spent fuel assembly degradation mechanisms that may affect their integrity and behaviour during handling in the encapsulation plant.

Current state of the art and progress since the 2016 RD&D Plan

Nagra monitors research programmes and, where necessary, takes part in projects assessing the integrity of spent fuel assemblies during dry interim storage in transport and storage casks and during transport to the encapsulation plant.

Since 2016, several activities have already been undertaken to further investigate the behaviour of spent fuel assemblies under dry storage conditions. For most of these activities, the experimental phase is ongoing and results and consequence analyses are expected by the end of 2022:

- In 2016, the ZET working group (Swiss nuclear power plants, Zwiilag and Nagra) started to coordinate the planning of systematic actions needed to provide confidence that spent fuel and HLW transport and storage casks will perform satisfactorily after long term storage and that the specific requirements will be fulfilled (ENSI 2018a).
- In particular, research projects examining the influence of hydrides on the behaviour of the cladding have been initiated. One of these projects, led by Nagra and conducted in close collaboration with PSI, focuses on the characteristics of crack development and its dependence on hydride content and orientation in spent fuel cladding of different burnups.
- Nagra undertook an experimental programme together with the EPFL and the Joint Research Centre of the Institute for Transuranium Elements (JRC-ITU, Germany) in 2016. It established a cooperation and related experimental campaign, with a duration of four years, to conduct load and impact tests on real spent fuel rods and to perform relevant pre- and post-test characterisation (Vlassopoulos et al. 2018a, 2018b, 2017, Linnemann et al. 2019).
- 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 programme was extended until 2020 to take advantage of complementary projects and therefore provides results with a much broader scope. In the past years, three topics were identified with gaps in knowledge related to spent fuel integrity, namely thermal profiles, cladding issues and stress profiles. Recent interim assessments, however, show no unexpected behaviour and thus justify the position that spent fuel will maintain its integrity during extended dry storage as well as during transport. In fact, it appears there will be substantial safety margins under normal storage and transport conditions.

- Nagra began an experimental programme to study the influence of dry interim storage conditions on the mechanical properties of spent fuel assembly structural material. This programme (Lazarus) is undertaken together with KKG and performed by the French nuclear reactor company Framatome. Samples have been taken from different materials and burnups, and mechanical tests are being performed for different temperature exposures and exposure durations.
- Nagra has been participating in the EURAD SFC work package (Spent Fuel Characterisation and Evolution until Disposal) since 2019. The project is expected to cover several issues and needs for waste management activities to support a precise determination of decay heat and reactivity of spent fuel assemblies. Regarding safety aspects, issues to be addressed are the reduction of uncertainties in safety-related parameters, as well as contributing to the further development of guidance on operational safety for both interim storage and fuel packaging facilities. Regarding increasing scientific and technical knowledge in waste management, both fuel and cladding degradation mechanisms (e.g. oxidation, corrosion, irradiation) that could affect their chemistries (e.g. oxidation state, chemical composition, microstructure) and hence alter their thermo-mechanical properties will be investigated by a combination of numerical calculations and experimental methods. These investigations will provide a thorough understanding of the mechanisms driving the behaviour of the spent nuclear fuel rods during their extended storage in both normal and accident conditions. As a basis, a state-of-the-art and technical gap analysis took place (final publication expected towards the end of the EURAD SFC work package).

Planned RD&D in the next five to ten years

The long-term plan for RD&D in the field of spent fuel integrity is shown and discussed in the Spent Fuel Roadmap (see Section 7.1). Activities to further investigate the behaviour of spent fuel assemblies during dry storage conditions and during transport and handling operations in hot cells planned for the short and intermediate term are discussed below:

- The collaboration with the Joint Research Centre of the Institute for Transuranium Elements (JRC-ITU) will be continued, and experimental studies on mechanical properties, especially regarding the cladding, will be extended to MOX and high-burnup fuel. These studies will focus on the effects of thermal loading and subsequent possible hydride reorientation on the mechanical material properties.
- Nagra participates in different tasks within the framework of the EURAD SFC work package, focusing particularly on numerical model building and analyses, and including new and upcoming experimental results from the JRC collaboration, as well as from the Lazarus project.
- Through ongoing participation in the ZET working group, Nagra monitors and follows developments in transport and storage cask ageing management.

The findings of the experimental programme, as well as ongoing international cooperation, are intended to provide additional input for the detailed assessment of working procedures for the handling of spent fuel assemblies in the encapsulation plant (see Section 8.4.9), as well as to provide a basis for safety studies and accident assessment in relation to operational safety (see also Section 8.6.2). In particular, the development and planning of working procedures for the handling of spent fuel assemblies in the encapsulation plant will be a focal point in the years following the general licence applications, with focused research projects foreseen in the area of spent fuel assembly measurement and characterisation techniques.

8.3.5 Optimisation of spent fuel loading in final disposal canisters

Objectives

The aim of this work is to optimise the loading of spent fuel assemblies from the transport and storage casks into the final disposal canisters that will be emplaced in the repository. This optimisation is necessary i) to satisfy a current 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.

More specifically, transport and storage casks will have to be docked and opened in a hot cell and spent fuel assemblies will have to be transferred to the final disposal canisters. For this purpose, an optimum sequence for unloading the spent fuel assemblies contained in different types of transport and storage casks and loading them into different types of final disposal canisters (holding various numbers and types of spent fuel assemblies) has to be devised.

Current state of the art and progress since the 2016 RD&D Plan

SIMAN (an acronym based on the underlying optimisation algorithm "Simulated Annealing") is a logistics optimisation programme that has been under development by Nagra since the early 2000s. It determines the optimum sequence of transport and storage cask unloading and final disposal canister loading operations under different boundary conditions (such as the starting time of HLW final disposal operations, number of transport and storage cask docking stations in the encapsulation plant, encapsulation plant capacity, etc.). The input data for this programme include i) the full spent fuel assembly database delivered by the utilities, ii) the transport and storage cask loading plans and iii) pre-calculated burnup- and decay-dependent spent fuel assembly heat outputs.

In the period since 2016, the SIMAN-II (Vlassopoulos 2015) code version has been updated to SIMAN-II+, which allows explicit simulation of the spent fuel assembly operations inside the hot cell. The updated version allows the investigation of potential changes in the boundary conditions (e.g. final disposal canister types, buffer storage options and surface facility design) on the number of final disposal canisters.

In parallel, a new version, SIMAN-III, has been developed which uses a specialised optimisation algorithm, giving much more flexibility in the boundary conditions and scenarios being investigated. In addition, SIMAN-III implements the newly calculated and improved detailed assembly-wise decay heat matrices, thereby improving the reliability of the results for the number of final disposal canisters, as well as unloading sequences.

Heuristic sensitivity studies were made based on new detailed calculations to assess the effect of different scenarios (e.g. encapsulation plant capacity, beginning and end times for the encapsulation plant operations, etc.). The results of these studies, as well as other ongoing efforts in this area, will contribute to the decision basis for the repository project that will be included in the general licence applications (Nagra NTB 24-11 planned) and its supporting documents.

Planned RD&D in the next five to ten years

Future activities aim to update and extend the SIMAN suite of codes with new features and codes that will improve the computational time for detailed scenario and boundary condition studies.

Additionally, interfaces for data handling within the foreseen, more broadly focused thermal optimisation projects following the submission of the general licence applications will be developed (as also described in the Tier 3 roadmap on thermal output in Section 7.3).

These results of past and ongoing efforts in this area will be integrated into broader optimisation workflows and will contribute to the decision basis for optimisation of the repository project, which will be a major activity continuing after the submission of the general licence applications in anticipation of the construction licences (Tier 2 Roadmap on optimisation for safety and implementation – see Section 3.2).

Summary of Section 8.3 – Radioactive waste and materials

Comprehensive knowledge of the radiological and material properties of all waste streams destined for disposal is key to the design and safety analysis of the planned repositories.

- A refined description of the inventory will be prepared for the general licence applications, leading to an update of the respective databases. The state of the art regarding waste conditioning is being followed closely in order to identify waste treatment options for optimisation in future programme stages.
- Further progress was made in reducing uncertainties in the safety analysis related to the waste characteristics:
 - The focus is mainly on the radionuclide release from spent fuel and the release rate of ^{14}C from L/ILW, since reducing these can contribute to increasing the safety margin. International efforts play a major role in targeting specific aspects of the spent fuel release, and in long-term experiments on ^{14}C release from metal and organic wastes.
 - While uncertainties with respect to glass dissolution remain and are being further investigated, they do not have consequences for post-closure safety.
 - Uncertainties regarding the gas produced by the waste have been further reduced by increasing confidence that corrosion rates of metals, which are the main source of repository gases, will be very low.
 - To ensure criticality safety, the methodology based on burnup credit was further developed and loading curves were obtained for nominal canisters. The method will be further improved to account for degraded configurations, so as to ensure criticality safety in the later stages of repository evolution.
- Assessing the state and the integrity of spent fuel after dry storage is mainly an issue related to handling and to the design of the encapsulation plant. Along with multiple international initiatives, Nagra also contributed significantly to investigations on spent fuel rods and structural materials.
- In the context of the thermal optimisation of the repository, logistics optimisation software has been enhanced to allow for more comprehensive analysis of canister loading options.

8.4 Design and technology development for the surface and underground facilities for the repositories and the engineered barriers

The general feasibility of a deep geological repository and its safe operation, backfilling and closure must be demonstrated on a conceptual level for the general licence applications. This engineering design work includes the surface facilities required for the operation of the repository, the underground facilities, the relevant safety and operational equipment and the engineered barriers.

For the site selection process and the pending general licence applications, varying depths of design (or varying levels of detail) are required. For the site selection, a safety-based comparison of the repository projects in each of the three siting regions is foreseen, and this requires a preliminary design for the engineered barriers. This level of detail is also necessary to ensure post-closure safety based on the planned repository design for the selected site(s). The planning work for the facility for underground geological investigations (*BEUU*) is based on state-of-the-art engineering practice, which has a proven record in various underground infrastructure projects. The generic design concepts for the tunnels, as well as the implementation of site-specific repository architectures, do not require new research or new methods, but are based on standard engineering processes. However, selected engineering developments, such as site-specific tunnelling methods (Section 8.4.3), may also be required for construction planning.

Planning at the conceptual design level is adequate for the surface facilities and their equipment. In addition to demonstrating the general feasibility, operability and nuclear safety of the facilities, the planning work also serves to define the space required for the facilities, to support environmental impact assessments, to ensure acceptance by the population and to estimate the costs. The surface facilities include conventional elements such as office buildings, workshops, administration buildings and facilities for securing the site, as well as nuclear plant components such as the encapsulation facilities for HLW and L/ILW. The design of these facilities is based on standard processes for structural engineering, whereas engineering development for certain other facilities is required. Specific needs for research activities are related to the very specific requirements on containers for L/ILW and canisters for SF and HLW.

The design work on sealing and backfilling has many distinctive interfaces. The dependencies on the actual waste specifications, the containers or canisters, the interaction between the tunnel lining and the host rock, and the issue of possible retrieval of the waste are examples. Sealing and backfilling must be planned in such a way that all related requirements and specifications can be met. Demonstrating the performance and elucidating the phenomenology and interactions of certain sealing and backfill elements is safety-relevant and is refined further in ongoing research projects.

This section describes many activities that are in the domain of engineering development to provide the context and are not RD&D in the strict sense. The relationship between the activities regarding design and technology development for the repository and the engineered barriers is shown in Fig. 8-7.

The outcomes of the activities will be integrated in the general licence applications (Nagra NTB 24-11 planned) and its supporting documents.

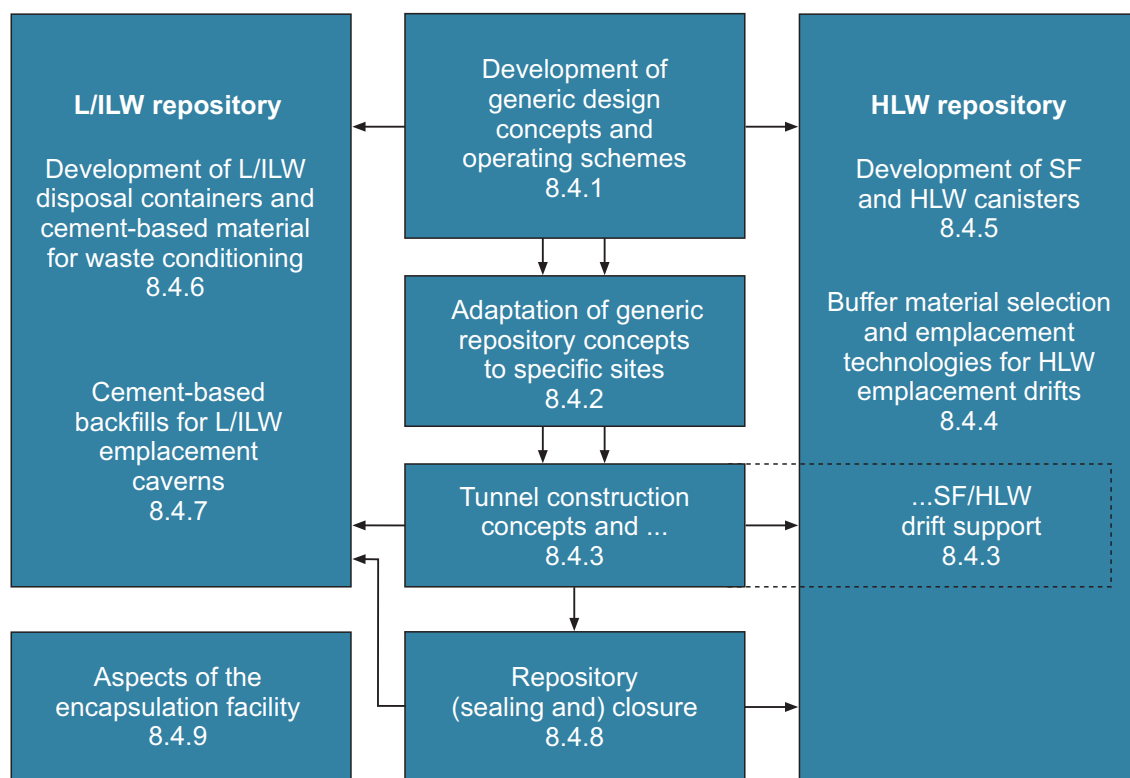


Fig. 8-7: Relationship between the RD&D activities regarding design and technology development for the repositories and the engineered barriers

8.4.1 Development of generic design concepts and operating schemes (including the pilot repository and potential waste retrieval)

Objectives

The objectives of the development of generic design concepts and operating schemes are the design of reliable and robust generic facility modules, including corresponding layout concepts, and the provision of a comprehensive design basis for the site-specific allocation of the waste and the layout of the current generic combined HLW and L/ILW repository project.

Current state of the art and progress since the 2016 RD&D Plan

The generic repository project has been further developed in a modular fashion in the years since the 2016 RD&D Plan (Nagra 2016b). The main focus has been on the reliable and robust design of the various facility modules (structures, systems, components) and their operability. The actual design status of the generic modules of the repository is shown in Fig. 5-10 and can be divided into the following main modules:

- Surface facilities: ensuring the general functions of waste reception, packaging and encapsulation. These functions include various structures such as facility services (supply, ventilation, drainage, etc.), maintenance, management and administration, as well as public information.
- Access facilities to the underground (as part of the underground facilities): used for transport of encapsulated waste and of backfilling and sealing material from the surface to the disposal level, as well as for personnel and construction material transport. These functions are performed either by shafts with lifts or by ramps for rail or road vehicles.
- Underground facilities at the disposal level: the main functions are the transport of waste to the final HLW and L/ILW disposal areas and its emplacement, concurrent backfilling and sealing, potential retrieval of radioactive waste, observation and monitoring and construction activities. These functions require various tunnel sections as well as underground structures for construction and operation logistics and facilities for protection and rescue. The underground facilities can be divided into submodules consisting of the main HLW and L/ILW disposal areas, pilot repositories, test and experiment areas and the central access area at the bottom of the access shafts.

A comparison of the construction and operation of a combined repository versus separate HLW and L/ILW repositories was conducted in Nagra (2020b).

Planned RD&D in the next five to ten years

The main activities for the generic design concepts are engineering development and advancement of technical methods for planning and operation of deep geological repositories. Digitalisation offers many new possibilities, which will be investigated in more detail in the years leading up to the general licence applications and beyond. In anticipation of the general licence applications, the conceptual design for the retrieval of the waste will be further detailed. Special focus for the operational planning will be on in-repository transport (autonomous vehicles) and remote handling (for transport, emplacement equipment and retrieval). Here, the exchange of experience with other waste management organisations will also play a key role.

Interdisciplinary, holistically integrated engineering is being advanced by means of the consistent application of the Building Information Modelling (BIM) method. This means that all engineering disciplines are included in a digital model serving as a single source of truth.

8.4.2 Adaptation of generic repository concepts to specific sites

Objectives

The objective for the general licence applications is to provide a site-specific conceptual design for the combined repository or the separate HLW and L/ILW repositories at the proposed site(s).

All of the work involves current engineering practice, including:

- siting and layout of the auxiliary access facilities above ground (as part of final site selection)
- provisional selection of the access variant and construction methods (this will be left open up to the general licence applications) based on risk analyses
- repository configuration based on long-term and operational requirements and
- preliminary design of underground structures based on site-specific geological models and understanding.

Current state of the art and progress since the 2016 RD&D Plan

Site-related repository conceptual design studies have been undertaken to provide a basis that allows input from local communities and other stakeholders to the decisions required in *SGT* Stage 3 concerning the siting and layout of the auxiliary access facilities. Access concepts and variants have been defined.

A shield tunnel boring machine (TBM) with segmental lining installation has been pre-selected as the current concept for the excavation of the HLW repository drifts. The use of shield TBMs has been proven to be a safe and reliable construction method in a wide range of rock conditions and for a range of excavation diameters. Recently, the third tube of the Belchen road tunnel has been constructed successfully – also partially within Opalinus Clay – with a large-diameter shield TBM. The construction of the Emscher sewage tunnel in Germany, with an inner diameter of 2.6 metres, showed that the construction method is also suitable for drifts with a very small diameter.

L/ILW caverns will be excavated conventionally by roadheader or using the drill-and-blast method.

Planned RD&D in the next five to ten years

In anticipation of the general licence applications, conceptual design studies will be produced, which will be progressively refined for future licensing steps.

Certain activities may have some RD&D character due to the first-of-a-kind nature of the facility, but these are expected to be minor.

8.4.3 Tunnel construction concepts and technology for the support of SF/HLW emplacement drifts

Objectives

The current project for the SF/HLW repository requires a safe and reliable emplacement drift construction concept that can be realised at a rate of approximately 2 km/year, including equipment operation and assembly and disassembly of the tunnel excavation equipment. A total of up to 20 kilometres of emplacement drifts have to be excavated within 13 years. Ideally, a full-face tunnelling machine will be used to meet these performance criteria and to excavate the rock with a 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 to reduce the extent of loosening and deformation. Due to the required diameter and length of the drifts, only mechanised tunnel construction methods are suitable: either with a gripper TBM and sprayed concrete liner or a shield TBM with segmental lining. The final selection of the construction method will be made with the application for the construction licence for the HLW repository and will mainly depend on the quality of the rock at depth.

The objective is thus to have a suitable excavation technology, together with appropriate materials and application methods, capable of providing adequate support of the SF/HLW emplacement drifts.

Current state of the art and progress since the 2016 RD&D Plan

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 suitability of various construction methods (excavation and rock support) has also been analysed in detail. For excavation at relatively shallow depths and with favourable rock mass conditions, a gripper TBM with a relatively late support installation may be suitable for controlling rock loosening. At greater depth and in unfavourable conditions, a shield TBM with a short shield would be the better choice to ensure work safety and to prevent loosening and overbreaks. For the expected rock conditions and depths, the segmental lining can easily be designed to accommodate the expected rock stress. A shield TBM with segmental lining support has thus been chosen as the current concept for the construction of the SF/HLW emplacement drifts. The description will be documented as part of the general licence applications (Nagra NTB 24-11 planned).

Materials and technology for support of SF/HLW emplacement drifts

Design concepts

The current design concept for the support of the SF/HLW emplacement drifts consists of a segmental lining, as shown in Fig. 8-8. The current construction method is applicable in a wide range of rock conditions and allows for an industrial-like tunnel construction, thus covering the inherent uncertainties at the present stage of the project.

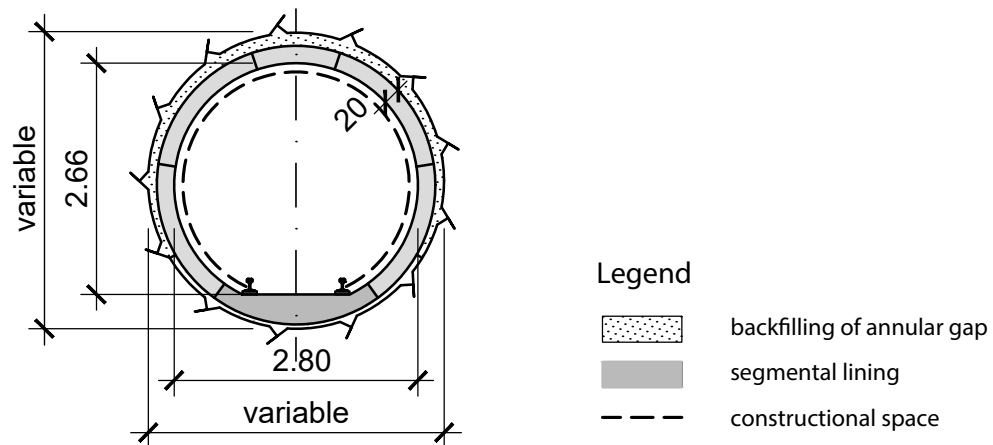


Fig. 8-8: Current lining concept for SF/HLW emplacement drifts

URL experience

In the past, several large-scale experiments on tunnel support have been performed in the Mont Terri Rock Laboratory, such as the construction of Gallery 08 (Ga08), the Mine-By (MB) experiment and the FE gallery. Further, low-pH cement has been tested successfully for wet-mix shotcrete applications during the EU project Engineering Studies and Demonstration of Repository Designs (ESDRED) in laboratory and field tests. Details can be found in the the 2016 RD&D Plan (Nagra 2016b).

Recently, with the extension of the Mont Terri Rock Laboratory (Gallery 18), four sections, each about 15 to 25 metres long, were monitored more intensively within the framework of the Tunneling Support (TS) experiment. The objective of the experiment was to test different support systems (i.e. support with steel sets or shotcrete with ring closure of the support at different times). Lining strains were monitored using fibre-optical sensors, and deformations were also monitored periodically to better understand the development of rock pressure and rock deformation. The rock was excavated by roadheader and supported either by shotcrete or by steel sets. This technique is not representative for the SF/HLW emplacement drifts, but rather for the operations and construction tunnels. The experiment showed that the envisaged support systems are suitable for the conditions encountered. Further observations of the weathering process in the section with the steel set support will give indications of its integrity over time. The applied monitoring methods have performed well so far. However, the interpretation of the circumferential strain measurements within the shotcrete lining using fibre optics is demanding due to time-dependent effects occurring within the recently emplaced shotcrete.

Planned RD&D in the next five to ten years

Tunnel construction

Observation of the development of strains and deformations in the TS experiment at the Mont Terri URL will continue. Further, degradation of the exposed rock in Section 2 of the TS experiment will continue to be monitored photogrammetrically to demonstrate the suitability of a rock support relying only on steel sets for sealing sections.

Pre-engineering aspects of the use of tunnel excavation equipment in combination with lining concepts will be addressed in case studies. These studies will involve collaboration with leading manufacturers of tunnel-boring machines. Based on the results of pre-engineering studies, specific aspects of tunnelling technologies will be tested.

The final definition of requirements for a tunnel-boring machine is foreseen later in anticipation of the construction licences to benefit from technological progress made in the coming decades. This will require intensive interactions with the tunnelling industry and its respective suppliers.

Materials and technology for support of SF/HLW emplacement drifts

The following studies are in progress:

- Improved understanding of geomechanical processes and structural models for tunnel analyses are being developed in conjunction with site-specific exploration (Sections 8.2.1.3 and 8.2.2.3). Based on this, an engineering approach (design basis and engineering tools) will be developed, verified, and established to support the site selection.
- Constructability of the reference lining concepts will be further improved based on site-specific data. The technology for certain construction details will be further developed and possibly tested in a URL during later stages of the programme in anticipation of its demonstration and application in the facilities for *EUU*.

8.4.4 Buffer material selection and emplacement technologies for HLW drifts

8.4.4.1 Buffer material evaluation for HLW emplacement drifts

Objectives

The buffer material MX-80 bentonite has been selected by various waste management organisations, and the status of characterisation is correspondingly advanced. It is recognised, nonetheless, that bentonites other than MX-80 that have similarly high montmorillonite contents can also be good candidates and might have advantages with respect to availability and cost. The objective of the following work is thus to identify various suitable bentonites that meet the requirements (e.g. swelling, hydraulic conductivity) for use as buffer material around the SF/HLW canisters and to investigate the extent to which the knowledge base for MX-80 bentonite can be transferred to these materials. A material will be selected for the general licence applications, while other options will continue to be evaluated.

As an alternative concept to using bentonite buffer, the use of a cement backfill as foreseen, e.g., in the Belgian HLW radioactive waste disposal concept, has also been evaluated. The final decision on the material to be used will be taken in advance of the construction licence applications.

Current state of the art and progress since the 2016 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 currently the reference material for the HLW repository buffer. However, other natural bentonites are also available and could provide alternatives 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 8.5.3.3 and described in Leupin et al. (2014) and 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 independent of the material used.

As already described in Nagra (2016b), there are bentonites of different origins that could be suitable for use as a buffer material. Since that report, advanced programmes (Posiva Oy, Finland and SKB, Sweden) have made significant progress towards industrial upscaling and quality assurance management as part of their construction and operating licences.

In the context of optimisation, the use of a cement backfill using pre-cast concrete elements has been evaluated as an alternative concept in an initial desk study (Cloet et al. 2019). The behaviour of the concrete with a customised cement recipe under repository conditions was evaluated with regard to the repository-induced effects. It was shown that the cement has a strong impact on the near-field chemistry, which is highly alkaline. This has implications for the steel corrosion rate, but also affects the dissolution of the spent fuel matrix as well as the HLW glass. Calculations of dose rates based on the potential release and transport of radionuclides have shown them to be slightly elevated compared with a bentonite buffer, but still within the limits set by ENSI-G03 (ENSI 2020). However, according to mechanical simulations, the anisotropic stresses on the concrete at a depth of 900 metres could lead to an early failure of the concrete elements due to earlier thermal damage, resulting in point loads on the canisters. The predicted potential failure of the concrete elements could be avoided by reinforcing them. Therefore, a follow-up sensitivity study was carried out (Wyrzykowski et al. 2019) that introduced reinforcement in the pre-cast concrete elements, demonstrating the technical feasibility of the concept at shallower depth with limited impact on radiological safety. Preliminary findings show that using a cement backfill does not result in a clear safety benefit compared with using bentonite. However, the cement backfill remains a potential alternative that might be further investigated in the future after the submission of the general licence applications.

Planned RD&D in the next five to ten years

To maintain maximum flexibility with respect to the type of bentonite that will eventually be selected, while fulfilling the necessary requirements, opportunities to extend 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 other waste management organisations (e.g. SKB, Sweden) 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. This type of international collaboration is expected to offer opportunities to advance the underlying understanding of key processes determining the suitability of different bentonites. The evolution of the intergranular pore space of the granular bentonite during the re-saturation of the emplacement drifts is considered to be key for many different processes, such as gas transport, the evolution of microbiology and the iron – bentonite front, etc.

This insight offers the potential to optimise the bentonite used since the intergranular pore space is mainly determined by the granulometry of the chosen bentonite. Future activities will explore opportunities to optimise the granulometry of different bentonites to meet the post-closure safety requirements by a larger safety margin.

More in-depth studies on the cement buffer concept, as well as other buffer alternatives, could be foreseen as part of the optimisation of the barrier concepts (from both a safety and implementation point of view) after the submission of the general licence applications. This is expected to lead to a deeper understanding of the post-closure evolution of alternative buffer materials under near-field conditions and to a more detailed description of the most promising concepts. The final decision on the buffer material is planned to be made well in advance of the submission of the construction licence application.

8.4.4.2 Buffer emplacement technology

Objectives

The buffer consists of granular bentonite material as well as pedestals made from pre-compacted bentonite blocks, the latter being emplaced together with the SF/HLW canisters.

The buffer emplacement technology is an integral part of the current waste emplacement concept, which envisages that the emplacement of each SF/HLW disposal canister on its bentonite support blocks will be directly followed by backfilling the surrounding open space with granular bentonite material. In the Full-scale Emplacement (FE) experiment at the Mont Terri Rock Laboratory, a prototype of a buffer emplacement machine has been developed and successfully deployed since 2015 (Nagra 2019a). As a result, the technical feasibility of buffer emplacement has been demonstrated and a prototype technology established. The main objective of the work was thus achieved. Additional demonstrations are being pursued for confirmation.

Further objectives that will be addressed mainly after the general licence applications concern prototype optimisation and automation aspects with regard to industrial application, quality control and quality improvement, as well as operational safety and radiation protection. The optimised prototype will serve as a basis for the development of the industrial-scale buffer emplacement technology.

Current state of the art and progress since the 2016 RD&D Plan

During the implementation phase (2009 – 2015) of the FE experiment, the main objectives related to the horizontal emplacement of granular bentonite material were achieved:

- Based on experience from previous experiments (EB, Engineered Barriers experiment (Mayor et al. 2007) and the ESDRED emplacement test (Bock et al. 2009), a prototype buffer emplacement machine has been designed, built and tested (Fig. 8-9). It has five screw conveyors (augers) that allow the homogeneous horizontal backfilling of disposal tunnels with granular bentonite material (Nagra 2019a).
- The minimum bulk dry density of 1.45 g/cm^3 , the target value for the bentonite buffer according to the Swiss repository concept (Hayek et al. 2015) to ensure that requirements related to post-closure safety are met (Leupin & Johnson 2013), was exceeded without any breakdowns or accidents.

Starting in 2019, the buffer emplacement machine developed to emplace granular bentonite material has been used in the HotBENT experiment at the GTS (Section 8.5.3.3). The machine (Fig. 8-10) was used successfully to backfill 70 metres of emplacement drifts. Some optimisation potential identified during the FE experiment was realised before application, and further experience for handling optimisation and commissioning of the machine has been acquired. As the buffer emplacement machine prototype was designed for tunnels with diameters ranging from 2.5 to 3 metres (the FE gallery was 2.7 metres in diameter, while the HotBENT gallery is only 2.28 metres), the machine has been modified and resized to fit into the HotBENT experiment gallery, demonstrating that the technology can be applied flexibly.



Fig. 8-9: Illustration of the 17-metre-long buffer emplacement machine built for the FE experiment

From Nagra (2019a).

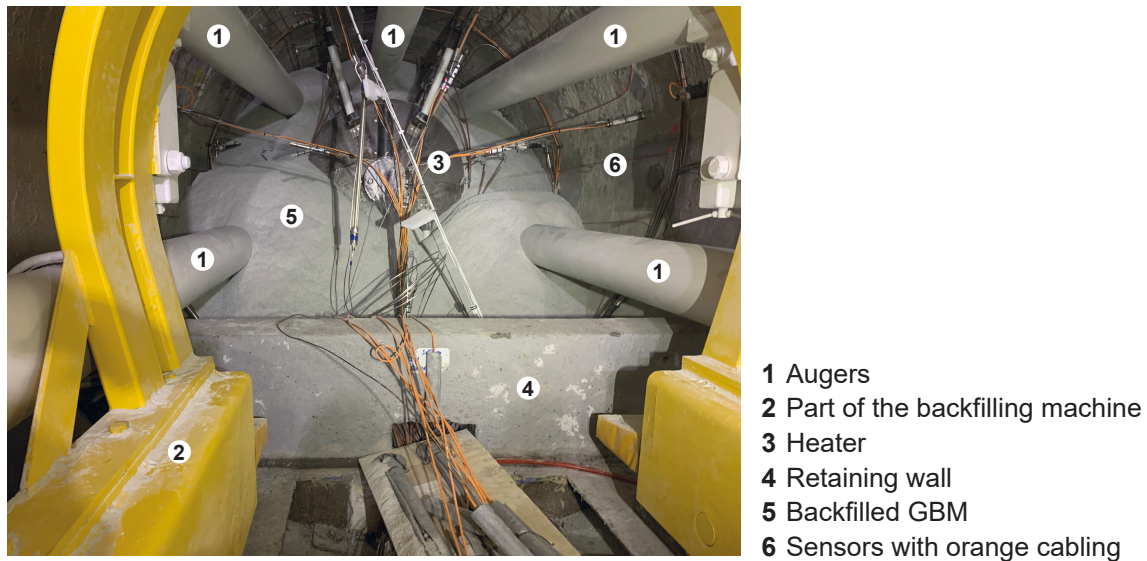


Fig. 8-10: Buffer emplacement in the HotBENT experiment with Wyoming-type granular bentonite material using a 5-auger backfilling machine

A spiderweb holds various sensors for monitoring the buffer. In the front, the lowest segment of a cement retaining wall can be seen. The heating device (that acts as a proxy for the canister) is partially visible behind the spiderweb. GBM: granular bentonite material.

Based on experience gained in the FE and HotBENT experiments, the screw conveyor system selected has been shown to be a suitable backfilling method that meets the following engineering requirements:

- 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

The method has also been further optimised and successfully demonstrated by Posiva (Finland) for the backfilling of the emplacement tunnels in the Finnish concept.

Planned RD&D in the next five to ten years

The successful emplacement of the buffer in the FE and HotBENT experiments demonstrates a good level of readiness with regard to emplacement technology. No further activities are foreseen for the general licence applications, apart from small refinements to the current methods.

After the submission of the general licence applications, further development of the backfilling technology, including remote handling, will take place as a basis for the submission of the construction licence applications. In this context, the prototype buffer emplacement machine will be further developed to an industry-standard tool, with reliability, efficiency and complexity optimised for day-to-day application. Further details of the planned activities in the field of buffer emplacement are presented and discussed in the Tier 3 Emplacement and Retrieability roadmap (see Section 7.10).

8.4.5 Development of SF and HLW canisters

Background and objectives

The long-term containment of SF and HLW requires adequate structural and corrosion performance of the disposal canisters. Furthermore, the impact of canister corrosion on other engineered barriers and on the host rock must not be detrimental to their performance. Satisfying these requirements can be ensured by appropriate material selection, design and manufacturing technologies for the canister.

The broad objective of the programme for the development of SF/HLW canisters is to ensure that a sound knowledge base is available for the selection of a suitable canister concept in time for the construction of the repository. 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 for implementing these concepts is adequately developed. In the shorter term, the main objective is to develop the current disposal canister concept to the required level of maturity for the general licence applications.

Activities on corrosion and on the long-term performance assessment of the SF/HLW disposal canisters are described in Section 8.5.3.1, while the Tier 3 Canister roadmap, discussed in Section 7.8, describes the activities foreseen up to 2060 when operation is planned to start.

Current state of the art and progress since the 2016 RD&D Plan

The organisation of Nagra's SF/HLW disposal canister programme is based on the outcome of a broad options evaluation study (Holdsworth et al. 2014) and consists of three main workstreams:

Development of the current canister concept

Nagra's current concept is a forged carbon-steel disposal canister, which was developed in some detail in 2012 (Patel et al. 2012) (see Fig. 8-11). The primary shortcoming of this design was that the post-weld heat treatment required to relieve residual stress in the closure weld led to an unacceptable overheating of the SF and HLW inside the canister. Several options to address the issue have been evaluated and shown to be feasible and effective. Currently, work is concentrated on the optimisation of the heat treatment process and the improvement of the accuracy of the associated temperature modelling.

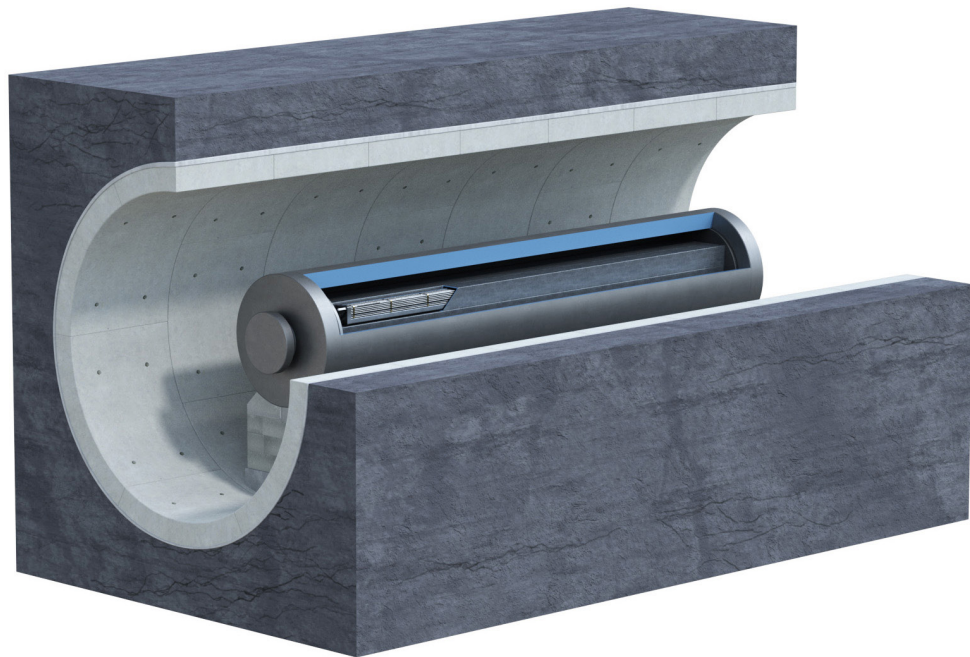


Fig. 8-11: Conceptual representation of the current carbon-steel canister concept

Development of an alternative canister concept

The long-term cooperation agreement with NWMO (Canada), initially established in 2013 to develop methods for coating carbon-steel canisters with copper, is ongoing. Both electroplating and cold-spray methods are being studied (Jakupi et al. 2015, Poirier et al. 2019, Vo et al. 2015, Li et al. 2020, Guerreiro et al. 2020, Yu et al. 2019, Tam et al. 2019), with electroplating considered for the canister body and lid and cold-spray coating for covering the closure-weld region of the steel substrate after sealing. The maturity of both methods has increased over the years and, currently, a series of full-scale prototypes is being manufactured (Chen et al. 2019). In parallel, the design development of the canister with regard to welding, inspection and structural performance as well as development of the necessary equipment is ongoing in Canada. Based on the abovementioned activities, Nagra has developed a design for a copper-coated canister according to the Swiss disposal concept and waste inventory (Diomidis et al. 2017, Diomidis & King 2020). The potential advantages of copper-coated long-lived disposal canisters has also led to the initiation of research elsewhere, broadening the availability of coating technologies (Hernandez-Selva et al. 2015, Chen et al. 2019).

Evaluation of further options

In addition to copper, other materials have been assessed as options for the coating of SF/HLW disposal canisters (Holdsworth et al. 2018). Titanium-, nickel- and ceramic-based coatings have been evaluated, based on criteria such as suitability and international experience, mechanical integrity, resistance to environmental damage and available coating technology. The most promising family of coating materials is titanium alloys, due to their extremely low corrosion rates, immunity to microbially induced corrosion and localised corrosion and the relative maturity of coating and cladding technologies. Their main shortcoming is hydrogen embrittlement, but this process is generally predictable and long canister lifetimes can be expected with confidence. Titanium alloy coating is currently not being further developed for disposal canisters, as copper coating has emerged as the preferred option.

As an alternative to the steel substrate for a copper-coated canister developed earlier (Bastid et al. 2015), the option of a cast-iron substrate has also been evaluated (Verdon et al. 2019). A cast-iron substrate would allow the incorporation of the internal structure supporting the spent fuel, and the extensive development of the cast-iron insert for Posiva's borehole emplacement concept (KBS-3, Sweden, Finland) has demonstrated the feasibility and structural strength of such concepts. Nevertheless, for a copper-coated canister, the cast iron would have to be welded to the lid. The closure concept has been developed, potential welding techniques assessed, and weld trials performed. The experimental evaluation indicated that none of the techniques presently able to weld cast iron is mature enough to provide welds of the quality needed for a disposal canister. As a result, the cast-iron substrate is currently considered to be non-feasible, but the development of cast-iron welding technology will be followed.

Designs for disposal canisters containing 12 BWR fuel assemblies and three HLW flasks are being finalised.

In a comparative evaluation of available options, the criticality and shielding of various candidate canister designs and materials were assessed (Gutiérrez et al. 2018).

Planned RD&D in the next five to ten years

Evaluation of options

In the coming years, the evaluation of options will mainly take place in the context of the EURAD CONCORD (Container Corrosion under Disposal Conditions; 2021 – 2024) work package that is being led by Nagra. After the submission of the general licence applications, the assessment of canister options will focus on manufacturing technology, design of internal components and sealing processes. The aim will be to optimise structural strength, subcriticality margins and cost. The assessment of new materials and processes that can lead to improved canister performance will be carried out on a continuous basis both by Nagra alone and as part of international cooperative efforts.

It is likely that one or more countries will have licensed repositories before Nagra applies for construction licences (~ 2050) and Switzerland will benefit from the associated development work. 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

In the next few years, further development of the reference steel canister will concentrate on finalising the work needed to reach the level of maturity required for the general licence applications. In addition to the heat treatment optimisation mentioned above, this is primarily linked to achieving material and weld properties that are needed to increase confidence in the feasibility of the selected concept and to increase the accuracy of the lifetime assessment (see Section 8.5.3.1). The necessary properties will be obtained by expert elicitation, literature reviews or weld trials and characterisation.

The further development of copper-coating technologies in collaboration with NWMO (Canada) will continue. The planned work primarily includes the serial production of several full-scale prototypes. This will lead to the optimisation of the upscaled coating process, the development of manufacturing maturity of the electroplating and cold-spray coating techniques as well as the characterisation and optimisation of coating properties.

After the general licence applications, the development of a steel canister, either as a standalone concept or as a substrate for a copper coating, will proceed, with the primary focus being on upscaling and on full-scale demonstration and testing. As before, the main need for technology development is related to activities that will take place in the surface facility, i.e. closure welding and the inspection of the weld. Upscaling of the sealing processes will be followed by large- and full-scale testing. Overall, the aim is to make the final decision on canister material and design in the late 2030s. This will allow approximately ten years for serial canister prototype manufacturing and testing in anticipation of the submission of the construction licence application.

8.4.6 Development of L/ILW disposal containers and cement-based material for waste conditioning

Objectives

L/ILW disposal containers have to provide suitable handling units for several waste packages. The space between waste packages emplaced in the disposal containers will be filled with a suitable material (e.g. mortar or aggregate). In addition, activated metal and concrete from the decommissioning of nuclear power plants will be placed directly in the concrete containers, which will again be backfilled with a suitable container infill mortar.

Containers and container infill materials have to fulfil various requirements related to long-term safety, handling, interim storage, operational safety, costs, retrievability, and regulatory measures (ENSI B05, ENSI 2018b). One of the objectives of the following work is therefore to understand the long-term chemical evolution of the cement-based components in an L/ILW repository in support of the development of requirements and the selection of materials, and to ensure that requirements are met.

The objective is to define the conceptual design for L/ILW disposal containers and for the container infill material, as well as to demonstrate their suitability, by the time the general licence applications are submitted. 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 2016 RD&D Plan

The development of new L/ILW disposal containers was undertaken in close cooperation with the waste producers, mainly in response to transport considerations; the large dimensions of the disposal containers foreseen in older concepts (LC-1: 26 m³ and LC-2: 14.3 m³) are difficult to handle during decommissioning and transport and restrict flexibility related to storage capacity during interim storage. Therefore, containers have been developed with smaller dimensions that are also optimised for interim storage (LC-84: 6.3 m³, LC-86: 9.4 m³). These two container types are mainly intended for the direct disposal of decommissioning waste. A third container, LC-86H (11.1 m³), with the same principal design, is intended for repackaging smaller waste packages, e.g. 200-litre drums for final disposal. The decision as to whether to use the LC-86H or containers with different dimensions is linked to the final L/ILW repository concept and is therefore still open. However, the concept of using cuboid concrete containers for L/ILW remains unchanged, and the fabrication of such containers for disposal purposes has been demonstrated.

The development of the LC-84 and LC-86 containers has been finalised (see also Fig. 8-12) and they have been approved as Type A packages conforming to the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR). The first 30 containers have, in the meantime, been produced for the dismantling of the *KKM*.



Fig. 8-12: Preparation of LC-84 for a Type A package drop test

A commercial cement-based mortar (DORODUR®, by Holcim) has been investigated for the backfilling of the disposal containers for decommissioning waste from *KKM*, and its composition has been defined. It meets the most important requirements: pH > 12, high porosity, little or no organic additives and little or no siliceous aggregates and has successfully passed handling tests. The tests required by the regulatory authority for cement-based backfills according to the ENSI Guideline B05 (ENSI 2018b) are to be concluded. These tests are not related to post-closure safety but test the suitability of the materials in the event of severe operational incidents.

Planned RD&D in the next five to ten years

The decommissioning of *KKM* started in 2020 and included waste packaging and transport to Zwiilag. The principal design of the LC-84 and LC-86 containers is therefore fixed. Development and production of other containers (e.g. LC-86H) will be initiated when (and if) needed, depending on the progress and outcome of *SGT* Stage 3 and on requests made by the waste producers. Optimisation of the concrete formulation to improve its workability or cost-efficiency while ensuring post-closure safety requirements can be performed or the formulation can be adjusted in the event of a change in the availability of the necessary raw materials.

The use of activated and/or contaminated concrete from decommissioning as an aggregate for a mortar used as a container backfill is an interesting option and will be further investigated. This option is strongly linked to the question of when certain waste types will be generated during decommissioning and how long raw waste can be stored before final conditioning of the waste packages has to be performed.

Activities for other backfill materials (e.g. cement and mortars used for applications within waste drums) will be continued. Within the next five years, the plasticiser that is used in most of these barrel-filling mortars for conditioning of operational waste and waste from medicine, research and industry will be replaced as the production of this superplasticiser will be stopped. A project has therefore been launched at PSI to develop alternative admixtures and, at the same time, further optimise the cement formulation with respect to meeting post-closure safety and implementation requirements.

The activities related to the L/ILW containers in the longer term are captured in the respective Tier 3 roadmap in Section 7.7.

8.4.7 Cement-based backfills for L/ILW emplacement caverns

Objectives

A concept for backfilling the L/ILW emplacement caverns will be part of the general licence applications. Backfill material will fill the void space between the cavern walls, the concrete containers and the transition area. The backfill materials will be cement-based, since this will provide high-pH conditions in the repository near-field favouring the retention of many radionuclides, suppression of microbial activity, low corrosion rates and favourable properties related to gas storage and transport. 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 2016 RD&D Plan

The long-term safety requirements for cement-based backfill materials are being reassessed for the general licence applications and cover the following aspects:

- The backfill material should exhibit favourable retention properties for radionuclides. This includes maintaining high-pH conditions (> 12) for a long time period and providing a suitable cement-based mineralogy for the sorption of many radionuclides.
- The backfill material should contribute to a chemical environment in the repository that keeps gas pressure in the cavern low and minimises gas-induced expulsion of porewater containing radionuclides. This can be achieved by ensuring high-pH conditions, which contribute to low steel corrosion rates, and by ensuring a significant interconnected porosity fraction (e.g. 20%) for gas storage with sufficiently high gas permeability to avoid high gas pressure build-up.
- Mechanical strength and material stiffness should provide sufficient mechanical support to avoid larger-scale impacts on the Opalinus Clay, but also contribute to favourable conditions for the mechanical stability of disposal containers.

To meet these requirements, use of the grain-supported monograin mortar (M1) is foreseen (Jacobs et al. 1994), which takes up stresses by grain-to-grain contact while preserving an interconnected long-term porosity between the grains. In a recent assessment, the chemical resistance and durability of M1 mortar has been calculated, based on thermodynamic and kinetic considerations and accounting for the impact of the pozzolanic reaction on the evolution of the pH of the pore solution (Kosakowski et al. 2020). Considering a continuous dissolution of the siliceous aggregates from all sides at given pH and temperature conditions, the model predicted that the pH drops to < 10.5 in less than 1,000 years, and additional carbonation due to the available CO_2 will eventually lead to neutral pH conditions (Kosakowski et al. 2020). The authors note that these calculations are very conservative, assuming that dissolution of the aggregates occurs from all sides, and that, in all stages, water and CO_2 are continuously available. In reality, once water and CO_2 are consumed at a local scale, the reaction will halt (Kosakowski et al. 2014, Wieland et al. 2018, Kosakowski et al. 2020). Nevertheless, this pH drop can be prevented by using calcareous aggregates instead of siliceous aggregates (Kosakowski et al. 2020), which inhibits the pozzolanic reaction and contributes to maintaining high-pH conditions over a longer period of time. For this purpose, a feasibility study for M1 mortar with limestone split has been launched. In the scope of this work, quantitative technical requirements for the backfill mortar are also being derived. Preliminary results indicate that it is possible to produce M1 mortar with limestone aggregates that meets the requirements in laboratory-scale experiments.

Planned RD&D in the next five to ten years

Quantitative technical requirements for the backfill mortar are being defined based on requirements derived from post-closure safety assessments, including the assessment of the impact of repository-induced effects (see Section 8.5.3.2). The processability, durability and on-site quality control of the mortar will be considered when defining the technical requirements, and the development will proceed according to the dedicated Tier 3 roadmap described in Section 7.7.

Technical parameters to be addressed include:

- type and grain dimension of the aggregates, which should ensure a high porosity and high (gas) permeability
- mechanical strength needed to assess (and limit) the effects from rock pressure
- hydration heat emission needed to assess potential impacts on the Opalinus Clay

The evaluation and testing of a suitable emplacement method to achieve the required properties will be initiated.

Activities will focus on confirming the suitability of the suggested mortar and performing the necessary adaptations. Additional laboratory tests are foreseen to enhance the durability of the mortar and ensure a high-pH environment in the post-closure phase for a significant time period. Results from the feasibility study with limestone aggregates are planned to be available in time for the general licence applications. Preliminary results of laboratory-scale experiments have already indicated that M1 mortar with limestone aggregates can be produced with the desired properties. However, further optimisation of the cement formulation and handling tests at small and larger scales will be performed after the submission of the general licence applications. In addition, chemical models for predicting the long-term durability of the material will be further refined.

The concept for the backfill mortar must also be compatible with the emplacement concept for the backfill and for the waste containers, as well as with the retrievability concept for waste containers. This concept will be further developed and optimised from both a safety and implementation point of view in anticipation of the construction licence application for the L/ILW repository.

8.4.8 Repository (sealing and) closure

Objectives

According to Art. 3 NEA, repository closure includes backfilling and sealing of all underground excavations, i.e. including the access tunnels/shafts, of a deep geological repository after the monitoring period.

Seals are part of the engineered barrier system and serve to prevent water flow and limit the transport of pollutants/radionuclides from the disposal area into the biosphere via the (backfilled) tunnel system and the EDZ. The sealing system includes various sealing elements and their associated mechanical confinement, each of which has to withstand a number of load scenarios and fulfil individual functions. Load scenarios and functions develop over time. The specific sealing elements include: i) seals with very low permeability and ii) seals with sufficiently high gas permeability (Engineered Gas Transport System EGTS; Section 8.5.2.2) to keep gas pressures in emplacement caverns (L/ILW) at an acceptable level, while still maintaining low permeability for water.

All access and handling tunnels/drifts/shafts will be backfilled to ensure that long-term convergence occurs in a predictable, controlled manner and at slow rates, preserving the functionality of the natural and engineered barriers (ENSI 2020). Moreover, any connections between water-conducting rock layers above host rock level and the waste emplacement areas created by shaft or ramp construction must be sealed off (NEO 2004).

The main objectives are the development of the conceptual designs based on the requirements for the different types of seals, in the first instance with a focus on revised requirements related to post-closure safety, but also related to construction feasibility. Methodological and technical options for design and construction will be developed and quality control measures will be proposed to ensure that the design requirements can be met. Detailed specifications for the design and construction of the seals will be developed later, in anticipation of the construction licences.

Current state of the art and progress since the 2016 RD&D Plan

In the current repository project, the waste emplacement drifts for SF and HLW are backfilled with bentonite immediately after the emplacement of the disposal canisters (Section 8.4.4.) and the emplacement caverns for the L/ILW are backfilled with monograin mortar M1 (Section 8.5.3.2). A first seal will be installed at the end of each drift and cavern immediately after backfilling has been completed. 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 conditions (Section 8.5.3.3). Concrete structures are also installed for mechanical reasons, as are transition layers to separate the concrete from the bentonite.

Gas permeable seals require a sealing element consisting of a sand/bentonite mixture. While the full-scale GAs-permeable Seal Test (GAST) at the GTS and supporting MiniGAST are ongoing experiments that aim to demonstrate the post-closure performance on a 1:1 scale seal, lessons could be learned from its construction particularly related to meeting the post-closure safety requirements and the homogeneity of the properties of the sealing element (Section 8.5.2.2).

Seals with a pure bentonite sealing element aim at limiting both water and gas flow to a minimum. A generic modelling study showed that aqueous radionuclide release via the underground access structures (including their EDZ) of a deep geological repository is low due to the extremely low water inflow to the dead-end tunnel system (Poller et al. 2014). These outcomes, together with the understanding of the overall system, help to define an upper limit for the required density of the bentonite to be emplaced.

Recent activities related to sealing include three types of work:

- Evaluation of alternative bentonite raw materials (Section 8.4.4.1).
- Industrial procedures for material processing, such as the production of high-density granular bentonite material and compressed bentonite blocks. In the context of the ongoing HotBENT experiment (Section 8.5.3.3), the procedures for material processing, including compressed bentonite blocks, have been reviewed and improved.
- Implementation procedures for horizontal tunnel sections, e.g. the manual installation of bentonite blocks in the interjacent sealing section of the FE experiment (Nagra 2019a), and emplacing different granular bentonite materials using a screw conveyor methodology (Large Underground Concept and Full-scale Emplacement (LUCEOX/FE) experiments (Köhler et al. 2015) and the HotBENT experiment (Section 8.5.3.3).

Further studies showed that the requirements on the backfilling of the access shafts and the various tunnels can also be fulfilled using processed Opalinus Clay as an alternative to a sand/bentonite mixture.

Based on these studies and the resulting updated requirements, generic sealing and closure concepts were developed (Nagra 2021g) from an operational and post-closure safety point of view and taking advantage of Nagra's system understanding regarding re-saturation of the repository after closure (Diomidis et al. 2016). The concepts are based on the current Nagra repository project, which reflects a combined repository. However, the concepts can also be applied to individual HLW and L/ILW repositories.

Planned RD&D in the next five to ten years

In 2023, the final results from the GAST and MiniGAST experiments described above will become available. Conclusions will be evaluated and integrated into the concept and design criteria, and material parameters for the gas-permeable seal are expected to be confirmed based on this. The GAST experiment will also be continued beyond the submission of the general licence applications. Before the submission of the general licence applications, performance assessment of gas-related issues will be conducted for the selected site(s), which will result in the refinement of the post-closure safety requirements regarding sealing and closure.

Following the development of the generic sealing and closure concept, as reported in Nagra (2021g), activities will focus on conceptual and desk design studies aimed at developing a site-specific sealing and closure concept based on the requirements. This will be reported in Nagra NTB 24-08 (planned) as part of the general licence applications.

Further insight will be gained from the continued exchange with international waste management organisations. Of particular interest will be the exchange with Andra (France), that has developed a sealing and closure concept for a repository in the Callovo-Oxfordian clay host rock as part of the construction licence application.

In the case where processed Opalinus Clay is further considered for backfilling the access drifts and tunnels, further characterisation and concepts for processing and emplacement will be developed.

In the future, the repository sealing and closure concept will be continuously updated and refined, also to ensure a consistency with the various components and other repository systems. More detail on future activities is given in the respective Tier 3 Sealing and Closure roadmap (Section 7.9).

8.4.9 Aspects of the encapsulation plant

Objectives

A prerequisite for the licensing of the HLW repository is the development of the scientific basis to ensure, within specified safety margins, the handling of the spent nuclear fuel and its encapsulation in disposal canisters. Specific issues, such as opening transport and storage casks, handling spent fuel in the packaging facilities and repackaging the fuel into the disposal canisters, must be properly addressed. Several safety-relevant issues have to be considered, from material ageing to the possible release of radioactive material from the cask/spent nuclear fuel.

The objective for the general licence applications is to consolidate the basic concepts to meet the prerequisites mentioned above. A detailed description of the design and the processes involved will be developed in anticipation of the construction licence applications. The investigation of spent nuclear fuel and the associated issues mentioned above are part of the RD&D programme. However, the development of the packaging facilities and related units is categorised as project development (engineering).

An important aspect that has an RD&D component is the description of spent fuel assembly behaviour. This includes the investigation of spent fuel integrity during interim storage (Section 8.3.4) and handling operations.

Other aspects depend on the outcome of investigations on spent fuel assembly behaviour and will be integrated into the engineering project development based on the state of the art. These aspects include:

- disposal canister loading optimisation (discussed separately in Section 8.3.5):
 - evaluation of the handling equipment and design of the encapsulation plant with regard to operational safety (safety regime, systems and functions, Section 8.6.2)
- decontamination and decommissioning:
 - operational safety aspects of decontamination and decommissioning of handling equipment, the encapsulation plant and transport and storage casks (safety requirements, systems and functions)
 - assessment of waste management procedures and of the equipment used for the different operating phases
 - determination of the degree and the type of contamination/activation of spent fuel transport casks (defining a reference and a worst-case scenario)

There are thus only a few RD&D developments that impact the design of the packaging facilities.

Current state of the art and progress since the 2016 RD&D Plan

A generic comparison regarding the potential location of the encapsulation plant is described in Nagra (2020c). In anticipation of the general licence applications, a conceptual design has to be developed and will be included in Nagra NTB 24-11 (planned) and its supporting documents. Several other waste management organisations already have detailed design concepts in place in anticipation of their construction licences (e.g. Sweden and Finland). International collaboration and exchange are thus essential as the know-how is already largely available.

In addition, several research activities have been initiated focusing on:

- potential degradation of spent fuel during long-term dry interim storage and the impact of transport and handling (Section 8.3.4)
- development of a revised version of the existing disposal canister fuel loading optimisation programme (SIMAN (Section 8.3.5))
- preliminary design studies of the encapsulation plant and planning of operational procedures, including the compilation of basic requirements (with regard to possible design variants)
- estimation of induced activation of the transport and storage casks and their disposal. This will be further elaborated after the submission of the general licence applications. The disposal of transport and storage casks is foreseen as part of project development (engineering) and will follow the state of the art in other countries that are dealing with similar issues. A preliminary design study of a treatment facility, including an assessment of the induced activation in transport and storage casks, was performed as part of the project development.

Planned RD&D in the next five to ten years

The planned activities related to the integrity of spent fuel and cladding are described in Section 8.3.4. The fuel loading optimisation programme of a disposal canister (Section 8.3.5) 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 significantly impact the design of the encapsulation plant.

Further issues related to the operation of the encapsulation plant with spent nuclear fuel that have to be addressed at the conceptual design stage include:

- estimation of induced activation and contamination in the encapsulation plant
- sensitivity analyses on cost-related aspects of the encapsulation operations (canister design, thermal criteria, logistics, etc.)

Other aspects will be covered as part of the engineering development of the project, based on the state of the art, in anticipation of the detailed design to be developed for the future licensing steps:

- handling of fuel assemblies in the encapsulation plant: normal operations and in case of incidents
- evaluation of requirements for the handling equipment
- measures/concepts for handling of damaged fuel assemblies
- decontamination techniques for the transport and storage casks

The topic of spent fuel characterisation and handling prior to its loading in the encapsulation plant has been identified as a programme aspect with a significant RD&D component and is therefore described as part of the dedicated Tier 3 roadmap in Section 7.1.

Summary of Section 8.3 – Design and technology development

The general feasibility of a repository and its safe operation, backfilling and closure must be demonstrated at the conceptual level for the general licence applications.

Multiple aspects of the subsurface infrastructure lie in the domain of engineering and infrastructure development. This applies specifically to the development of generic design concepts and operating schemes and their adaptation, first to the specific sites in the three siting regions and ultimately to the selected site(s).

- Based on a deepened analysis of the anticipated behaviour of the rock mass, a shield tunnel boring machine (TBM) with segmental lining support has been chosen for construction of the SF/HLW emplacement drifts. Different tunnel support systems have been successfully tested.
- The buffer emplacement technology for meeting the post-closure safety requirements was already demonstrated at a 1:1 scale in the FE experiment in the Mont Terri Rock Laboratory, and further experience is being gained in large-scale emplacement experiments at the Grimsel Test Site (GTS). Evaluation of alternative, more widely available bentonites that fulfil the requirements continues in the context of the optimisation process.
- The design of the HLW carbon steel disposal canister has progressed. In anticipation of the general licence applications, a larger-scale feasibility demonstration will be pursued. The development of alternative canisters continues, with a major focus on copper-coated canisters that have reached a high level of maturity as a result of international developments.
- The design and prototype production of the L/ILW disposal containers has been completed. Their sizes are now also optimised for interim storage. Options for infilling the containers have been further elaborated.
- The cement-based backfill for the L/ILW emplacement caverns has to be designed such that the requirements for post-closure safety are met (radionuclide retention and gas storage capacity). The focus of the work is on selection of the aggregates and the engineering properties of the selected compositions.
- For sealing and closure of the repository, variants that are optimised for post-closure requirements and implementation are being investigated. This is supported by international plug and seal demonstrations and the 1:1 gas-permeable seal performance demonstration (GAST) at the GTS and its supporting laboratory experiments.

The conceptual design and preparation of the surface facilities is based on standard engineering practice and, in this phase, does not require specific RD&D activities. An exception is the encapsulation plant, which still has the potential to be significantly optimised based on the canister loading concepts that will be applied in the context of thermal optimisation of the repository design and operation.

8.5 Evolution of safety-relevant properties and processes in the near-field

Two safety functions of a radioactive waste repository are **complete containment** of the radionuclides for a period of time and **immobilisation, retention and slow release** of radionuclides (Section 5.2.4). The repository near-field is expected to contribute to these safety functions over the course of the assessment time period by providing a range of favourable safety-relevant functions and properties.

The near-field will evolve over time due to the various interactions between the engineered and natural repository barriers. For safety assessment, it is necessary to identify any processes or circumstances that could lead to significant adverse perturbation of the safety-relevant properties of these barriers. This section describes the RD&D that is required with respect to the post-closure evolution of the repository near-field to identify such processes and circumstances.

The RD&D needs regarding post-closure evolution are driven by the safety functions and component-specific functions of the engineered and natural barriers and the requirements on expected performance and the associated performance indicators and targets derived from them. To formulate sensible indicators, a detailed understanding of the evolution of the repository has to be in place, which is challenging since the processes involved are strongly coupled and occur in a complex environment. The relationship between different parts of the description of the near-field evolution, including its components and development, is given in Fig. 8-13. Section 8.5.1 provides a general description of the evolution of the near-field as well as of the activities undertaken to achieve an enhanced understanding of saturation, temperature evolution and gas transport. These processes affect the entire near-field and cannot reasonably be discussed at the level of individual barriers. This section thus provides an overview, while other more detailed sections describe the evolution and the needs for RD&D at the level of the individual barriers or 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 main focus is on the early saturation times of the repository when strong gradients occur.

When radionuclides are mobilised during later stages of repository evolution, radiological consequence analysis requires 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 8.5.4 (see Section 8.2.2.1 for far-field host rock transport, retention processes and parameters).

Overall, the planned RD&D programme aims to refine the fundamental understanding, develop modelling capabilities, and increase the data support to describe the near-field evolution, to evaluate adherence to requirements and to support the analysis of the consequences of any resulting radionuclide releases.

The last full integration of Nagra's understanding of near-field evolution took place as part of its safety assessment in 2002 (Nagra 2002a). The next full description of the repository evolution and assessment of the safety-relevant aspects, including the formulation of the requirements, are planned for the safety case documented in Nagra NTB 24-10 (planned) and its underlying documents which will form part of the general licence applications.

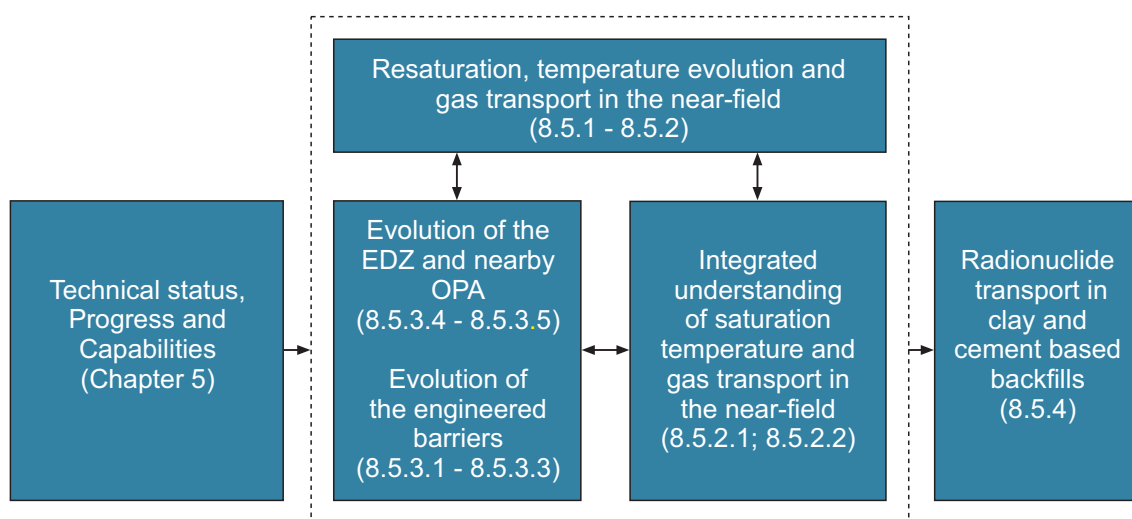


Fig. 8-13: Relationship between different parts of the description of near-field evolution in Section 8.5, including its components and development described in the subsections

In the context of optimisation, while the focus here is on the current concepts, supporting activities targeting the description and evaluation of the near-field for potential alternative concepts are also described where appropriate (e.g. activities related to a copper-coated canister, while the concept is currently a carbon steel canister).

8.5.1 Description of near-field evolution

The evolution of both the L/ILW and HLW disposal areas is driven by thermo-hydraulic gradients created by repository construction, heat-generated radioactive decay as well as chemical interactions occurring under repository conditions (e.g. concrete, metals, organics). While an important driving force in the case of the L/ILW disposal area is gas pressure build-up (Fig. 8-15), heat build-up from radioactive decay has an important impact on the HLW repository (Fig. 8-14).

After waste emplacement, the evolution of the safety-relevant properties of the SF/HLW 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.

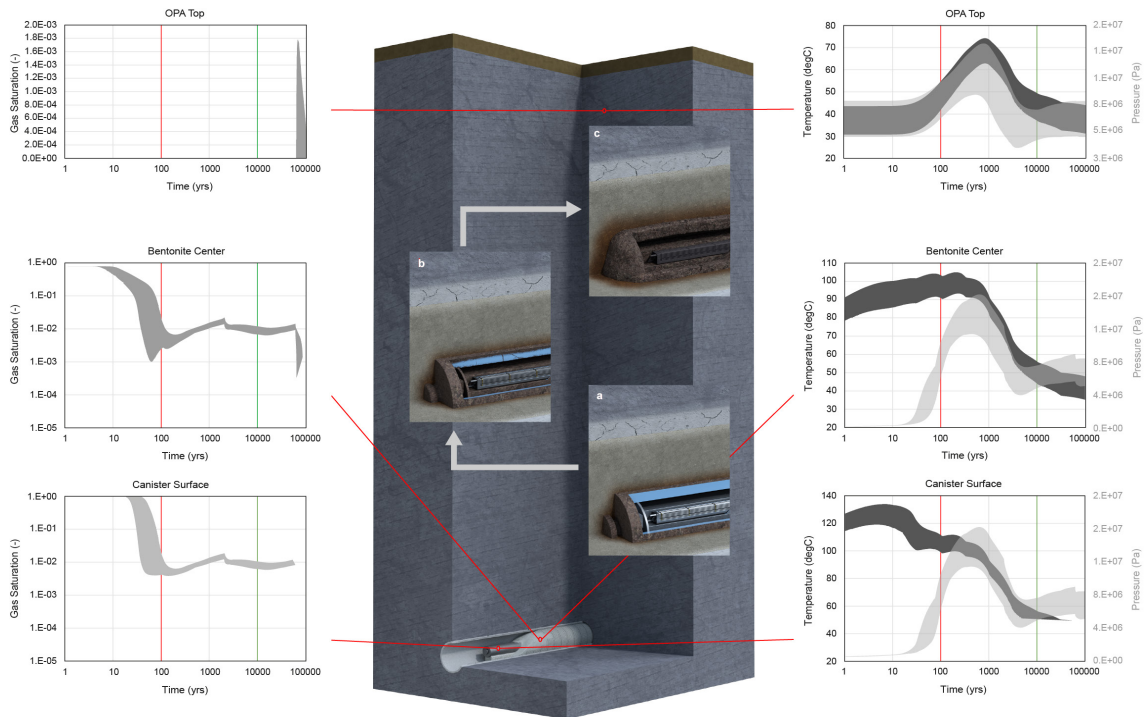


Fig. 8-14: Overview of the expected evolution of the main processes in an HLW repository, based on a compilation of modelling reports and experimental data

The letters within the boxes correspond to: (a) full saturation (b) canister breaching (c) no metal left.

The decay heat from SF and HLW will lead to higher temperatures within and around the repository for several thousands of years. The effects of this heat on the engineered and natural barriers cannot be completely eliminated but can be kept low enough by ensuring sufficient duration of interim storage and suitable waste emplacement density. The bentonite buffer will become saturated within the first few hundreds of years (depending on the host rock properties), after which pore pressure in the buffer will increase to that in the surrounding host rock. Gas will be generated through corrosion of the steel used in tunnel support and the canisters and will percolate as a gas and/or aqueous phase through the engineered barriers and into the rock. Gas transport through the saturated bentonite and tunnel support will not cause any irreversible damage. Gas will follow the pathways with the lowest entry pressures, including connected pores along the largely sealed EDZ.

Other potentially significant processes include:

- Degradation of the cementitious lining segments and migration of high-pH porewater within these elements into thin layers of adjacent host rock and bentonite, where chemical interactions can occur (not shown in Fig. 8-14) and locally lower the porosity at the interfaces. Alkaline porewater from the lining segments will to some extent exchange the cations in the bentonite near to the interface with the buffer to yield calcium-dominated smectite.
- Canister breaching due to corrosion, anticipated after at least 10,000 years, will lead to ingress of water, and increase the area of the corroding surfaces. Spent fuel and vitrified waste will then start to dissolve slowly, thereby releasing radionuclides. Radionuclides will diffuse into the bentonite buffer, where the largest part will be immobilised.

Fig. 8-15 gives a similar overview for the L/ILW emplacement caverns. The construction of the caverns and emplacement of the waste will take around 15 years in total. The timeline for waste emplacement, together with the emplacement procedures adopted, will set the initial conditions for the hydro-mechanical and chemical (HMC) long-term evolution of the L/ILW near-field.

Thermal disequilibrium is short-lived and limited to the operational (cooling of the host rock due to tunnel ventilation) and early post-closure periods, after which the exothermic reactions in the cementitious backfill will cease. Thermal effects are expected to have a negligible effect on the chemical or physical processes.

Thereafter, the evolution of the L/ILW near-field is essentially controlled by the saturation of the backfilled emplacement caverns, gas production by the waste and the physico-chemical interaction of the inflowing porewater with the cementitious backfill and the waste materials. Gas pressure evolution will counteract saturation, which may take tens of thousands of years. Model calculations indicate that there could be a period during which gas will expel porewater from the caverns 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, as well as the potential for porosity changes and cement – clay interactions.

Overall, it is shown that the repository-induced effects can be described based on present understanding and that the effects will remain below the identified criteria identified in Leupin et al. (2016a, 2016b). However, further RD&D activities are foreseen to refine the assessment of repository-induced effects, while new data and findings will continue to be integrated into the understanding of the near-field evolution. This will also contribute to the refinement and justification of the requirements on expected performance. A full update is foreseen in preparation for the general licence applications.

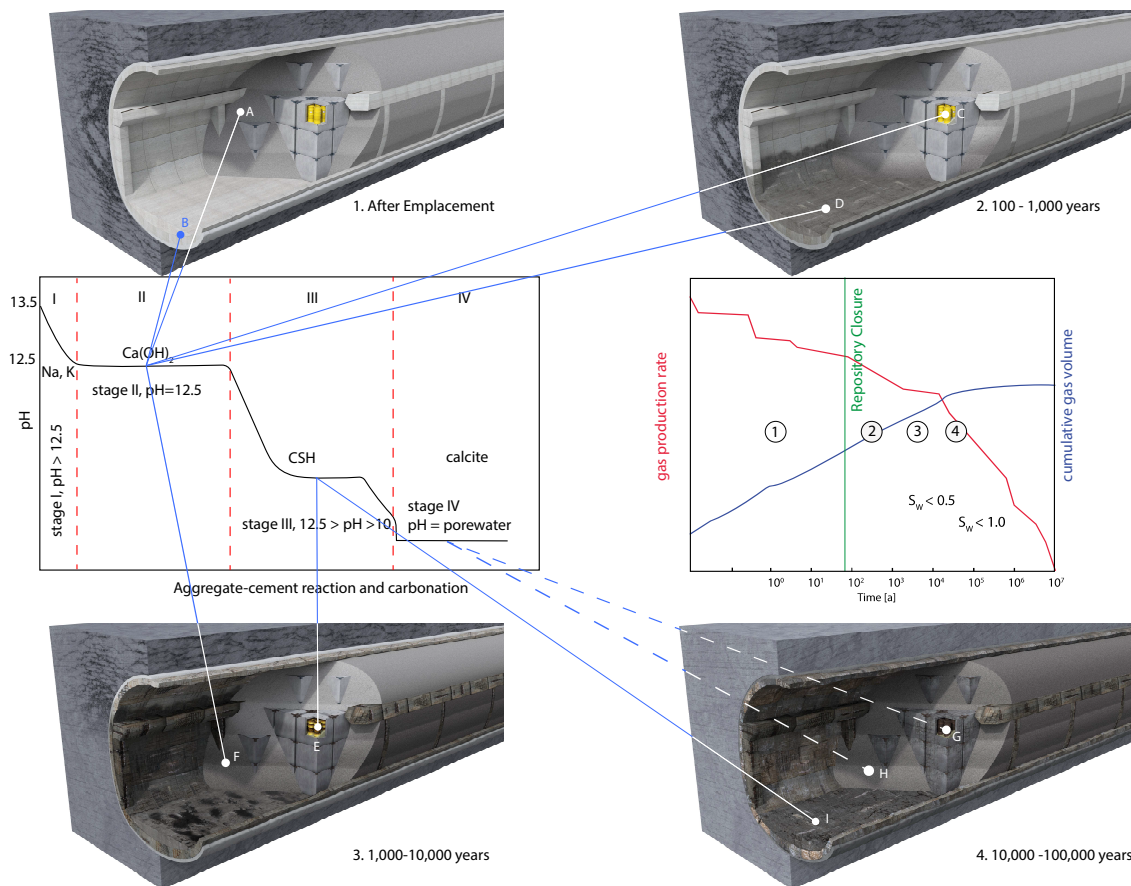


Fig. 8-15: Overview of the expected evolution of main processes in the L/ILW part of a combined repository

These diagrams show four stages of the L/ILW cavern (1 – 4 in the centre-left-hand figure and corresponding figures of the cavern in clockwise arrangement) and the evolution of the cementitious components (I – IV in the centre-right figure). The cement properties mainly evolve through internal cement degradation processes (carbonation and alkali aggregate reaction) and with the exchange of porewater at different rates depending on cement composition and properties.

For a conservative consideration of the gas production rate in the gas performance assessment, the onset of gas production is assumed when the cavern is sealed off (immediate full saturation and anoxic conditions). The initial water content of the concrete (when applied) might result in a short period of corrosion gas production right after emplacement. The pores of the concrete will thus be initially gas-filled. Upon closure, water saturation will progress. Where the relative humidity is high enough, corrosion can take place. Corrosion gas that dissolves in the porewater does not contribute to a build-up of gas pressure. Once the solubility limit has been reached, a gas phase is formed, and the gas pressure increases. Full water saturation of the cavern is only expected towards the end of the time period under consideration (100 ka).

8.5.2 Re-saturation, temperature evolution and gas transport in the near-field

The evolution of the L/ILW near-field displays fundamental differences compared with the HLW near-field in terms of saturation, temperature evolution and gas transport. In terms of RD&D activities, dedicated research programmes are needed for both the bentonite buffer of the HLW repository and the concrete-based near-field of the L/ILW repository to address their expected evolution and possible deviations therefrom. Specific objectives, the current state of research and future needs are discussed in the following paragraphs.

8.5.2.1 SF/HLW near-field

Objectives

In the safety concept for SF/HLW, the buffer in the SF/HLW emplacement drifts provides a well-defined interface between the disposal canisters and the host rock. The assigned component-specific functions include strong retention of radionuclides, a suitable environment for the disposal canisters and the waste forms, and compatibility with the favourable conditions in the host rock. In the context of a performance assessment, the main objective is to further reduce uncertainties by producing a refined description of the impact of the thermal pulse, the saturation of the SF/HLW near-field and the release of corrosion gases from the canister surface on some of the key parameters describing the performance of the buffer and the host rock. Due to the coupled nature of the processes involved, an understanding of saturation requires an understanding of temperature evolution, gas production processes associated with canister corrosion, gas transport, geomechanical evolution and self-sealing of the surrounding excavation damaged zone (EDZ). While work on these individual processes is presented separately in Sections 8.2.2.2 to 8.2.2.6, the combined impact of these processes from the scale investigated in URLs to the repository scale is discussed in this section.

Particular focus is on furthering the understanding of the temporal evolution of the conditions anticipated in the repository in terms of their expected evolution and deviations therefrom. Given the scale and timeframes involved, numerical (THM) modelling is an important aspect, but it has 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 for the near-field and a demonstration of how the safety-related requirements can be met. A rigorous assessment of the associated parametric uncertainties, conceptual uncertainties and scenario uncertainties is an integral part of any THM near-field modelling in support of performance assessment.

Current state of the art and progress since the 2016 RD&D Plan

In Nagra's RD&D programme, improving the understanding of the saturation of the SF/HLW near-field has been a high priority over the last two decades. A synopsis of early experimental investigations and numerical studies as part of the Opalinus Clay project was given in Nagra (2002a, 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 Euratom 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 in late phases (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.

The follow-up Euratom PEBS (Long-term Performance of Engineered Barrier Systems) project concentrated on the prediction and evaluation of THM processes in the SF/HLW near-field during the early and late saturation phases. The experimental work included the dismantling of the Mont Terri EB (Engineered Barriers) experiment, which demonstrated that dense bentonite pellets evolve to a swollen material indistinguishable from swollen 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 & 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 and apply them to the long term.

In the Euratom FORGE project (Shaw 2015) on the fate of repository gases, Nagra's activities were related to the HLW programme, concentrating on gas transport along the EDZ and gas transport in the intact host rock. The results are summarised in Harrington (2013). A comprehensive synopsis of experimental findings with a focus on gas transport in Opalinus Clay was compiled in Marschall et al. (2013).

The Full-scale Emplacement (FE) experiment started in early 2010 at the Mont Terri Rock Laboratory and is a full-scale multiple heater test in the Opalinus Clay (Müller et al. 2015, Nagra 2019a). The main objective of the FE experiment has been to investigate SF/HLW repository-induced THM coupled effects on the host rock at repository scale and to validate existing coupled THM models. Observations during the first five years largely confirmed Nagra's existing understanding (Lanyon et al. 2020). A dedicated prediction-evaluation exercise aimed at predicting the FE near-field evolution during the first three years after the onset of heating (Papafotiou et al. 2018) has provided valuable insight into the predictive capability of existing TH modelling approaches. Modelling benchmarks with different THM codes as part of the international FE Modelling Task Force (Section 8.2.2.4) built further confidence in the technical readiness of the existing THM modelling framework (Alcolea in prep.).

As part of the Äspö Task Force on Engineered Barriers, Nagra has been participating in several modelling tasks with a focus on gas transport and homogenisation of the buffer system in the late re-saturation phase (Dieudonné et al. 2017, Madaschi & Laloui 2019, Romero & Gonzalez-Blanco 2019). 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.

Dedicated sensitivity studies with generic 2D and 3D models of the HLW near-field and of the entire HLW repository, respectively, addressed the impact of saturation, heat, gas transport and physico-chemical processes on repository evolution (Papafotiou & Senger 2014b, Senger et al. 2014a, Papafotiou & Senger 2016b, Diomidis et al. 2016). Estimates of saturation 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. The aim of probabilistic sensitivity analyses was to assess the effect of uncertain input parameters on the modelling results (Papafotiou & Senger 2016b). Hydromechanical couplings on the evolution of stress and deformation in the repository near-field, including canister movements in response to the buffer saturation process, were the subject of dedicated modelling studies at the component scale (Dupray et al. 2014).

Further sensitivity analyses encompassed both gas transfer within individual repository components and the behaviour of the overall system. Special emphasis was placed on the release path along the EDZ of the backfilled SF/HLW tunnels and through the seal sections (Section 8.5.3.4). For this, the existing coupled hydromechanical approach (Alcolea 2018) was extended to account for site-specific differences of the EDZ extent.

Leupin et al. (2016a) concluded that the issues of thermally-induced and gas-induced pressure build-up in the repository near-field can be addressed through appropriate repository design (e.g. adapting the repository footprint). In this context, a new criteria-based indicator workflow has been developed, which allows for model-supported assessment of repository performance and repository optimisation, with a particular focus on repository-induced effects, as a contribution to the upcoming site selection process and general licence applications.

Planned RD&D in the next five to ten years

The MARIE indicator workflow, which has been developed for the assessment of the 13 site selection criteria according to the Sectoral Plan (SFOE 2008), will be revised to account for the latest results of the recent site investigation programme. For the assessment of the site-specific HLW repository projects, the new THM databases and the final versions of the site-specific repository layouts will be integrated. Furthermore, new probabilistic features will be introduced in the modelling workflow to address the parametric and conceptual uncertainties of the HLW repository projects, as stipulated in Criteria Group 3 of the *SGT* (SFOE 2008). As part of the new EURAD GAS work package initiative (Section 8.2.2.2), Nagra is involved in a generic benchmark exercise (GAS Task 4) aimed at the conceptualisation and evaluation of gas transport on the repository scale. The activities include a comparison of performance assessment approaches of the participating waste management organisations with respect to the gas issue and a benchmark exercise using a generic repository concept. Another modelling benchmark is performed as part of the EURAD HITEC work package, with the emphasis on the non-isothermal early saturation phase of the HLW near-field. The modelling activities as part of EURAD are complementary to the code verification and model validation tasks of the FE Modelling Task Force (Section 8.2.2.4). Together with participation in other international modelling platforms (e.g. EBS Task Force), these benchmark exercises contribute to the general confidence-building process in support of the model-based assessment of repository performance.

Long-term monitoring of the buffer saturation processes in the HE-E and the FE experiments at the Mont Terri Rock Laboratory will be continued and will feed into the expansion of the existing database for THM model validation (input for EURAD and the FE Modelling Task Force).

Deterministic and probabilistic assessment of the parametric and conceptual uncertainties associated with the thermal pulse and gas release from a HLW repository is foreseen in the context of a broader initiative on probabilistic performance assessments. The associated activities include safety-related robustness assessments of individual repository components and of the entire repository (total system performance) and cost-related repository optimisation as an extension of a recent pilot study.

Implementation of features for mimicking capillary versus viscous fingering of gas transfer along the EDZ of the backfilled SF/HLW tunnels and through the seal sections will be the subject of further model development (recent requirement of the Expert Group on Nuclear Waste Disposal, EGT). The topic will be addressed as part of the EURAD GAS work package, together with other gas-related impacts on the HLW near-field (e.g. gas-induced mobilisation of bentonite particles).

Further developments will complement the toolbox for coupled THMC modelling of HLW near-field processes. In particular, a new development project has started recently, aimed at coupling the saturation of the HLW near-field with canister corrosion and gas production. The hydro-chemical coupling will be realised by developing an efficient lookup table approach. Validation of the approach will be conducted by benchmarking the simplified lookup table approach with a fully coupled thermo-hydro-chemical model. Another modelling initiative will focus on long-term stress evolution in the immediate vicinity of the HLW canisters as a contribution to the canister development activities (Section 8.4.5).

These aspects will be further elaborated in the context of optimisation of the repository layout and distribution of the thermal load, especially in anticipation of the detailed design development for the submission of the construction licence applications.

8.5.2.2 L/ILW near-field

Objectives

The main component-specific functions of the cementitious near-field within and around the L/ILW emplacement caverns are to contribute 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 the saturation of the near-field. The main objective of the work described below is to develop an improved description of the development of the L/ILW near-field during the saturation phase and of subsequent pressure recovery under conditions as close as possible to those anticipated in the repository.

A particular focus is on the temporal evolution of the distribution of water saturation and pore pressure as basic input to the assessment of radionuclide transport within the engineered barriers and also on the chemical and microbiological evolution of the L/ILW near-field. This latter aspect is covered in Section 8.2.2.6, 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 8.5.3.5.

Given that the processes are highly coupled, and considerable periods of time are involved, the development of a description of the evolution of the L/ILW near-field requires strong support from coupled models, relying on an up-to-date experimental hydromechanical database to cover the full range of cementitious backfill materials under consideration in both pristine and altered states. Processes such as water and hydrogen consumption, salt precipitation, iron and sulphate transfer in the unsaturated state and transfer of volatile gas components have to be addressed to further improve overall hydrochemical understanding.

Overpressures generated by gas production in the near-field have to be constrained so that they do not affect the integrity of the barriers or cause induced seismicity. It is possible that gas pressure will lead to pathway dilation in the Opalinus Clay. This process will not 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 decreases. However, if pressures can be kept sufficiently low (e.g. through design measures) to exclude this process, this would simplify the analysis of the system and increase robustness. Finally, gas pressurisation could potentially lead to the displacement of porewater in the near-field and far-field, thus affecting the retention in the Opalinus Clay.

Current state of the art and progress since the 2016 RD&D Plan

In Nagra's previous RD&D programmes, the emphasis of the research activities related to the L/ILW near-field 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 Gas Migration Test experiment at the GTS, a comprehensive survey of the gas transport properties of cementitious material was undertaken and complemented using Nagra's own results (Lanyon & Rüedi 2008).

A comprehensive appraisal of gas release from a generic L/ILW repository was presented in Nagra (2008a), comprising a detailed assessment of the saturation conditions in an 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).

A major component of the EGTS as an engineering solution for gas release along the backfilled structures of an L/ILW repository are gas-permeable seal sections (Section 8.4.8). The design, construction and operation of the full-scale Gas-permeable Seal Test (GAST) at the GTS is seen as a cornerstone in support of Nagra's safety concept for an L/ILW repository (see separate text-box below). After the technical feasibility of building such structures at full scale was successfully demonstrated by mid-2012 (Teodori et al. 2013), a long-term test programme was initiated to demonstrate the effective functioning of gas-permeable seals at repository scale. Preliminary gas injections were performed in 2015 (Spillmann et al. 2015).

Nagra's participation in the Euratom FORGE (Fate of Repository Gases) project (Shaw 2015) 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 permeability, which is reduced).

3D sensitivity studies on gas release from a generic L/ILW repository were conducted as part of *SGT* Stage 2, addressing the impact of saturation, gas transport and chemical processes on the evolution of the L/ILW near-field after waste emplacement (Senger & Papafotiou 2014, Papafotiou & Senger 2014a, 2016a, Diomidis et al. 2016, Papafotiou et al. 2018). Estimates of saturation time and pressure recovery time were achieved for a broad spectrum of geological settings. Complementary probabilistic sensitivity analyses investigated the effect of uncertain input parameters on the modelling results (Papafotiou et al. 2017). A new modelling approach was developed to address concrete degradation processes in the L/ILW near-field in an efficient way using so-called lookup tables (Finsterle & Spycher 2019).

Leupin et al. (2016c) and Diomidis et al. (2016) already concluded that the issue of gas pressure build-up can be addressed through appropriate design of the L/ILW repository and supported by additional engineering measures (e.g. the EGTS) if needed. A new criteria-based indicator workflow was developed, which allows for the model-based assessment of repository-induced effects (MARIE) as a contribution to the upcoming site selection and the safety case for the selected sites to be documented in Nagra NTB 24-03 (planned) and Nagra NTB 24-10 (planned) and their supporting documents.

Planned RD&D in the next five to ten years

An assessment of the conceptual and parametric uncertainties associated with gas release in the L/ILW near-field will be conducted (Section 8.2.2.2). The MARIE indicator workflow, which has been developed for the assessment of the 13 site selection criteria according to SFOE (2008), will be revised to consider the latest insights from the recent site investigation programme. For the assessment of the site-specific L/ILW repository projects, the new gas-related databases (including gas source terms, impact of volatiles, EDZ) will be integrated and the final versions of the site-specific repository layouts will be implemented. The updated geological databases will also allow the development of an optimised repository design with respect to gas release, as required in ENSI (2018c). Furthermore, new probabilistic features will be introduced in the modelling workflow to address the parametric and conceptual uncertainties of the L/ILW repository project, as required in the *SGT* (SFOE 2008).

Modelling of capillary pressure-saturation relationships and relative gas/water permeability relationships for the various cementitious materials is required in support of a detailed assessment of the saturation conditions and gas pressure build-up around the waste containers. Additional gas-related laboratory work will concentrate on the cementitious EBS components, particularly 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 L/ILW near-field will be completed (coupled hydro-chemical modelling of saturation-dependent metal corrosion and concrete degradation).

The GAST experiment at the GTS will be continued beyond the submission of the general licence applications. The final 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.

The elements above will feed into a detailed description of the ILW and L/ILW near-field evolution and will be further elaborated in the context of optimisation of the repository layout and the mitigation of the gas issue, especially in anticipation of the detailed design development for the submission of the construction licence applications, as described in the respective Tier 3 roadmap for the gas issue (Section 7.4).

Gas transport in the repository: GAST and MiniGAST experiments

The key objectives of the GAST (GAs-permeable Seal Test) and MiniGAST experiments are directly related to the concept of the "Engineered Gas Transport System" (EGTS, Nagra 2008a): (1) demonstration of the effective functioning of gas-permeable seals at a realistic scale and with realistic boundary conditions (proof of concept), (2) validation and, if necessary, improvement of current conceptual models for the saturation and gas-transport processes in sand/bentonite seals, and (3) determination of upscaled gas/water permeabilities of sand/bentonite seals.

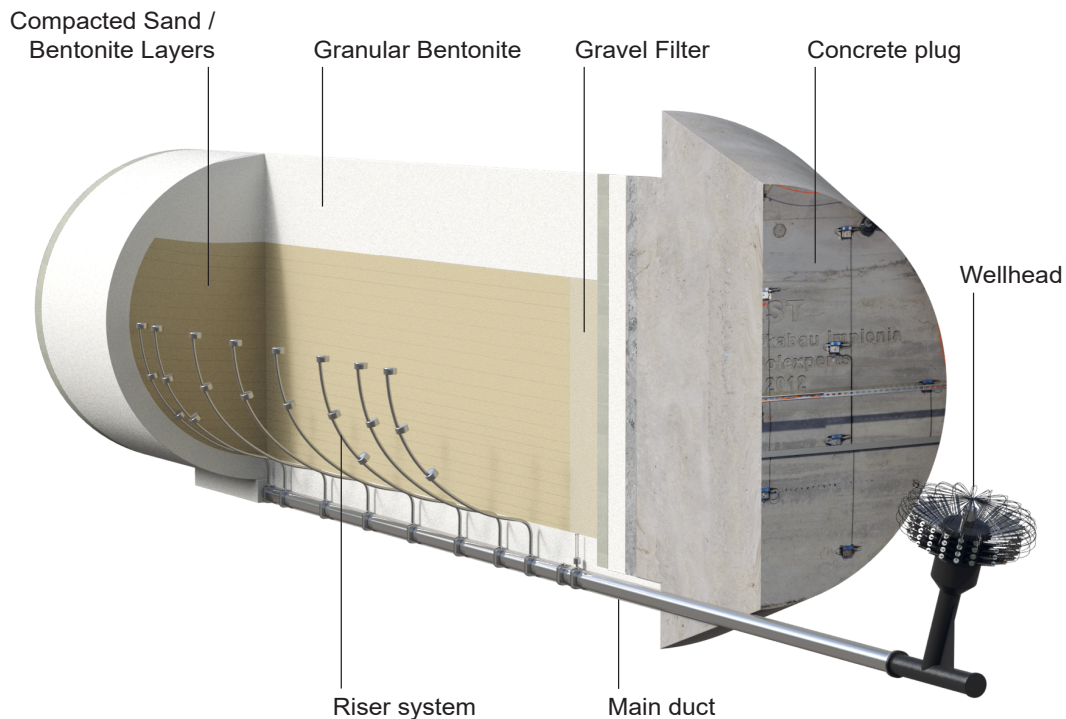


Fig. 8-16: Schematic illustration of the full-scale GAST experiment

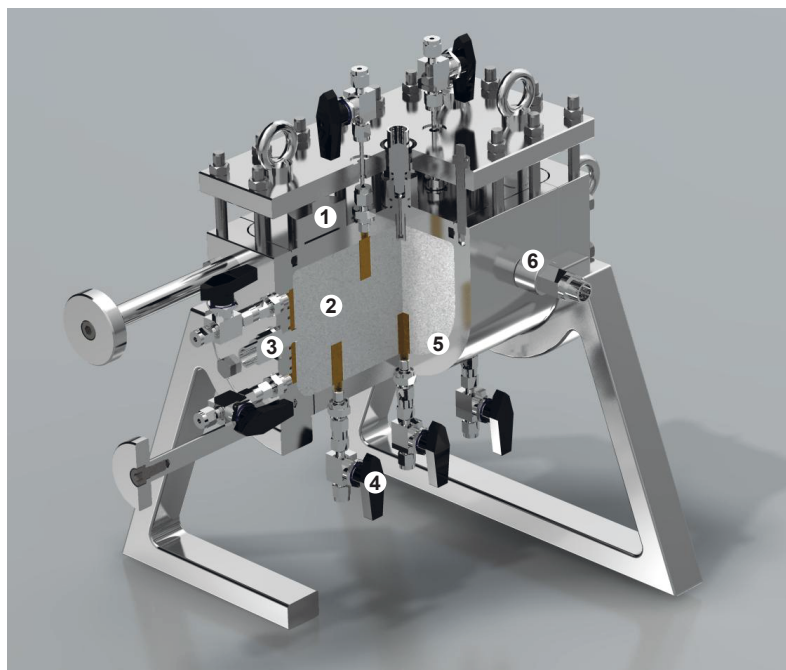
The experiment features a sand/bentonite body (80/20%) which is confined by two permeable filter elements and encased in pure bentonite.

After a ~ 29-month pressurisation and saturation phase of the GAST system (see Fig. 8-16), the first set of gas property tests was performed in early 2018. The objective of these tests was to determine the effective functioning of the system for the full gas flow test. Important properties of an EGTS have been demonstrated with this test, i.e. low gas entry pressure and gas transport in the sand/bentonite system, as well as low permeability on saturation.

Confidence gained with the gas property tests facilitated the planning of the continuation of the GAST experiment; currently the pressure/saturation homogenisation at a higher-pressure level is ongoing. The gas flow test is planned for 2022, accompanied by a comprehensive data analysis and reporting in 2023.

A laboratory programme in support of the GAST full-scale experiment was initiated in 2019 with the construction of two mock-up-size test cells (the so-called "MiniGAST" experiment). It mitigates the longer-than-anticipated re-saturation time needed for GAST. The aim of MiniGAST is to mimic the GAST setup and boundary conditions on the decimetre scale and thereby support the interpretation of the gas flow test and allow confirmation of the gas transport processes in sand/bentonite seals at various scales.

The design of the MiniGAST test cell allows for a layered sand/bentonite seal installation comparable to that of GAST. The entire face saturation of the specimen was used to minimise the saturation time of the system (see Fig. 8-17). The first decimetre-sized cell was built and commissioned in 2020, and the first gas flow test results from MiniGAST are expected for 2021.



- 1 Load Cell
- 2 Sand / Bentonite
- 3 Pore Pressure Sensor
- 4 Drainage Ports
- 5 Bentonite Layer
- 6 Total Stress Sensor

Fig. 8-17: Illustration of the MiniGAST cell

8.5.2.3 Evolution of a combined repository

Objectives

For a combined repository for L/ILW and SF/HLW, sufficient distance between the L/ILW caverns and the SF/HLW emplacement drifts has to be ensured to avoid adverse interactions. The regulatory authority provides further requirements to be considered in *SGT* Stage 3 of the site selection process (ENSI 2018c). The purpose of the RD&D activities on the evolution of a combined repository is to evaluate these interactions and develop the workflow to define the placement of the combined repository for L/ILW and SF/HLW in the siting regions.

Current state of the art and progress since the 2016 RD&D Plan

A generic feasibility study for a combined repository aimed at assessing the potential interaction between the disposal system for SF/HLW and that for L/ILW has been described in Leupin et al. (2016a, 2016b). The focus of this modelling exercise was on pressure development associated with:

- gas generation from the degradation of radioactive waste materials and corrosion of waste canisters and
- heat generation from radioactive decay in SF/HLW

since these were potentially the most significant causes of interaction between the two systems. Based on the modelling study, it appears that the pressure regimes in the L/ILW and SF/HLW repositories evolve rather independently. The results suggest that a horizontal separation distance of a few hundred metres between the L/ILW repository section and the SF/HLW repository section is sufficient to avoid interference in the pressure build-up between these two parts of a combined repository.

In response to the recommendations of the regulatory authority (ENSI 33/649; ENSI 2018c), a new research project was initiated in 2019 aimed at developing a quantitative workflow for the determination of the minimum respect distance between the HLW and L/ILW emplacement rooms of a combined repository, applicable to the three potential siting regions in Northern Switzerland (Nagra 2021c). The proposed methodology considered not only gas and heat generation as sources of possible interactions, but also the aspect of transport of volatile radionuclides along the back-filled underground structures. Simulations with generic and semi-generic repository models confirmed the findings of previous assessments, indicating that a horizontal separation distance of a few hundred metres is sufficient to avoid safety-relevant interactions between the HLW and L/ILW emplacement rooms. The proposed workflow will be applied to the site-specific repository projects in anticipation of the site selection and the submission of the general licence applications.

Planned RD&D in the next five to ten years

Thermo-hydraulic models for a combined repository will be established for the three siting regions. The models will be used to assess the performance of the combined repository as compared with two separate repositories for HLW and L/ILW. If the decision is taken to prepare licence applications for a combined repository, further modelling activities will concentrate on the safety-related optimisation of the combined repository in the proposed siting region.

Due to the enormous size and complexity of the 3D thermo-hydraulic models for combined disposal, model developments will be initiated to reduce the computational effort. These include the development of particle-tracking methods for the simulation of transport of volatile radionuclides and other post-processing tools for visualisation and animation of the modelling results.

If a combined repository is the subject of a general licence application, these activities will continue in order to further optimise the repository project for the construction licence applications.

8.5.3 Individual engineered barriers and the surrounding Opalinus Clay

8.5.3.1 Corrosion of SF and HLW disposal canisters

Background and objectives

The major component-specific function of the SF and HLW canisters is to provide a period of complete long-term containment of the wastes (ENSI 2020). Eventually, a combination of mechanical and corrosion processes will lead to canister breaching, allowing the ingress of water and the mobilisation of radionuclides. Even after breaching, the canisters will contribute to the retardation 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 corrosion programme is to increase confidence in canister lifetime predictions by improving understanding of relevant corrosion mechanisms, quantifying corrosion rates of candidate canister materials under repository-relevant conditions and developing methodologies for predicting their long-term evolution and impacts. Mechanisms that can lead to an acceleration of canister degradation, such as localised corrosion, stress-corrosion cracking, hydrogen embrittlement and the influence of microbial activity, are of particular interest. Overall, corrosion interacts strongly with processes occurring in the surrounding bentonite. Therefore, corrosion rates provide input to the modelling of saturation and gas transport in the near-field (Section 8.5.2) and the evolution of the bentonite buffer (Section 8.5.3.3).

Current state of the art and progress since the 2016 RD&D Plan

Research on the corrosion of canister materials has continued in various national programmes, both for steel (Necib et al. 2019, Uyama et al. 2019, Bouttemy et al. 2018, Mercier-Bion et al. 2018, Bourdelle et al. 2017, Liu et al. 2017, Mohamed-Said et al. 2017, Necib et al. 2017b, Robineau et al. 2017, Xu et al. 2017, Zhang et al. 2017, Grousset et al. 2016, Necib et al. 2016) and for copper (Martino et al. 2019, Chen et al. 2018a, Hall et al. 2018, Hedin et al. 2017, Hedin et al. 2018, Huttunen-Saarivirta et al. 2018, Ibrahim et al. 2018, Turnbull et al. 2018, Björkbacka et al. 2017, Caporuscio et al. 2017, Chen et al. 2017, Forsstrom et al. 2017, Huttunen-Saarivirta et al. 2017, Johansson et al. 2017, King et al. 2017, Kosec et al. 2017, Ottoson et al. 2017, Qin et al. 2017, Hung et al. 2017, Martino et al. 2017, SKB 2019c). An interesting new development has been the optimisation of the French (Crusset et al. 2017) and Japanese (Ogawa et al. 2017) disposal concepts based on recent steel corrosion data. Regarding copper, significant effort was invested in modelling the transport of sulphide, which is the main corrosive species, through the near-field for various disposal concepts, both internationally (Wersin et al. 2017, Petersen et al. 2017, Briggs et al. 2017a, 2017b) and in Switzerland (Pekala et al. 2019a, Pekala et al. 2020, Cloet et al. 2017). Critical to the durability of copper coatings is the risk of galvanic coupling with the underlying steel substrate if a through-coating flaw exists. However, recent studies have

shown that this is only possible in the presence of oxygen, and thus does not constitute a long-term risk in the repository (Standish et al. 2017, 2018). In addition to the experimental and mechanistic studies that have been published widely, recognised experts from the international scientific community have summarised the state of the art, identifying knowledge gaps and providing guidance for future RD&D (Padovani et al. 2017).

As part of Nagra's activities, the corrosion of carbon steel in saturated anoxic bentonite has been addressed in benchtop studies (Smart et al. 2017a). Carbon steel and copper corrosion under saturated and anoxic conditions is also being studied in situ in a clay (Smart et al. 2017b, Necib et al. 2017a, Reddy et al. 2020b) and in a granite host rock (Engel et al. 2019, Reddy et al. 2020a). A synthesis of the results obtained from these studies and their consequences for canister performance have been reported (Diomidis et al. 2021). The development of a new approach for the assessment of canister lifetime with the aim of increasing the realism of the description of repository evolution has begun. It consists of a probabilistic model for the evaluation of the time when canisters breach that takes into account inherent variabilities in the disposal system and uncertainties in mechanisms and parameter values. The model includes chemical-mechanical interactions, such as loss of wall thickness due to corrosion and decrease of fracture toughness due to hydrogen embrittlement.

Recent results from the FE-G experiment at Mont Terri indicate that the aerobic period in the repository will be much shorter than initially thought (Giroud et al. 2018, Tomonaga et al. 2019). This is an important input to corrosion and canister lifetime assessment as the presence of oxygen is a prerequisite for a number of corrosion mechanisms, such as localised and crevice corrosion. Nevertheless, the corrosion of carbon steel and copper coatings continues to be studied in unsaturated bentonite during the oxic to anoxic transition.

Planned RD&D in the next five to ten years

The planned work for the coming years deals with two main subjects: the continuation of ongoing work on corrosion processes on candidate canister materials under repository conditions and the further development of probabilistic canister lifetime assessment. The canister lifetime will then be assessed again using in-situ data for the selected repository site and state-of-the-art corrosion rates, which will be one of the most important results for the general licence applications. International research collaboration will be pursued with the aim of addressing common open questions within the radioactive waste management community also as part of the EURAD CONCORD work package (2021 – 2024) that is being led by Nagra. Further work is also planned to advance understanding of the fate of oxygen in the repository, which will combine in-situ monitoring with benchtop experiments aimed at unravelling the underlying mechanisms.

The specification of the work on corrosion is presented in relation to the work on canister development (Section 8.4.5) and will therefore also reflect new developments in canister design and materials. Consequently, in the longer term, corrosion studies and work in support of lifetime assessment will increase in scale, reflecting the increased maturity of the design of the disposal canister. Further optimisation of candidate materials with respect to canister performance will take place after the submission of the general licence applications.

The Tier 3 roadmap in Section 7.8 illustrates the RD&D on corrosion together with the RD&D on the canisters that is foreseen up to ~ 2060.

8.5.3.2 L/ILW disposal containers, container backfill material and cement-based barriers

Objectives

Cementitious materials will be present in most elements of the L/ILW repository, including the tunnel support system, cementitious backfill (Section 8.4.7), disposal containers and the mortar used in the disposal containers for the conditioning of decommissioning waste and as part of the waste drums (cemented waste in waste drum; Section 8.4.6). As noted previously, the component-specific 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 based on a suitable mineralogy and porewater composition and to provide a highly alkaline environment that ensures low microbial activity and low corrosion rates. Furthermore, cement-based elements, such as the tunnel support, the disposal container and the backfill mortar, also have the more practical function of contributing to the mechanical strength of the repository as well as providing gas storage capacity to reduce gas pressure increase in the cavern (M1 monograin mortar and the mortar for the decommissioning waste DORODUR, Sections 8.4.6 and 8.4.7). Chemical interactions (such as waste-cement interaction, internal cement degradation processes due to aggregate – cement interaction, carbonation or cement – clay interaction) may affect the chemical environment and alter its safety-relevant properties. Therefore, the impact of these chemical reactions on the conditions in the repository must be assessed as described below. The impact of other interactions on the host rock is addressed in Section 8.5.3.5.

Current state of the art and progress since the 2016 RD&D Plan

An overview and assessment of the various chemical reactions that may occur in an L/ILW repository have been described in various studies (Kosakowski et al. 2014, Leupin et al. 2016b, Wieland et al. 2018, Kosakowski et al. 2020, Leupin et al. 2016c, Kosakowski & Smith 2014). Internal degradation of cement and cement degradation due to groundwater ingress are well studied, and a degradation model is available (Berner et al. 2013, Kosakowski et al. 2014). Other well described reactions include corrosion, carbonation of cement due to CO₂ production from organic waste degradation and the alkali-silica reaction between silicate-rich aggregates and cement (Schwyn 2008, Cloet et al. 2014, Wieland et al. 2018, Kosakowski et al. 2020, Wieland & Kosakowski 2020). More elaborate attempts to unravel the processes leading to cement degradation include the use of multi-level pore-scale reactive transport models (Prasianakis et al. 2017) where, e.g., the carbonation and leaching of cement-based materials are modelled over various pore dimensions (Patel et al. 2021). Furthermore, work related to the stability of zeolites (Ma et al. 2021, Ma & Lothenbach 2020a, 2020b) and the uptake of Fe in calcium silicate hydrate (C-S-H) (Mancini et al. 2020) has been performed. More complex to assess are the impacts of the organic waste degradation products and of microbial interactions on cement stability.

To assess local pH evolution and gas release, studies on local heterogeneities resulting, e.g., from cement-waste interaction have been assessed in Wieland et al. (2018) and in Kosakowski et al. (2020), where the chemical evolution of different waste types in combination with different types of aggregates (siliceous vs. calcareous) was modelled. The chemical evolution of selected cement-based elements and the impact of their degradation on the local chemical environment within the repository were also accounted for (Sections 8.4.6 and 8.4.7). The results revealed that the main factor controlling the extent of reactions (degradation of organics and release of CO₂ and CH₄, corrosion of metals resulting in H₂) is the availability of water and the pH-buffering capacity of the cement system due to the presence of portlandite or C-S-H with a Ca/Si ratio > 1.6. The consumption of water (which is present on the educt side of most chemical reactions) will lead to

a halt of the reaction after a few hundred years, which limits gas generation (Kosakowski et al. 2020, Wieland et al. 2018). Further, it was shown that using carbonaceous instead of siliceous aggregates limits the extent of the degradation reaction and of gas generation and contributes to the preservation of the required high-pH conditions. However, this only applies if a minor amount of organic material is present (which degrades to CO₂ and leads to carbonation, see Fig. 3-24 in Kosakowski et al. 2020). The alkali-silica and carbonation reaction for different cement materials can be tabulated in lookup tables that are employed in coupled chemical modelling (Finsterle & Spycher 2019).

Planned RD&D in the next five to ten years

The activities will focus on an enhanced understanding of the transport processes for water, gas and ions and their chemical interaction in a clay – cement system. A synthesis on transport across cement – clay interfaces, including upscaling, is foreseen. The transport of gas and water in partially saturated systems will be important for the performance evaluation of the Engineered Gas Transport System (EGTS). The evolution of the porosity of the elements that contribute to the release (backfill mortar, sand-bentonite mixture, etc.) will be assessed, updating a preliminary assessment by Kosakowski & Smith (2014) and introducing arguments that the porosity during the period of gas generation remains sufficiently high to ensure that gas release from the repository is maintained. These aspects will be documented in Nagra NTB 24-10 (planned) and its supporting documents.

Beyond the general licence applications, Nagra aims to continue monitoring the state of the art in this area and to participate in international initiatives. The choice of cement-based materials for the L/ILW cavern construction will be specified in more detail for the construction licences. To support the safety case, thermodynamic calculations complemented by small-scale laboratory tests on the cement material must be performed to evaluate the performance of the envisaged cement and concrete formulations and their impact on the near-field. The description of the degradation of these cementitious materials will be updated according to the state of the art by accounting for additional degradation mechanism, such as ion attack (e.g. sulphate or chlorine attack).

8.5.3.3 Bentonite-based barriers (buffer, backfill, seals)

Objectives

In the current repository project, bentonite is used:

- in the form of compacted bentonite blocks and granular bentonite material as a buffer surrounding the SF and HLW canisters
- in the form of a sand/bentonite mixture in the Engineered Gas Transport System (EGTS) and
- in the form of granular bentonite material and/or blocks in other repository sealing and closure structures.

Design and technology development related to these components is discussed in Sections 8.4.4 and 8.4.8.

The main objective of the work is the development of an enhanced understanding of the processes occurring during repository evolution that may affect the capacity of these components to fulfil their safety-related requirements over relevant timescales (e.g. as set out for the buffer in Leupin et al. 2014). These requirements are formulated in terms of safety-relevant performance indicators and targets for the parameters that quantify these attributes.

The HotBENT experiment at the Grimsel Test Site

The international partner project HotBENT (High Temperature Effects on Bentonite) at the GTS is carried out to study the THMC effects of high temperatures (high thermal loading, i.e. $> 150\text{ }^{\circ}\text{C}$ at the emplacement canister surface) on the performance of bentonite as a buffer material at realistic scales and under in-situ conditions. The aims are to enhance the existing databases and understanding of buffer performance in terms of its robustness with respect to high temperatures. In addition, the experimental design will allow investigation of the effects of high temperatures on corrosion, microbiological processes, buffer-concrete interactions and gas-related processes. The outcomes are expected to contribute to design optimisation (buffer dimensions, canister and tunnel spacing) and/or disposal optimisation, e.g. canister loading options and interim storage strategies.

HotBENT consists of four heaters (three of them set to $175\text{ }^{\circ}\text{C}$ and one to $200\text{ }^{\circ}\text{C}$ at the surface), resting on compacted bentonite block pedestals and surrounded by granular bentonite material, see Fig. 8-18. Parameters such as temperature, water, gas and total pressure, saturation and strain are monitored in 28 instrumented sections by more than 1,200 sensors to capture the THM evolution (Fig. 8-18). These measurements are complemented by gas sampling throughout the duration of the experiment. Two types of bentonite are investigated (Wyoming and Czech-BCV).

The experiment was constructed in 2020-2021. The two front heaters and Sector 2 (Fig. 8-18) will be dismantled and analysed after approximately five years, whereas the remaining two heaters and Sector 1 are planned to be retrieved much later (after up to 20 years, ~ 2041) of constant heating. An intermediate plug (Plug 1, Fig. 8-18) will allow the dismantling of Sector 2 with no or minimal disturbance to Sector 1. Four boreholes parallel to the gallery and approximately one metre away from it will allow the geosphere pressure to be increased in a controlled manner and consequently decrease hydration times.

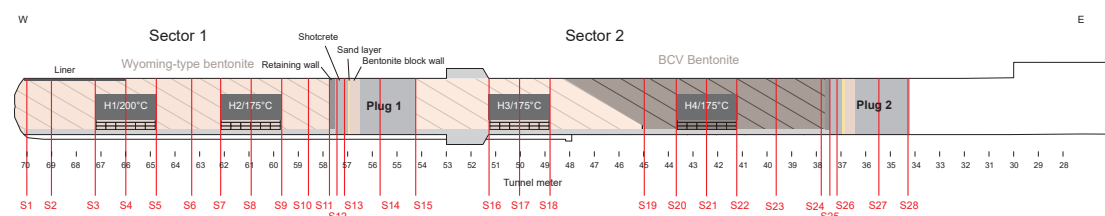


Fig. 8-18: The HotBENT experiment layout at the Grimsel Test Site in the former FEBEX gallery

Sector 1 consists of heater 1 (at $200\text{ }^{\circ}\text{C}$) and heater 2 ($175\text{ }^{\circ}\text{C}$), resting on compacted Wyoming-type bentonite blocks and surrounded by Wyoming-type granular bentonite material. Plug 1, a sandwich plug consisting of a retaining wall, a bentonite block hydration wall, a sand filter and a low-pH shotcrete segment, separates Sector 1 from Sector 2.

Sector 2, consisting of heaters 3 and 4 (both at $175\text{ }^{\circ}\text{C}$), is constructed of two bentonites, where heater 3 rests on compacted Wyoming-type bentonite blocks and is surrounded by Wyoming-type granular bentonite material while for heater 4, the buffer material is Czech-BCV bentonite. Plug 2 (same configuration as plug 1) closes the experiment. The red lines are the instrumented sections.

The HotBENT project is very similar to the Full-scale Emplacement (FE) experiment at the Mont Terri Rock Laboratory (Müller et al. 2017), but with the following main differences: i) it runs at higher temperatures and ii) it is subject to different surrounding geosphere-hydrosphere conditions (granite vs. claystone). It therefore enables the comparison of processes, phenomena and effects on the bentonite buffer at different temperatures and degrees of saturation. In addition, the HotBENT experiment provides information on further temperature upscaling effects and THM development, which are not available from the previous FEBEX (at the GTS) or the ongoing HE-E experiment (at the Mont Terri Rock Laboratory).

Specific areas where improved understanding and modelling capabilities will be sought are:

- THM evolution of the bentonite buffer and backfill barriers
- stability of the bentonite buffer at elevated temperatures
- chemical and microbiological processes that might affect the component-specific functions of the bentonite buffer and backfill barriers, including interactions with other engineered materials
- migration of repository-generated gases through the bentonite buffer and other bentonite-based barriers.

The development of models and data used to evaluate radionuclide retention and transport in the bentonite buffer and other bentonite-based barriers in support of the safety assessment is discussed in Section 8.5.4.

Current state of the art and progress since the 2016 RD&D Plan

There is now ample evidence and acceptance of the fact that the bentonite buffer is an efficient hydraulic, mechanical and chemical barrier that will protect the canisters and attenuate the release of radionuclides. Sand-bentonite mixtures foreseen for the sealing and possibly for the backfilling elements as part of the closure concept of the repository have been thoroughly characterised in Manca (2016). Such sand-bentonite mixtures are discussed in conjunction with gas transport in an L/ILW repository (see insert in Section 8.5.2.2).

Processes during saturation (focus on the HLW repository)

The relatively short transient thermal gradient around the canisters will give rise to chemical, hydraulic and mechanical coupled processes in the near-field. In spite of the steady improvement of the model descriptions of these processes, along with an increase in the experimental evidence underlying these descriptions, it is not yet possible to accurately describe all of the above-mentioned processes in a single numerical model. The thermal and thermo-hydraulic evolution of the bentonite buffer can be reasonably well captured by the state-of-the-art THM models. However, the capability of these models to predict mechanical behaviour is less advanced, although qualitative trends observed in the experiments can be captured. The recently developed dual porosity framework, which has been incorporated in THM as well as in THC models, appears to offer a robust and consistent framework to represent coupled THMC processes. A number of different features and observations can be readily explained within this framework (Jenni et al. 2019b).

Water saturation – The suction of the undersaturated bentonite and the availability of host rock porewater control the water saturation of the bentonite. Accompanying geochemical processes are outlined below. The closer it is to the canister, the longer it takes for the bentonite to saturate. Evaporation and vapour transport may induce precipitation of soluble salts close to the canister (sauna effect). Based on recent findings, however, this effect is expected to be small and reversible (Birgersson & Goudarzi 2017).

Gas transport – At the onset of saturation, the partly saturated buffer contains large amounts of air. Many laboratory-scale and large-scale experiments have shown that the increasing pressure of the gas in the saturating buffer leads to dissolution of the gas in the infiltrating porewater (Romero & Gonzalez-Blanco 2019).

Homogenisation – There are numerous experimental observations indicating that homogenisation of density/porosity variations is effective during buffer saturation and swelling. However, data also suggest that some inhomogeneity will remain after saturation (Dueck et al. 2019). Preliminary THM modelling (i.e. from the EBS Task Force and/or the Euratom BEACON project) generally indicate a fairly good description of the homogenisation process, but uncertainties remain, for example related to the mechanical properties of pelletised material.

Chemical and mineralogical evolution – During saturation of the bentonite with host rock porewater, transient behaviour of porewater salinity with fairly high chloride concentrations in the "free" porewater due to the osmotic membrane properties of the clay is expected. The thermal gradients will induce a limited redistribution of accessory minerals, including dissolution of gypsum on the "cold" side and reprecipitation of anhydrite/gypsum on the "hot" side (Hadi et al. 2017). At the interfaces with cement and steel, chemical and mineralogical changes are likely to be larger than when induced by heat alone. Because of strong chemical gradients at the cement – clay interface, diffusion followed by dissolution/precipitation processes will occur on the clay and on the cement sides (Jenni et al. 2019b). The impact of heat on bentonite properties is being further investigated in the HotBENT experiment (see insert above in this section).

Corrosion of the steel canister will release iron species that will form a corrosion layer but may also react with the clay. The amount of bentonite that will be affected by corrosion products, as well as how it will be affected, will depend on how redox-active the buffer is (Hofstetter et al. 2014). Corrosion of a Cu-coated canister (an alternative to the current concept) will lead to interaction of the oxidised Cu(I,II) with the clay. The amounts of Cu released will be small once the oxic period has ceased due to the low corrosion rates (Johansson et al. 2020).

Microbial activity – Initially, microbial activity will be limited in the unsaturated bentonite because of the low water activity. Once a higher moisture content is reached, however, conditions may become more favourable for microbes because of higher water activity, increased availability of nutrients and more moderate temperatures (SKB 2019c). On the other hand, due to buffer swelling, the fraction of small pores will increase at the expense of the larger pores, which will limit microbial activity therein (Dueck et al. 2019). The main concern is the possibility that microbial sulphate reduction could produce gaseous H_2S , which could diffuse towards the canister. Bounding analyses show, however, that the host rock does not provide enough sulphate for this process to be safety-relevant (Jenni et al. 2017, Cloet et al. 2017). Enhanced hydrogen consumption by microbial activity in sand/bentonite mixtures as a way of mitigating gas pressure build-up is being investigated as an optimisation measure in the MA-A (Platform Microbial Studies) experiment in the Mont Terri Rock Laboratory (see insert later in this section).

Processes after saturation

Once saturation is complete (after about 100 – 200 years), the heat output from the waste due to radioactive decay will be considerably lower, and temperatures in the buffer will have decreased well below 100 °C. The initial variations in porosity and density will have largely disappeared and the material will have gained a homogeneous nanoporous structure.

Gas transport – If constant gas production rates are assumed, the release of hydrogen from steel corrosion may not be fully compensated by dissolution and diffusion through the buffer. A separate gas phase will form and, when the pressure is close to the confining pressure, gas pathways will also form, the nature of which is not fully understood. However, it appears now that when more realistic gas production rates are assumed, a gas phase is not expected to form from the anaerobic corrosion of canisters in the long term (Leupin et al. 2021).

Porewater chemistry – The porewater composition in the buffer will slowly evolve via diffusive exchange with the surrounding Opalinus Clay porewater but will also be affected by alteration of the cement lining. The differences between the porewaters in the buffer and rock will, in general, be fairly minor, although there will be a gradient in sulphate as long as gypsum in the bentonite is not completely dissolved (Jenni et al. 2019b).

Iron – bentonite interaction – The aerobic phase of the repository will only last for a short period of time, according to recent evidence from large-scale, in-situ experiments. Anaerobic corrosion of steel then follows, which will consume water and produce hydrogen gas. Mobile Fe(II) released as a result of the anaerobic process will interact with smectite in the bentonite and precipitate as Fe(III)-hydroxides if oxidised by residual oxygen. If all residual oxygen has been consumed, the Fe(II) ions released by corrosion will be incorporated into the surrounding bentonite and may interact with the interlayer cations (Leupin et al. 2021).

Microbial processes – The compacted saturated bentonite, with its high swelling pressure and nanoporous structure, provides a hostile environment for microbes. Thus, at high densities, all microbial activity comes to a halt (Smart et al. 2017a).

Long-term stability of montmorillonite – The thermodynamic stability of montmorillonite under repository conditions and, more generally, in low-temperature environments, is difficult to establish. Kinetic considerations as well as information from natural analogues, however, suggest that montmorillonite will persist under circumneutral pH conditions for long time periods. Moreover, transport arguments have also been put forward that support a very limited dissolution of the amount of montmorillonite in the buffer.

Planned RD&D in the next five to ten years

Gas transport – Different activities are contributing to a better understanding of the phenomenology related to the transport of gas:

- Nagra's participation in the EURAD GAS work package will allow it to develop arguments that gas transport through the HLW near-field (including the EDZ) does not impair the safety-relevant properties of bentonite. These efforts will also allow uncertainties in the conceptualisation of gas percolation in compacted bentonite to be reduced.
- A significant part of the demonstration of the functionality of the EGTS comes from the full-scale GAST experiment and the accompanying smaller-scale mini-GAST experiment (see insert in Section 8.5.2.2 for more details).

- To underpin the functionality of the EGTS for the period of concern, a significant effort is being put into understanding the evolution of the interfaces where chemical gradients could lead to the loss of gas-related porosity. A synthesis will be provided to support the general licence applications, which will include the work by Luraschi et al. (2020).

Homogenisation – The understanding of the homogenisation process and the prediction of homogenisation under repository conditions will be improved within the EBS Task Force and within the Euratom BEACON project. This will focus on hydromechanically coupled processes and their conceptualisation.

Iron – bentonite interaction – Significant progress has been made, resulting in a considerable reduction of uncertainties regarding the impact of corroding steel embedded in bentonite. In large-scale experiments such as FEBEX and ABM, no signs of smectite alteration due to steel corrosion were found. In laboratory-scale experiments, however, the formation of iron-rich silicate minerals could be observed. Contrary to the field experiments, most of these experiments were carried out with suspensions of ground bentonite (or claystone) and powdered iron, leading to large reactive surface areas and promoting fast kinetics. As Leupin et al. (2021) showed, the evolution of the interface is controlled by corrosion kinetics and evolving transport properties of the compacted bentonite, resulting in a strongly time-dependent evolution. In this regard, laboratory-scale experiments lead to an overestimation of the phenomena to be expected in the HLW near-field. The EURAD ACED work package is dedicated to reactive transport experiments and modelling thereof to better constrain the impact of diffusing Fe(II) from corrosion on the safety-relevant properties of bentonite.

Gas consumption by bacteria: the MA-A experiment at the Mont Terri Rock Laboratory (Burzan 2021)

The MA-A experiment was initiated to test the hypothesis that subsurface microbes, if well characterised, can be beneficial for the performance of the repository. The ultimate goal of this experiment is the development of the scientific basis to design a repository that takes into account the presence and activity of microbes. Anaerobic steel corrosion of waste and waste canisters will lead to a build-up of hydrogen gas. To avoid any potential losses of the integrity of the host rock, strategies to mitigate the risks arising from gas pressure build-up are under investigation. The operations tunnels will be backfilled upon closure of the repository and can provide favourable conditions for the microbially mediated removal of excess gas. Thus, microbial growth within a porous matrix in the backfill material could be envisioned as an additional safety aspect, via the net decrease in gas pressure within the repository.

In-situ research in the framework of the MA-A experiment in the Mont Terri Rock Laboratory has revealed the potential of hydrogen-oxidising bacterial colonies, carrying out both sulphate reduction and methanogenesis. Four bioreactors containing an 80/20 mixture of quartz and Wyoming bentonite were supplied with natural Opalinus Clay rock porewater, which is rich in sulphate, and with hydrogen gas, which was added daily.

After a short time period, sulphate-reducers were observed to be active in areas of the bioreactors where the sulphate-rich porewater and hydrogen gas mixed. Sulphide, which results from the reduction of sulphate, was found to precipitate with iron phases. Additionally, methane was detected in the gas phase, suggesting the activity of methanogenic archaea. While sulphate reduction leads to a net decrease in gas pressure, methane is a gas component, and its formation leads to a reduction of the gas pressure by a factor of ~ 5 due to its stoichiometry.

Thus, stimulating the growth of microbes in the right location can contribute to a reduction in gas pressure.

Transport calculations (Leupin et al. 2016c) suggest that sulphate diffusion is the limiting factor for the consumption of repository-generated gases. The MA-A experiment (Fig. 8-19), however, shows that, when sulphate becomes limiting, hydrogen gas is readily converted to methane. Methanogenesis was only observed in a sand/bentonite matrix. Similar experiments in an Opalinus Clay matrix (MA experiments) did not result in the formation of methane.

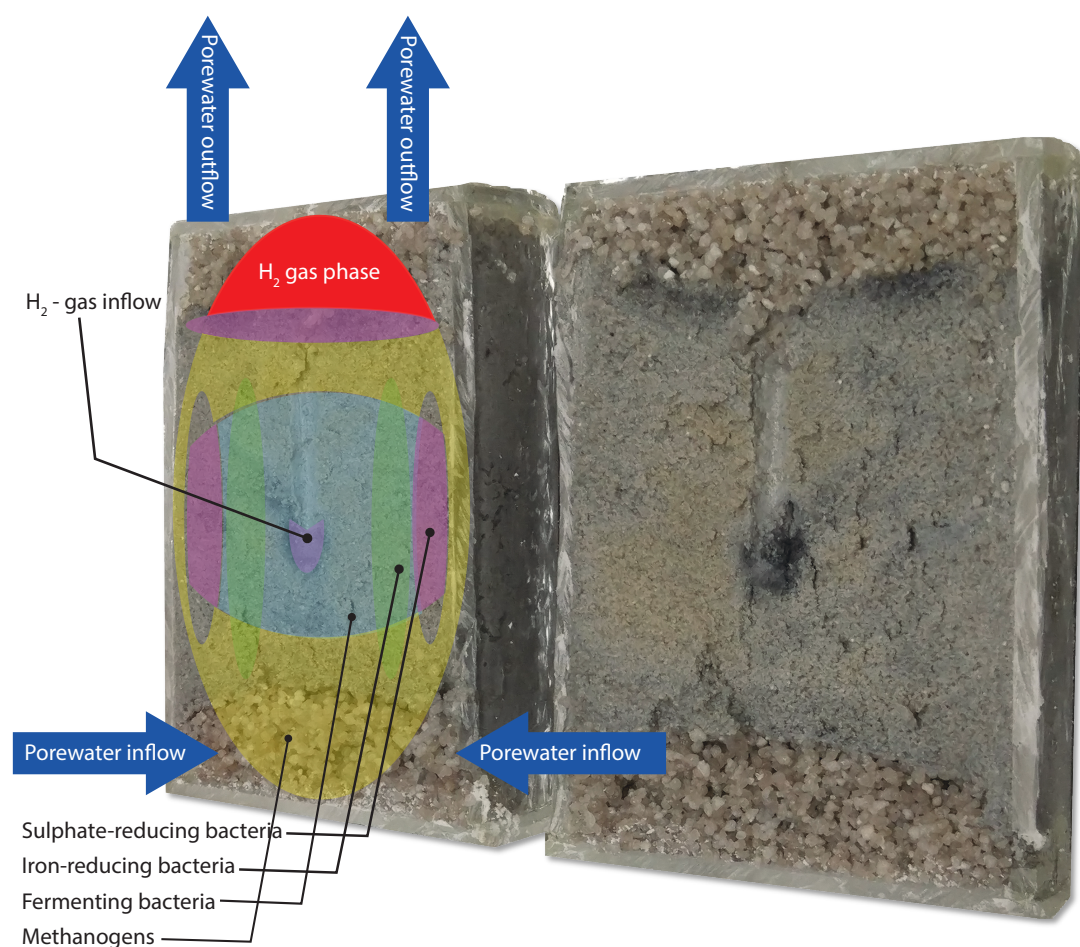


Fig. 8-19: MA-A bioreactor cut in half, showing the different bacterial colonies mapped on the 80/20 quartz (sand): bentonite mixture

Depending on the abundance and availability of nutrients, bacteria may not always settle where conditions are most favourable. An important finding was that sulphate-reducing bacteria occur adjacent to methanogens. This shows the relevance of microenvironments for the development of bacterial activity as described in Burzan (2021).

Microbial processes – Several initiatives have been launched to better understand the factors determining the bentonite material densities that can limit microbial activity. The expected outcome is that a great variety of available bentonite materials can be optimised to reduce the likelihood of microorganisms thriving in pure bentonite environments. The investigations regarding microbial gas consumption in the tunnel backfill (now based on sand/bentonite mixtures – see insert above) are planned to continue to further evaluate this optimisation opportunity.

The understanding of the bentonite performance has become very mature, especially as the bentonite barrier is a key aspect of safety cases supporting licensing documentation in Sweden and Finland. In the future, the state of the art will continue to be followed, largely through participation in international initiatives.

8.5.3.4 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 construction of the tunnels and consolidates after the emplacement of the tunnel support. The formation and evolution of the EDZ alters safety-relevant properties of the host rock adjacent to the emplacement rooms, sealing zones and other underground structures. It can result in an increased porosity and in the creation of new or the reactivation of old fractures, thus potentially 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.

The main objective is to obtain an enhanced understanding of the development of the EDZ around the emplacement rooms, sealing zones and shafts and its impact on the component-specific functions of the engineered barrier system under conditions close to those anticipated in the L/ILW and HLW repositories. This is particularly relevant since the EDZ around backfilled underground structures can be a potential release path for radionuclides as well as a possible pathway for corrosion- and degradation-generated 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 saturation. In this context, a performance target (referred to as safety function indicator criteria in Leupin et al. (2016a, 2016b)) has been developed that the axial flow rate of water in the EDZ around the SF and HLW emplacement drifts and along the EDZ around the backfilled and sealed access routes should remain below 10^{-8} m s^{-1} . Note that no such target is set for the EDZ around the L/ILW emplacement caverns due to the fact that the hydraulic conductivity of the interior of the emplacement caverns is already rather high ($\sim 10^{-6} \text{ m s}^{-1}$). There are also requirements concerning the potential impact of the EDZ on the barriers provided by the bentonite buffer and host rock (Leupin et al. 2016a, 2016b). These requirements and targets will be reassessed for the safety case and will be reported in Nagra NTB 24-10 (planned) and its supporting documents.

Current state of the art and progress since the 2016 RD&D Plan

A particular focus is 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 failure 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

An update of the synthesis by Lanyon et al. (2014a) on the state of the art in EDZ-related research at Mont Terri has been made. It now includes general statements about the implications of the site-specific rock properties for the extent of the EDZ. As part of this update, the data from existing in-situ experiments, with excavations oriented along the bedding and perpendicular to the bedding strike, were analysed and revised in terms of deformation behaviour and pore pressure evolution. The significance of the tectonic overprint (inventory of tectonic features) and sedimentary variability (facies inventory) has been further explored.

Lisjak et al. (2015a, 2015b) performed comprehensive numerical interpretations of the shape and extent of the EDZ in the FE and HG-A experiments in the Mont Terri Rock Laboratory. The hydromechanical evolution of the EDZ as a transport path for radionuclides and gas has been addressed in Marschall et al. (2017), including insights from the HG-A experiment (Alcolea et al.), and the development of a numerical workflow for determining the hydraulic efficiency of the EDZ around the seal section, which has been tested using experimental data from Mont Terri. A further extension of this approach has been implemented, dedicated to statistical inference of spatial variability of the EDZ along the tunnel axis (Alcolea et al. 2017, Alcolea & Marschall 2016). The new approaches for geostatistical representation of the EDZ as a heterogeneous structure around the backfilled underground structures of a deep geological repository were implemented in the recent performance assessment workflows for site selection (Alcolea 2018).

Planned RD&D in the next five to ten years

Nagra's understanding and concepts draw on experience gained at the Mont Terri Rock Laboratory where:

- Rock support takes the form of shotcrete (and anchors), steel sets (FE and Gallery 18) or is not used (HG-A, FE).
- EDZ investigations have been predominantly in the shaly facies (and some in the sandy facies in Gallery 08 (Ga08) in the Mont Terri Rock Laboratory).
- The stress field is unusual (possibly inclined and more anisotropic).

Conditions in the deep geological repository may be significantly different, especially with regard to the timing and nature of support during excavation, since the repository project now foresees a segmental lining support as described in Section 8.4.3. Experience gained underground in environments that are more relevant in this respect (such as the Meuse/Haute Marne URL (France), or Belchen tunnel (Switzerland)) will be included in the assessment basis. Future research activities will focus on the EDZ dynamics and evolving transport properties of the EDZ in the case of segmental lining support.

Logging data from the deep borehole campaign will also be used to link borehole stability (as an indicator of an EDZ) to such properties. Examples are the correlation of the clay mineral content and seismic velocity as 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 and will feed into engineering models for tunnel design.

The EDZ performance target is largely controlled by assumptions around self-sealing, but the corresponding target for EDZ extent is related to the prediction of mechanical processes. It is known that mechanical failure leading to EDZ formation is initiated ahead of the tunnel face at the Mont Terri Rock Laboratory. For the most part, the FEMDEM (finite element method – discrete element method) and related models capture this by core softening or similar algorithms. It would be advantageous to build confidence that such algorithms provide reliable descriptions of the extent of EDZ fracturing.

A major step forward will be the in-situ EDZ characterisation that will take place as part of the exploration programme during the construction of the facilities for the *EUU*. In anticipation of the construction licences, the knowledge base as a whole will be reassessed.

8.5.3.5 Chemical interactions at cement – clay interfaces and in the EDZ

Objectives

Chemical interactions are expected at the interfaces between the Opalinus Clay and/or bentonite and the cementitious components of the repositories. These reactions are of interest because they may directly affect the safety-relevant properties of the clay materials. The main objective of the work described below is thus to assess the chemical evolution of the Opalinus Clay and/or bentonite in contact with cementitious components and to understand its impact on the evolution of the safety-relevant properties of the clay materials.

Current state of the art and progress since the 2016 RD&D Plan

Several key reports on near-field evolution have been published since the earlier key reports on this topic by Bradbury et al. (2014) and Kosakowski et al. (2014b). These earlier reports summarised scientific evidence underlying the description of the chemical environment at the interface between Opalinus Clay and cement in an HLW repository and/or an L/ILW repository, respectively. Clay-cement interactions, waste-cement interactions, precipitation and dissolution of minerals and changes in pH and ionic strength were further elaborated in the later reports.

A milestone has been the assessment of repository-induced effects in Leupin et al. (2016a, 2016b) and in Jenni et al. (2019b), which contextualised the scientific findings and assessed their impact based on an indicator method, thus providing a clear focus for outstanding work.

Chemical interactions at the cement – clay interface might locally affect porosity and permeability. Over the last 12 (Yokoyama et al. 2021) years, experimental and modelling work (e.g. within the Cement – Clay Interaction (CI) experiment at the Mont Terri Rock Laboratory) has shown that interactions at cement – clay interfaces start almost immediately upon contact between these materials, but progress very slowly and are spatially limited (i.e. up to ~ 0.1 mm of reaction zone after five years (Jenni et al. 2014) and increasing to ~ 0.1 – 0.2 mm after 10 years with clay mineral dissolution below detection; Bernard et al. 2020). Cement paste/shotcrete-clay interaction experiments at the Meuse/Haute Marne URL and at Tournemire in France came to the same conclusions regarding the high clay stability and the precipitation of secondary (poorly crystallised)

minerals in concrete (Gaboreau et al. 2011, 2012). Cement-bentonite interaction, as studied within the scope of the CI experiment revealed the dissolution of cristobalite up to around 10 mm from the interface and the presence of an Mg phase and calcite precipitation in the bentonite up to 20 mm from the interface after five years of interaction. Due to diffusion-dominated transport, the reaction front progressed slowly in the following five years (Yokoyama et al. 2021).

Thermodynamic modelling (e.g. Berner et al. 2013, Bradbury et al. 2014, Cloet et al. 2019) and experimental data (e.g. Dolder 2015, Shafizadeh 2019, Shafizadeh et al. 2020, Luraschi et al. 2020) have shown that a pH change in porewater and ion exchange by diffusion result in a reduction in the porosity of the clay rock adjacent to the cement material. Luraschi et al. (2020) demonstrated that such skin zones of low porosity strongly affect the diffusive transport of tritiated water and $^{36}\text{Cl}^-$ across the interface. From these results, it can be assumed that such interfaces hinder the further progression of the alteration front into the clay. Further process understanding in the scope of the Euratom CEBAMA (CEment-BASed MATerials, Properties, Evolution, Barrier functions) project has significantly improved the understanding of cement-clay interaction and the modelling of the cement – clay interface.

Other phenomena affecting the chemical evolution of the Opalinus Clay around the engineered structures are related to microbial activity in the EDZ, where it has been suggested that microbes may consume hydrogen and reduce sulphate to sulphide. Regarding microbial activity, significant progress has been made as a result of several experiments at the Mont Terri Rock Laboratory (e.g. MA and MA-A (Microbial Activity): Leupin et al. 2017a, PC (Porewater Chemistry): Wersin et al. 2011, HT (Hydrogen Transfer): Vinsot et al. 2014) and an extensive research programme at EPFL, as well as the Euratom MIND (Microbiology in Nuclear Waste Disposal) project that helped to contextualise the research findings. In particular, several taxa of microorganisms that can be expected in the EDZ have been identified and their activity has been studied (Stroes-Gascoyne et al. 2013). Sulphate-reducing bacteria have been recognised as an important type of microorganism that can consume H_2 if enough sulphate is present (Daumas et al. 2014), thus providing a potential sink for repository-generated gas. The impact of microbial activity has also been investigated by Andra (France), SKB (Sweden) and ONDRAF/NIRAS (Belgium), for example in the BN (Bitumen Nitrate; Bleyen et al. 2017) experiment at the Mont Terri Rock Laboratory and in the microbial experiments at the Äspö URL in Sweden.

As Opalinus Clay porewater contains sulphate that can be reduced to sulphide by microorganisms (Leupin et al. 2017a), any adverse consequences must be assessed. The bentonite buffer around the canister, when emplaced at sufficiently high density, is characterised by its small pore size and 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 canister corrosion rates. However, as the fractures that comprise the EDZ have a tendency to close over time (Section 8.2.2.5), these reactions are thought to be limited both in space and in time (Cloet et al. 2017). Furthermore, compacted bentonite is an effective diffusive barrier that significantly limits the transport of sulphide potentially produced in the EDZ (Sellin & Leupin 2013). The potential impacts are considered in the assessment of canister corrosion rates in Section 8.5.3.1.

Planned RD&D in the next five to ten years

There are residual uncertainties regarding the relationship between porosity and permeability and between porosity and diffusivity during saturation. Another topic that requires some attention is the impact of cation exchange on the swelling capacity of clay as a result of cement-clay interaction. These topics will support the safety case and will be reported in Nagra NTB 24-11 (planned) and its supporting documents.

The impact of various types of cement on the Opalinus Clay and on bentonite has been studied in the Mont Terri Rock Laboratory within the scope of the CI experiment for over 12 years. Various boreholes are filled with different types of cement and bentonite and periodically sampled during borehole campaigns to investigate the interactions between these materials and the extent of the alteration zones between the different cements and the Opalinus Clay. The next sampling campaign is foreseen from 2027 to 2029. Within the CI experiment, a new experiment has been created called the CI-D experiment, where hyperalkaline Portland cement porewater is circulated through an Ordinary Portland Cement (OPC). The circulated fluid contains radioactive tracers (HTO and ^{36}Cl) that are periodically sampled. The aim is to understand the transport of these tracers across the cement – clay interface under relevant conditions. The experiment will be overcored post-mortem and the extracted drill core analysed. In the framework of the CI-D experiment, different modelling teams model the cement – clay interface and predict the evolution of the porosity and diffusion kinetics of the tracers across it. A parallel modelling study from the CI experiment will focus on models that look at the impact of the cement on clay and make predictions regarding the extent of ion exchange and its impact on the swelling capability of the bentonite.

Finally, an enhanced assessment of the porewater evolution in Opalinus Clay and in buffer and backfill materials, taking into account changing redox conditions resulting from waste interactions and the microbial alteration of hydrogen and methane, will be conducted. This will include coupled reactive transport modelling to assess the impacts of mineral dissolution and precipitation reactions and will contribute to improving the assessment of repository gas generation and of the saturation of the L/ILW emplacement caverns.

Following the major progress made in the last decade, it is expected that concepts and models will further converge in the future. Nagra will continue to follow advances in the state of the art, mainly through international initiatives.

8.5.4 Radionuclide transport in clay- and cement-based backfills

Objectives

In the past 25 years, extensive work has resulted in several databases of sorption and diffusion parameters and solubility limits being compiled by Nagra and other waste management organisations for clay- and cement-based backfills, providing a solid basis for dose calculations in the provisional safety analyses (Nagra 2014b). The objective is to address some of the remaining aspects and also to perform updates of the databases in *SGT* Stage 3 to ensure that they remain state of the art.

Current state of the art and progress since the 2016 RD&D Plan

Clay-based buffer and backfill

Diffusion and sorption are the dominant processes governing radionuclide transport and retention in clay systems (see Sections 6.2.3 and 8.2.2.1 for more details). In *SGT* Stage 2, the diffusion and sorption parameter values for safety-relevant radionuclides in bentonite, Opalinus Clay and the confining units were intensively studied (van Loon 2014, Baeyens et al. 2014a, 2014b). Solubility limits in compacted bentonite systems have also been documented by Berner (2014). In recent years, other waste management organisations have also published sorption databases for bentonite, including NWMO (Canada) (Vilks & Yang 2018) and JAEA (Japan) (Sugiura et al. 2018). Further RD&D work is currently being conducted to address residual uncertainties (Section 8.2.2.1).

The sorption database for compacted bentonite systems for *SGT* Stage 3 will be based on the same approach as the database for clay rocks (Section 8.2.2.1). Work conducted by PSI on the sorption of Cs^+ , Ni^{2+} , Eu^{3+} and Th^{4+} on montmorillonite, MX-80 bentonite and altered buffer materials is reported in Fernandes et al. (2017). Regarding diffusion processes in compacted bentonite systems, the same approach for deriving diffusion databases for the containment-providing rock zone (Section 8.2.2.1) will be applied to derive bentonite diffusion data for the safety assessment in *SGT* Stage 3. Glaus et al. (2017) provided a summary of the experimental results obtained from various diffusion experiments with positively and negatively charged radiotracers in compacted Na-montmorillonite and in a natural bentonite, with the results of these experiments being applied in the compilation of the diffusion database for bentonite in *SGT* Stage 3.

Cementitious materials

Diffusion and sorption are also expected to be the dominant processes governing radionuclide transport and retention in cementitious materials. Nagra's most up-to-date databases of sorption parameters and diffusion coefficients in a cementitious environment were published in 2014 (Wieland 2014). Other waste management organisations have also compiled databases for sorption and diffusion in cementitious environments using similar approaches over the last several years (SKB 2014, Posiva Oy 2013a, 2013b, Sugiura et al. 2018, Ochs et al. 2016). AFm and AFt phases mainly control anion uptake in hardened cement pastes, while the retention of metal cations (actinides and lanthanides) is predominantly controlled by C-S-H phases (Wieland 2014, Tits & Wieland 2018). The cement sorption and diffusion databases will be updated for *SGT* Stage 3, using the same approach as in *SGT* Stage 2, but including new information on sorption competition due to stable elements and recent RD&D findings on remaining uncertainties.

Work within the Euratom CEBAMA project (2015 – 2019), including contributions by PSI, helped to resolve some remaining uncertainties regarding radionuclide sorption in cementitious near-fields. The interaction of a range of safety-relevant elements (Be, C, Cl, Se, Tc, Mo, I and Ra) with different cementitious solid phases were studied within the CEBAMA project (Duro et al. 2020, Grambow et al. 2020, Grangeon et al. 2020, Nedyalkova et al. 2020, 2019, Rojo et al. 2018). Furthermore, experimental and modelling work is currently being conducted at PSI and will continue until 2022, studying the uptake of Al, Si and Ca on the most important cement phases. Over the last ten years, research on the interaction between cement and corrosion products

(Fe³⁺), as well as Fe³⁺ incorporation, has been carried out at PSI and at the Swiss Federal Laboratories for Materials Science and Technology (EMPA) (Dilnesa et al. 2011, 2012, 2014, Mancini et al. 2020). It appears that Fe³⁺ can substitute for Al in Si-hydrogarnet and might be incorporated into monocarbonate phases. Mancini et al. (2020) further showed that Fe³⁺ can also be taken up by C-S-H under high-pH conditions. Recent studies on the transport of HTO and ³⁶Cl across clay-cement interfaces in the CI-D experiment at the Mont Terri Rock Laboratory (Shafizadeh 2019, Shafizadeh et al. 2020, Luraschi et al. 2020) have provided a robust experimental dataset on the influence of clay-cement interactions on the diffusive transport of ions and neutral species.

Planned RD&D in the next five to ten years

Clay-based buffer and backfill

The continuing work and knowledge gained on residual uncertainties in sorption and diffusion processes in compacted bentonite systems described above will be included in the sorption and diffusion databases for the bentonite buffer in support of the safety assessment for *SGT* Stage 3 over the next years. The PSI/Nagra thermodynamic database is currently being updated to ensure it is state of the art for all radionuclides to be considered in the safety assessment in *SGT* Stage 3 and will be published soon. The solubility limit database for compacted bentonite systems from *SGT* Stage 2 (Berner 2014) will be updated by 2023.

Beyond the activities in EURAD and the RD&D work described in Section 8.2.2.1 regarding diffusion and sorption in clay systems, Nagra and PSI will continue studying and participating in international research on this topic, although no additional laboratory programmes beyond the submission of the general licence applications are currently planned.

Cementitious materials

Similarly to bentonite systems, the sorption and diffusion databases for cementitious materials will be updated for the safety assessment in *SGT* Stage 3 over the next years, incorporating the most recent evidence and knowledge.

As part of the EURAD ACED work package (2019 – 2023), PSI will study the incorporation of iron in C-S-H, AFt and AFm phases to expand recently developed solid solution models for these phases and provide a chemical-thermodynamic basis for improved reactive transport modelling in iron-containing cementitious systems. Within EURAD CORI (2019 – 2023), EMPA will investigate the sorption of low-molecular-weight organics on the main phases present in hydrated cements: C-S-H, AFm and ettringite.

As described in Section 8.3.3.4, the CIM experiment currently running at the GTS studies the transport and retardation processes of ¹⁴C and ¹²⁹I through aged cementitious backfill and will thereby support the development of a method to upscale laboratory results to the field scale.

The databases will be published in Nagra NTB 24-03 (planned) and Nagra NTB 24-11 (planned) and their supporting documents.

After the submission of the general licence applications, Nagra will follow up the state of the art mainly through international initiatives, while a full update of all databases is foreseen in anticipation of the submission of the construction licence applications.

Summary of Section 8.5 – Evolution of safety-relevant properties and processes in the near-field

The RD&D needs in this domain are driven by the component-specific functions that have to be fulfilled with respect to the post-closure safety assessment. This requires a detailed understanding of repository evolution, both for HLW and L/ILW, which is challenging as the processes are highly coupled and the environments are complex.

HLW near-field:

- Understanding of the thermo-hydro-mechanical (THM) evolution has deepened through continuation of a series of large-scale URL experiments and benchmarking of their respective models. A repository-scale THM assessment workflow has been developed to support site selection and repository optimisation.
- Progress in the estimation of corrosion rates under repository-relevant conditions means that reference corrosion rates can now be estimated realistically, resulting in lower gas generation rates in the early stage of the HLW repository evolution.
- The widespread application of bentonite in the designs of advanced international waste management programmes means that understanding of the evolution of the bentonite barrier has reached a high level of maturity, allowing the remaining issues specific to the Swiss concept to be tackled. Higher temperature performance of bentonite is being investigated in the context of the thermal optimisation of the HLW repository.
- The characterisation of the EDZ based on investigations in the Mont Terri Rock Laboratory has now been summarised and integrated, while upscaling methods for performance assessment of the EDZ have been developed. The role of the EDZ as a preferential flow path for radionuclides was shown to be minimal in a dead-end HLW emplacement drift concept.

L/ILW near-field:

- The thermo-hydro-mechanical workflow mentioned above also extends to the L/ILW near-field to assess the impact of gas generation and the interactions between the HLW and L/ILW sections of a combined repository. The performance confirmation of gas-permeable seals was further developed and will be finalised in anticipation of the general licence applications.
- The cementitious near-field of the L/ILW repository is characterised by strongly coupled hydro-chemical processes. From a post-closure safety point of view, ensuring a high-pH environment and favourable gas-related properties is key. A broad spectrum of experiments, from the molecular to the URL scale, along with their respective modelling, generally leads to converging outcomes in terms of safety-relevant impacts. While certain interactions can now be shown to be self-limiting (e.g. cement-clay interactions), some significant uncertainties remain for other issues, which will be difficult to reduce (e.g. related to the heterogeneity of the waste). These will be integrated into the safety analysis by defining bounding assumptions.
- Microbial investigations suggest that in the selected backfill materials (and possibly the EDZ) are likely to host microbial activity which, if it can be shown to have beneficial impacts with respect to gas mitigation, can potentially be optimised.

Knowledge of radionuclide transport in clay- and cement-based backfills has reached a high level of maturity and the synthesis will be integrated into the sorption and diffusion databases for the safety case for the general licence applications.

8.6 Safety assessment

As described in Chapter 5, 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 (2020). The results of the next formal safety assessment, along with additional evidence and arguments, will be synthesised in a safety case and published in Nagra NTB 24-10 (planned) and its supporting documents.

According to ENSI (2020), a safety case, and thus a comprehensive safety assessment, is a requirement for all major steps in a disposal programme. 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 8.8.1). Thus, specific activities are continuously needed to keep pace with international good practice regarding the structure, content and presentation of the safety assessment and representing the state-of-the-art scientific understanding (see also the Tier 2 roadmap on safety optimisation in Section 3.2).

Safety assessment also involves demonstrating that the impacts of internal and external processes detrimental to the safety functions (Section 5.2) 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 hydromechanical state of the rock, see Sections 8.2.2.2 to 8.2.2.5, and of the near-field, Section 8.5.2). External processes include geological and climatic phenomena (Section 8.2.1.5).

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 8.6.1 and those concerning operational safety assessment are described in Section 8.6.2.

8.6.1 Post-closure safety assessment

Objectives

The main objective is to further develop the methodology and assessment tools so that post-closure safety assessments that support the site selection and the general licence applications meet the requirements set out by ENSI (2020). Particular focus lies on a consistent methodology across all aspects of safety assessment, including coherent treatment of uncertainty and risk.

Current state of the art and progress since the 2016 RD&D Plan

Post-closure safety assessment is a key element of a repository safety case (OECD/NEA 2013). The sourcebook of international activities related to the development of post-closure safety cases for deep geological repositories (OECD/NEA 2017) documents recent international activities in developing safety cases and thus in particular regarding post-closure safety assessment.

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. Among the most recent ones are the safety options report in France (Andra 2015), the generic safety cases for a repository in sedimentary rock in Canada (NWMO 2018), and the post-closure safety assessment for a proposed repository concept for spent nuclear fuel in Sweden (SKB 2019a). It should, however, be noted that the assessments have been made in the context of a specific programme milestone. Thus, the level of technical detail differs among the assessments.

Based on the Nagra 2016 RD&D Plan (Nagra 2016b) and the references therein, it is apparent that safety assessment methodology is well established and that only few open issues remain with respect to safety case development and key components of the safety case. Nevertheless, over the last few years, international achievements comprise:

- Update of the International FEP (IFEP) List (OECD/NEA 2019a), a comprehensive and structured generic list of factors relevant to the assessment of the long-term safety of deep geological repositories, developed by the OECD/NEA Integration Group for the Safety Case (IGSC).
- Linked to the above update, the NEA launched a new web-based platform for its FEP database. This new database has been designed to allow a full version control of all lists and is intended to provide a home for all releases of the NEA IFEP List in the future. Moreover, it has been designed to allow waste management organisations to upload and manage their own project-specific FEP lists. Nagra contributed its FEP list from its demonstration of disposal feasibility, the so-called *Projekt Entsorgungsnachweis* (Nagra 2002a), during the platform development.
- The IAEA HIDRA (Human Intrusion in the Context of Disposal of Radioactive Waste) project considered how to counter potential future human actions that could disturb areas occupied by radioactive waste disposal facilities. The second phase, conducted from 2016 to 2018, focused on the practical implementation of the HIDRA approach and documentation of country-specific examples. It provided a forum for regulatory authorities, operators and other interested parties to share information about approaches to considering human intrusion.
- Systematic approaches regarding the interplay of technical feasibility, engineering design issues, operational and post-closure safety, and non-technical challenges such as safety case communication (OECD/NEA 2018).
- Launch of the Uncertainty Management Network (UMAN) work package within EURAD which addresses the management of uncertainty relevant for safety.

Nagra participates in these international efforts and projects, e.g. as active member of the OECD/NEA Integration Group for the Safety Case (IGSC), through contributions to the EURAD UMAN network, or by actively following the HIDRA project.

Up to the general licence applications, Nagra is undertaking safety assessments that will underpin its proposals for site selection and the safety assessments that feed into the safety cases for the repositories at the proposed site(s) (to be published in Nagra NTB 24-03 planned and Nagra NTB 24-10 planned). For the former, more detailed requirements on the methodology have now been set by the regulatory body (ENSI 2018c). While the methodology is – both in quantitative and qualitative terms – similar to that applied in *SGT* Stage 2, the focus is on consistency between assessments supporting site selection and assessments for the post-closure safety case. The separation of RD&D topics for the two types of assessment as stipulated in the 2016 RD&D Plan is thus not continued.

As outlined in the 2016 RD&D Plan, and in line with international developments and newly available ENSI guidelines and precisions, Nagra has placed an emphasis on:

- Consolidating the overall safety strategy and safety assessment methodology. The reporting structure for the safety assessments (main reports and pertinent reference reports; see also Chapter 5) has been defined and closely follows the methodology adopted.
- Developing 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, for use within Nagra and its supply chain (Smith et al. 2019).
- Updating the FEP management methodology and building a comprehensive FEP catalogue for Nagra's generic repository systems. A completeness check using the OECD/NEA's updated international FEP database and FEP lists of other disposal programmes has been performed.
- Advancing the procedures for identifying scenarios and defining corresponding assessment cases in accordance with international good practice (e.g. the synopsis of the Integration Group for the Safety Case (IGSC) scenario development workshop (OECD/NEA 2016)).
- Reviewing the modelling strategy and computer codes in an international context and consolidating the strategy to be applied for the general licence applications. It is foreseen that the strategy and codes will remain almost identical to those applied during the site selection process so far, the only relevant adaptation being the application of the multi-phase flow code TOUGH3 for analyses related to volatile radionuclides.
- Adapting and extending the models and methods to evaluate the impact of geological processes that may lead to exposure of the repository to changes in the surface environment and thus to estimate the radiological consequences of hypothetical deep glacial erosion of the repository.

Planned RD&D in the next five to ten years

Several safety assessment-related RD&D activities are currently underway or planned:

- The handbook on uncertainty management (Smith et al. 2019) will be updated based on hands-on experience during the application of the methodology and considering input from international collaboration, e.g. through the EURAD UMAN network. Emphasis will also be placed on methods for quantifying risk, a requirement associated with Protection Objective 2 in ENSI (2020).
- The FEP management methodology will be refined based on the results of the completeness check and with special emphasis on the potential interaction of FEPs. Upon completion of site selection, the methodology will be applied to derive a comprehensive site-specific FEP catalogue from the generic FEP list.
- The methods for assessing the consequences of future human actions will be further consolidated, in particular considering the results of the IAEA HIDRA project (see state of the art above).

- The methods and tools used for biosphere modelling will be developed further, including recent advances in, e.g. the BIOPROTA project (International Forum for Biosphere Modelling). 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.
- The methods for assessing the effects of operational safety aspects and incidents (e.g. fire-protection measures, accidents, safeguards, radiation protection measures, etc.) on post-closure safety will be refined.
- In the context of repository-induced effects due to construction, operation, and closure and processes occurring after closure, the link and interplay between performance assessment and safety assessment will be further established. This will help to determine the safety relevance of specific thermo-hydro-mechanical-chemical (THMC) processes and to develop safety arguments or feedback to site selection and repository design. The latter will also gain importance in the context of optimising the repository design in the project phases after the general licence applications.
- Scoping calculations are being developed to conceptualise the impact of the long-term geological evolution on the dose calculations.
- The possibility of using complementary safety indicators in addition to dose and risk (e.g. comparison with natural radionuclide concentrations and fluxes) will be re-examined.

The above-listed RD&D activities, along with new knowledge arising from site investigation and RD&D activities in other areas, will lead to further refinement of the existing safety strategy and methodology (including conceptual models and assessment codes) and the concurrent development of the input datasets. It is, however, not expected that significant modifications will be needed to meet the requirements on post-closure safety assessment in the period up to the general licence applications.

After submission of the general licence applications, Nagra will have to regularly update the safety case for the following milestones in its disposal programme, e.g. the construction and operating licence applications. Related RD&D topics and activities are expected to emerge. Further RD&D activities may also be initiated following the regulatory review of the safety assessments carried out in *SGT* Stage 3.

International collaboration will continue to maintain a state-of-the-art capability in assessment strategy and methodology. These aspects are discussed and further developed, e.g. in the OECD/NEA Integration Group for the Safety Case (IGSC), EURAD joint programming or within the framework of IGD-TP.

8.6.2 Operational safety assessment

Objectives

Operational safety reports are required for the general licence applications (Art. 11 NEO, ENSI 2020, ENSI 2018c) containing:

- a quantitative, site-specific hazard analysis to determine the frequency and load cases for potential external events/hazards
- a comprehensive and suitable accident assessment with the focus on potential nuclear and radiological impacts and consequences for the emplacement phase (including a discussion of potential consequences for post-closure safety)
- a (qualitative) 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

To meet these requirements, the know-how for operational safety assessment has to be developed, including:

- formulation of relevant accident scenarios (including probability and load cases)
- preparation of the required information and data for the corresponding dose calculations, including the development of a concept for the classification and characterisation of L/ILW and HLW
- definition of safety concepts and associated requirements for the minimisation/exclusion of malfunctions and accidents, to ensure (i) personnel safety and protection of life and health as well as (ii) environmental protection. The concepts to be considered include the nuclear safety and radiation protection concept (including the allocation of controlled zones), the fire protection concept, the ventilation concept and the escape and rescue concept (all closely connected with repository design and technology development, see Section 8.4)

The accident assessment, dose calculations and the definition of safety concepts 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 safe operating procedures. For this reason, operational safety is closely connected with RD&D related to repository design and technology development for the repository and the engineered barriers (Section 8.4).

Operational safety assessment does not require extensive RD&D efforts from Nagra since advantage can be taken of 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). Planned activities have the broad objective of further developing the operational safety assessment methodology and the associated assessment tools so that they lead to comprehensive safety assessments that meet the requirements for the general licence applications set out in ENSI (2020) and other regulatory guidelines (e.g. ENSI 2018c).

Current state of the art and progress since the 2016 RD&D Plan

A systematic operational safety assessment for an L/ILW as well as an HLW repository was performed based on a generic repository design (including relevant design variants). The assessment includes internal and external events and takes international recommendations and databases into account (e.g. the EGOS (Expert Group on Operational Safety) hazard database). The evolution of conditions following the occurrence of an incident/accident was systematically investigated, including different potential damage states of the system components. The objective was the characterisation and optimisation of measures and safety systems, based on the internationally recognised defence-in-depth concept, the derivation and definition of requirements for the repository design and layout, waste package design and operational procedures with a view to the minimisation or exclusion of malfunctions and accidents. The development of a radiation protection concept was completed (including the allocation of controlled zones). Another important outcome was the identification, quantitative description and discussion of potential design-basis accidents and beyond-design-basis accidents.

As part of the radiological assessments, dose calculations were performed for normal operation as well as for design-basis accidents identified in the safety assessment. The required information and data for these dose calculations (e.g. nuclide- and accident-specific release fractions for L/ILW and HLW and waste package retention factors as well as spreading and exposure functions) were reviewed and, if necessary, adapted to the current state of the art. Furthermore, these updated data were used in the completely revised SISAN-III (Simplified Safety Analysis) tool, which was developed and implemented with the purpose of waste characterisation and acceptance, i.e. to ensure that waste produced today must be treated such that the resulting waste packages can be disposed of in one of the planned repositories.

The findings of all the assessments will be included in the general licence applications' documentation and indicate that a deep geological repository can be operated safely in line with the protection objectives specified by law (ENSI 2020, NEA 2003, NEO 2004, UVEK 2009, RPA 1991, RPO 2017). Furthermore, the requirement for safe operation of such a repository was found to have no bearing on site selection (except in the event of flooding, which is ruled out by appropriate selection of the site(s) for the surface facilities and shafts).

Planned RD&D in the next five to ten years

The main areas of RD&D are strongly connected with the RD&D topics of repository design and technology development (Section 8.4) and will be focused on the optimisation and further development of measures and safety concepts to ensure nuclear safety and radiological protection as well as the conventional safety (protection of life and health). Therefore, international collaborations (e.g. EGOS, the Expert Group on Operational Safety) 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, especially other waste programmes).

8.7 Development of the concept for repository monitoring

Objectives

Monitoring is an important part of the deep geological disposal concepts for radioactive waste. A key feature of the Swiss concept is the monitoring of a pilot repository containing a representative amount of waste, as defined by the Swiss Expert Group on Disposal Concepts for Radioactive Waste (EKRA) (EKRA 2000, ENSI 2020). However, post-closure safety does not depend on monitoring or the ability to monitor, and is provided by passive means with a multibarrier system (Art. 11 NEO, ENSI 2020).

In the current stage of Nagra's programme, monitoring is focused on geological monitoring in the wider area and in the siting regions and to concept development for later stages. However, monitoring features prominently in the development and implementation of a repository because it can provide repository implementers, expert reviewers and lay stakeholders with in-situ data over the different phases of the repository project. The observed data may be used to provide input to the staged repository implementation and closure processes, to confirm the predicted repository evolution at a very early stage and to contribute to operational safety. Comparison of the monitoring results with prior performance assessments and process models contributes to increased stakeholder confidence regarding the disposal system.

The development of the concept for repository monitoring is a stepwise procedure, beginning with the development of a monitoring plan at the conceptual level. The concept will be refined during each step of the repository planning and realisation process. The first monitoring concept has to be developed for the general licence applications. ENSI (2020) requires an overarching monitoring concept covering the construction phase, operational phase and monitoring period. The overarching concept will integrate the different monitoring programmes and show how they are connected.

Therefore, the objective for the next RD&D phase is to finalise the first monitoring concepts for the selected site(s) for the general licence applications (Nagra NTB 24-07 planned) and to make progress on planning the monitoring for underground geological investigations in anticipation of the next licensing step.

Current state of the art and progress since the 2016 RD&D Plan

Studies conducted since 2016 have focused on concepts for underground and surface-based monitoring, strategic aspects of monitoring parameter selection 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 the Development and Demonstration of Monitoring Strategies and Technologies project (Modern2020) as part of Euratom. The project focused on further developments in the implementation of repository monitoring during the operational and monitoring phases to support the post-closure safety case, including finding ways of effectively engaging with stakeholders throughout this process (Galson Sciences Ltd 2019). The project results provide strategies for selecting and maintaining a list of monitoring parameters and for responding to monitoring results that are applicable to different repository concepts and national contexts. The focus was on the monitoring of the engineered barriers and near-field rock. Nagra contributed an approach to identifying parameters for the Swiss case that would be useful from the point of view of demonstrating both long-term safety and technical feasibility. Within the

Modern2020 project, research and development on monitoring technologies (e.g. wireless data transmission, power supply sources, non-intrusive monitoring techniques, fibre-optic sensing) were performed with the aim of making them suitable for repository monitoring (Sakaki et al. 2019). In addition, a common methodology for establishing the components of the monitoring system was established, and in-situ demonstrations of the implementation of monitoring technologies in large-scale experiments were conducted (Andra 2019).

Besides international research, Nagra developed its first site-independent concepts and plans for repository monitoring. The development of these concepts and plans is a stepwise procedure. For surface-based monitoring of the environment and the geological surroundings of the repository, including baseline measurements, the first site-independent concept shows which processes and parameters are important, where, in a generic manner, they will be monitored, what monitoring techniques will be used, when measurements start and how long they are planned to last (Fanger et al. 2021). Furthermore, the first plans for data management, as well as data and sample archiving, are presented. In addition, a first generic concept for the underground geological investigations (*EUU*) was formulated that describes the plans during construction activities and shows what experiments and investigations are envisaged in the facilities for underground geological investigations for the construction licence and for the operating licence applications. Moreover, a reference report was prepared summarising the basic and site-independent considerations on a conceptual level regarding the overarching monitoring concept (Nagra 2021d). It describes the current plans for the different monitoring programmes and how they are integrated and connected and provides an overview of the regulatory requirements.

Use of monitoring techniques and sensors in generic URLs

Monitoring the response of the host rock during construction and during the evolution of the engineered barrier system and near-field rock during the operation and monitoring period requires reliable techniques. Therefore, state-of-the-art monitoring techniques and prototype sensors have been used in several in-situ experiments in URLs to further develop, evaluate and test 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 development of the monitoring concept of the pilot repository. Different monitoring technologies were implemented to compare and evaluate their performance under repository-like conditions (Müller et al. 2017). After seven years of heating (Fig. 8-20), valuable experience was obtained on:

- sensor calibration
- performance and reliability of sensors, especially fibre-optic distributed temperature and strain sensing (Vogt et al. 2019)
- improvements in and evaluation of differences and synergies of various non-intrusive geophysical monitoring techniques (Maurer et al. 2019)
- management of data from several hundred point-sensors and about 2.5 kilometres of fibre-optic sensing cables resulting in more than one million measurements per day (Yeatman et al. 2019)

Monitoring of the time-dependent and spatially distributed deformations in different tunnelling supports in the Mont Terri Rock Laboratory was carried out successfully in the Testing Different Tunnelling Support in Sandy Facies during Excavation of Gallery 2018/19 experiment (TS) by means of various fibre-optic strain-sensing systems. The TS experiment generated beneficial experience for fibre-optic sensor installation in shotcrete and on steel arches, as well as for selec-

tion of fibre-optic strain sensors and measurement techniques. In bentonite and sand-bentonite mixtures with high water saturation, valuable experience regarding monitoring technologies after eight years of monitoring was gained in the framework of the GAST experiment at the GTS (Section 8.5.2.2).

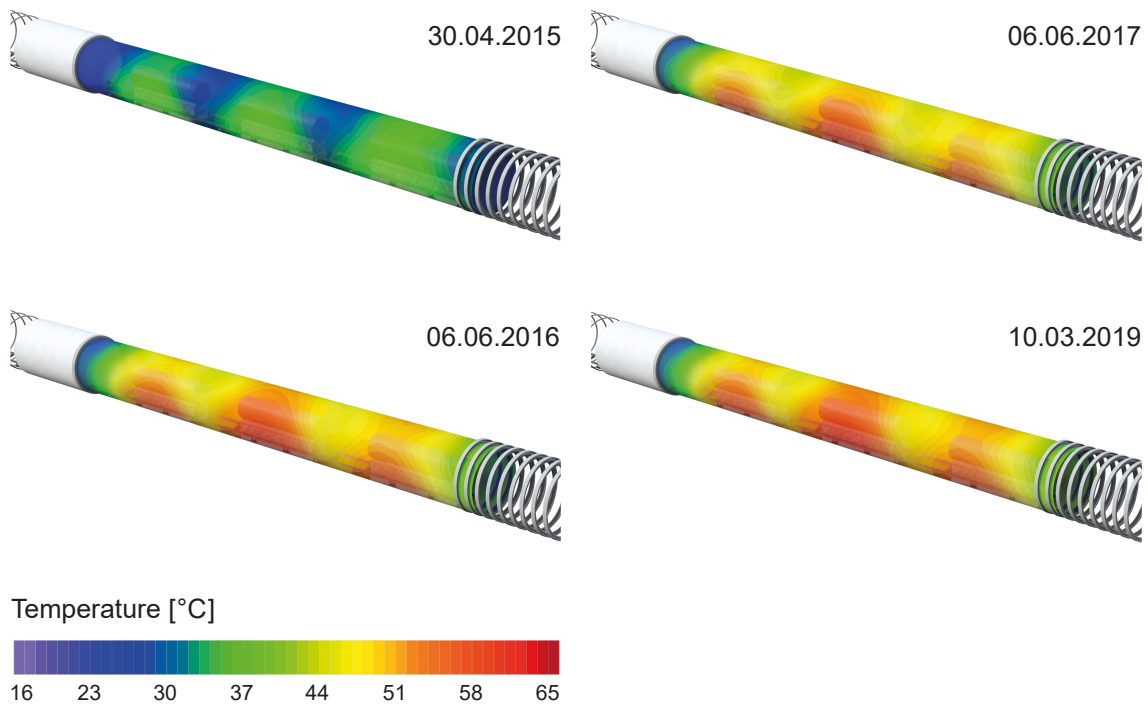


Fig. 8-20: Evolution of the temperature distribution along the tunnel wall of the FE experiment measured by means of distributed temperature sensing

Monitoring projects implemented in the siting regions

Since 2016, the two surface monitoring projects, i.e. the permanent broadband seismic monitoring network and the permanent GNSS network, were successfully continued to monitor geodynamic movements (Garrard et al. 2018). In 2021, a borehole seismometer will be installed at the depth of the Opalinus Clay in the deep borehole at Bülach to complement the permanent seismic monitoring network. Moreover, in all three siting regions, new long-term monitoring systems for observations of hydraulic heads in the Opalinus Clay and in its surrounding formations and aquifers will be installed. In addition, long-term monitoring continued in the Benken deep borehole (Jaeggi & Vogt 2020).

Planned RD&D within the next five to ten years

For the general licence applications, the generic concepts will be further developed to finalise the first monitoring concepts for the selected site(s) (Nagra NTB 24-07 planned) and supporting documents. While Nagra has to develop a monitoring plan for the pilot repository at the conceptual level at an early stage, decades will pass until the monitoring of the pilot repository starts, and significant technological development of monitoring techniques is expected, especially for fibre-optic sensing, wireless data transmission and non-intrusive monitoring techniques.

International research

Participation in international research projects, as well as bi- or multilateral projects, and close cooperation with other waste management organisations, especially those that are more advanced, will continue. In 2021, the Monitoring Equipment and Data Treatment for Safe Repository Operation and Staged Closure (MODATS) work package was launched as part of EURAD. The MODATS work package aims at addressing detailed questions regarding monitoring data that were identified, but not resolved, in previous Euratom projects (Galson Sciences Ltd 2019). Therefore, the MODATS work package will develop generic guidance and quality-assurance plans for monitoring data acquisition, data validation and data management. Full-scale experiments in URLs, e.g. Nagra's FE experiment, will serve as detailed examples for elaborating parameter requirements, quality-assurance plans, data management approaches and gap analysis, and for identifying good practice. In addition, the MODATS work package will conduct research on the improvement and further development of innovative monitoring techniques, including their demonstration in full-scale experiments. Within the MODATS work package, Nagra will further develop fibre-optic monitoring techniques, and will work on data validation and data management aspects and joint inversion of geophysical data.

Generic URLs

Current long-term experiments in which monitoring plays an important role are running at the Mont Terri Rock Laboratory (the FE and HE-E experiments) and at the GTS (GAST). They will provide valuable knowledge about the long-term performance (> 10 years) of the implemented, state-of-the-art monitoring techniques. At the GTS, the newly implemented HotBENT experiment will provide unprecedented experience on monitoring techniques under very high temperature conditions.

Baseline monitoring

The start of baseline monitoring is planned for the late 2020s once the technical assessment of the general licence applications by the authorities is complete. Measurements will be intensified before shaft construction begins. Therefore, the concept for baseline measurements of the surface-based monitoring of the environment and the geological surroundings will be refined and concretised for the general licence applications. The RD&D with respect to environmental and baseline monitoring will include exchange with partner organisations. In addition, monitoring targets and planned equipment will be periodically updated in the light of new technical developments.

Underground monitoring concept for the facilities for underground geological investigations

Up to the submission of the general licence applications, the focus will be on technology screening for underground monitoring, on exchange with partner organisations and on coordination with ENSI regarding the concept for underground geological investigations. After submission of the general licence applications, the concept for the on-site underground geological investigations will be refined. Together with Nagra's engineers, the site-specific facilities for underground geological investigations will be optimised regarding the space and arrangement for the required experiments, underground exploration activities and monitoring features. In addition, the planning of the underground geological investigations will be elaborated in detail as a basis for the EEU licence application documents.

As monitoring has been identified as a programme aspect with a significant RD&D component, it has been developed in a Tier 3 roadmap in Section 7.2, where the main activities and how these are connected are highlighted up to the operation of the repositories.

8.8 Other topics

8.8.1 Socio-economic and environmental impact of a repository

In the context of the Sectoral Plan, 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 for sites that offer equivalent levels of operational and post-closure safety. The optimum arrangement of the surface facilities and the accesses to the repository are relevant for the economic development of a siting region. The analysis of the spatial planning situation and socio-economic impacts thus provides an additional basis for decision-making.

In *SGT* Stage 2, socio-economic and environmental studies were prepared in collaboration with the population of the siting regions defined in Stage 1, and the social, demographic, environmental and economic impacts of a repository were evaluated (for the results, see BFE 2014). In *SGT* Stage 3, the impact of a repository on society, the economy and the environment will be examined in greater detail by the SFOE and the siting regions. The aim is to improve the data and information required for decision-making by monitoring the socio-economic and environmental impacts. The siting regions will propose strategies, measures and projects for sustainable regional development and compile the background information necessary for determining compensation measures.

An Environmental Impact Assessment will be carried out in support of the general licence applications (Nagra NTB 24-05 planned). It will include a report on compliance with spatial planning (Nagra NTB 24-06 planned). The application documents will be thoroughly reviewed by the federal authorities with respect to security, spatial planning and environmental criteria, and the siting cantons and regions will also be able to comment on the applications.

8.8.2 Preservation and transfer of information across generations

Preserving information on the deep geological repository over long timescales is required not only for safety reasons by, e.g., reducing the likelihood of human intrusion, but also to facilitate retrieval of the waste should this be required and, more generally, to 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, Swiss legislation includes provisions on the preservation of the relevant documentation in archives (Art. 40 NEA, Art. 71 NEO), as well as on the marking of the disposal site (Art. 69 NEO). Compiling documentation on the repository is an activity that spans the entire lifetime of the facility and must be initiated early in the process. Nagra keeps an extensive archive of scientific and technical documentation covering nearly fifty years of research, as well as other documents relevant to decision-making.

The marking of a deep geological repository, on the other hand, may be strongly influenced by local factors and can not in acronymonly be addressed in detail after a site has been selected. According to the ENSI-G03 Guideline (ENSI 2020), the corresponding concept is therefore expected as part of the construction licence applications.

Like Switzerland, other national programmes are actively seeking to improve their understanding of the preservation of information across generations. Between 2011 and 2018, the "Preservation of Records, Knowledge and Memory across Generations" (RK&M) initiative of the Nuclear Energy Agency of the OECD acted 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 has made a significant contribution to the compilation of the project results.

Important findings presented in the final report of the RK&M project (OECD/NEA 2019b) 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 and geographical scope. This system should offer a variety of transmission mechanisms that are either integrated with, or complementary to, one another. Archiving policies and marking strategies have been found to be important components of such a system, but other mechanisms have to be developed and implemented in order to maximise information accessibility, understandability and survivability over the timescales considered.

In the framework of the follow-up initiative "Information, Data & Knowledge Management" (IDKM), Nagra will continue, together with many other organisations, to work on guiding principles and practical solutions for implementing information preservation in the long term. The roadmap of the new project, including specific activities, is currently in preparation. In the meantime, the conclusions of the RK&M project will continue to be presented and discussed in Switzerland.

8.8.3 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 to reduce the volume and radioactive decay time of materials that are to be disposed of in the repositories, and include:

- partitioning technologies (e.g. aqueous reprocessing and pyroprocessing)
- 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)

These technologies are still in the RD&D stage and when they could be applied at the industrial scale is uncertain. During this period, substantial investment will be needed to develop the required infrastructure (new reactor types, large facilities for partitioning, etc). In case the technologies can be upscaled, this will not eliminate the need for a geological repository. Next to the reduction of the waste volume, the post-closure assessment time in the safety case can potentially be shortened.

Nagra follows international efforts in transmutation, such as the developments of TerraPower on molten salt and sodium-cooled reactors, the GE Hitachi PRISM sodium-cooled fast reactor and the progress of the MYRHHA accelerator-driven system project in Belgium. Additionally, Nagra monitors international developments on both aqueous and pyroprocessing partitioning programmes. This will be continued in the future, with the aim of assessing 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).

9 References

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Appendix A1: Conditions attached to the 2021 Waste Management Programme and the 2021 RD&D Plan

These conditions are translated from the Federal Council (Bundesrat 2018): *Verfügung zum Entsorgungsprogramm 2016 der Entsorgungspflichtigen, Schweizerischer Bundesrat* (Swiss Federal Government), 9. November 2018.

The conditions are addressed in several documents, and a complete overview is provided in the Waste Management Programme (Nagra 2021h; Appendix A7). In the Appendix A1, the respective chapters of the RD&D Plan (this report) as well as major supporting reports addressing these conditions are listed.

Directive	
4. Conditions of the Federal Council for the 2016 and 2021 Waste Management Programmes	Addressed in
Clause 6.3 Waste volumes: As part of future Waste Management Programmes, Nagra has to outline the waste volumes that are currently expected and document that these are bounding. Nagra also has to describe the methodology on which this prediction is based, what differences there are compared to earlier predictions and how these differences are to be justified and evaluated. <i>This condition is addressed in NTB 21-01 (Nagra 2021h).</i>	Nagra 2021h (NTB 21-01)
Clause 6.4 Realisation plan: In future Waste Management Programmes, Nagra has to outline its preparations for the long-term archiving of information on the deep geological repositories. For the construction licence application, nuclear energy legislation and the ENSI-G03 Guideline (ENSI 2020) require a project for the monitoring phase, a facility closure plan as well as concepts for retrieval, marking and temporary closure in times of crisis. The corresponding preparatory work also has to be presented in future Waste Management Programmes. <i>The 2021 RD&D Plan addresses this condition through the Nagra Roadmap as described in Chapter 3, with the Tier 2 Optimisation Roadmaps indicating realisation and documentation until return to greenfield and with detailed Tier 3 roadmaps describing monitoring and sealing and closure activities until 2060 in Chapter 7. The current state of the art on relevant topics and activities foreseen in the near future is described in Section 8.8.2 for preservation and transfer of information across generations, Section 8.7 for monitoring and in Section 8.4.8 for sealing and closure.</i> <i>This condition is also addressed in NTB 21-01 (Nagra 2021h) in general and the supporting documents on monitoring and sealing and closure.</i>	Nagra 2021h (NTB 21-01) Nagra 2021g (NAB 21-12) Chapter 3 Chapter 7 Chapter 8

4. Conditions of the Federal Council for the 2016 and 2021 Waste Management Programmes (continued)	Addressed in
Clause 6.5 Current experience and the latest developments in science and technology: In the next Waste Management Programmes, Nagra has to demonstrate that, based on current experience and the latest developments in science and technology, all necessary measures have been taken to meet the legally stipulated protection objectives for the construction and operation of a deep geological repository as well as after its closure. With regard to enhanced safety, appropriate optimisation measures have to be outlined and verified, and their appropriateness evaluated in an overall context (i.e. operational safety, long-term safety, transport safety, personal doses, new waste arisings etc.). <i>The 2021 RD&D Plan addresses this condition through the Nagra Roadmap as described in Chapter 3, with the Tier 2 Optimisation Roadmaps indicating optimisation of safety until return to greenfield. The link between safety and the latest developments in science and technology is made in Chapter 4. The current status of the Nagra repository project and the safety case is described in Chapter 5. The detailed contribution of programme aspects with a significant RD&D component to the safety optimisation process is captured in the Tier 3 roadmaps for ten selected topics (Chapter 7). Many aspects of the latest developments in science and technology supporting the current safety case and further optimisation are described in detail in Chapter 8.</i> <i>This condition is also addressed in NTB 21-01 (Nagra 2021h) in general and the supporting document on optimisation.</i>	Nagra 2021h (NTB 21-01) Nagra 2021a (NAB 21-10) Chapter 3 Chapter 4 Chapter 5 Chapter 7 Chapter 8
5. Requirements of the Federal Council for the 2016 Waste Management Programme modified for the 2021 and future Waste Management Programmes	
4.1 RD&D Plan: Together with the Waste Management Programme, Nagra has to submit a Research, Development and Demonstration (RD&D) Plan documenting the purpose, scope, type and temporal sequence of future RD&D activities. Future RD&D Plans should include a comprehensive list of all important open questions from Nagra's viewpoint, together with information on how and within what time frame Nagra plans to answer these questions. The list should also indicate which questions are critical for reaching the next milestones and how the required solutions can be achieved in a timely manner. In addition, it should describe the consequences that would arise if the milestone targets are not or not fully met. <i>The 2021 RD&D Plan addresses this condition through the Nagra Roadmap as described in Chapter 3 with the Tier 2 Optimisation Roadmaps indicating optimisation of safety and of implementation until return to greenfield. The link between the programme development and optimisation and the purpose, scope, type and temporal sequence of future RD&D activities is described in Chapter 4. Nagra is of the opinion that open questions are best captured by defining programme aspects that have a significant RD&D component and developing a dedicated roadmap for each of these with a planning horizon up to 2060 when the repositories go into operation. These are described in detail in Chapter 7 and highlight activities that are important for reaching the next milestones and explaining how the required solutions can be achieved in a timely manner. If important milestone targets are not fully met, this can result in a delay of the licensing process, but no unsolvable RD&D issues are expected to be encountered as the programme is in a mature state and the site characterisation is well advanced. The nearest milestones are described in detail in Chapter 8 for the entire RD&D programme.</i>	Chapter 3 Chapter 4 Chapter 6 Chapter 7 Chapter 8

5. Requirements of the Federal Council for the 2016 Waste Management Programme modified for the 2021 and future Waste Management Programmes (continued)	Addressed in
4.2 Overall deep geological disposal system: In future Waste Management Programmes, Nagra has to outline how the overall deep geological disposal system is to be implemented technically and temporally and how the individual research and development activities are connected to each other and to the milestones and decisions related to realising a deep geological repository. With regard to its decisions, Nagra has to demonstrate when and why it will undertake which research projects and developments, and where and when it will set which priorities. For safety-relevant decisions, different alternatives have to be considered, and a project has to be selected that is beneficial overall to safety. Decisions made have to be documented together with their justification in a manner that remains valid in the long term so that they also remain transparent in the future. <i>The 2021 RD&D Plan addresses this condition through the Nagra Roadmap as described in Chapter 3 where the main milestones for realising the deep geological repository are documented at Tier 1. In the Tier 2 Optimisation Roadmaps, optimisation of safety and of implementation and decisions needed to reach the milestones at Tier 1 are described until return to greenfield. The link between the programme development and optimisation and how the individual research and development activities are connected to each other is described in Chapter 4. Key programme aspects with a significant RD&D component and the relevant decisions are identified in Chapter 3 and developed as Tier 3 roadmaps in Chapter 7. There, it is also demonstrated when and why Nagra undertakes which research projects and developments, and where and when it will set which priorities. The link with the safety-relevant decisions documented in the Tier 2 roadmaps is provided. The current status and decisions made in the repository project are described in Chapter 5, which also describes the requirements management system that documents decisions made (justified to remain valid in the long term).</i> <i>This condition is also addressed in NTB 21-01 (Nagra 2021h) in general and the supporting document on optimisation.</i>	Nagra 2021h (NTB 21-01) Nagra 2021a (NAB 21-10) Chapter 3 Chapter 4 Chapter 5 Chapter 7
6. Requirements of the Federal Council for the 2021 Waste Management Programme	
5.1 Reduction of potential gas production: In the 2021 Waste Management Programme, Nagra has to outline whether it is necessary to further reduce potential gas production from metallic waste, or whether changes should be made to resulting requirements on repository-specific waste properties with a view to the realisation of deep geological repositories. <i>This condition is addressed specifically in NTB 21-01 (Nagra 2021h).</i> <i>The 2021 RD&D Plan contributes to answering this condition by providing an overview on the RD&D activities related to gas production and the decisions needed for the realisation of the repository until its planned operation in 2060 in the dedicated Tier 3 roadmap in Chapter 7. The RD&D activities that are related to the estimation of the gas source term are described in Section 8.8.3.5 and those related to gas transport in Sections 8.2.2.2 and 8.2.2. The knowledge base will be integrated to provide an update of the gas synthesis report (Diomidis et al. 2016, NTB 16-03) that will be based on the selected site(s) for the general licence applications.</i>	Nagra 2021h (NTB 21-01) Diomidis et al. 2016 (NTB 16-03) Chapter 7 Chapter 8

6. Requirements of the Federal Council for the 2021 Waste Management Programme (continued)	Addressed in
5.2 Pilot repository: In the next Waste Management Programme, Nagra has to further concretise the scope and content of the measurements for monitoring a pilot repository for HLW or L/ILW and to outline present-day knowledge with regard to the interpretation or interpretability of the measured data, as well as to ensure that the knowledge gained can be transferred to the main repository. <i>This condition is addressed specifically in NTB 21-01 (Nagra 2021h) and the supporting report on the integral monitoring concept (including EUU facilities and pilot repository).</i> <i>The 2021 RD&D Plan contributes to answering this condition by providing an overview on the current RD&D activities related to monitoring and monitoring concepts in Section 8.7.</i>	Nagra 2021h (NTB 21-01) Nagra 2021d (NAB 21-11) Chapter 8
5.3 Consequences of a combined repository: In the 2021 Waste Management Programme, Nagra has to outline the existing variants for a combined repository solution with a view to avoiding potential safety-relevant impacts on the individual repository sections. In addition, the relative spatial requirements and the variants aimed for from a safety perspective have to be included. <i>This condition is addressed specifically in NTB 21-01 (Nagra 2021h) and the supporting reports regarding the consequences of a combined repository for construction and operation on the one hand and the post-closure impact on the other hand.</i> <i>The 2021 RD&D Plan contributes to answering this condition by providing an overview of the current state of the art and RD&D activities related to understanding of the safety-relevant properties and processes in the repository near-field in Section 8.5.</i>	Nagra 2021h (NTB 21-01) Nagra 2020b (NAB 19-15) Nagra 2021c (NAB 20-31) Chapter 8
5.4 Closure variants: In the 2021 Waste Management Programme, Nagra has to outline and compare potential closure variants as preliminary work for creating a concept for the general licence application. <i>This condition is addressed specifically in NTB 21-01 (Nagra 2021h) and the supporting report comparing potential closure variants as preliminary work for creating a concept for the general licence applications.</i> <i>The 2021 RD&D Plan contributes to answering this condition by providing an overview of the state of the art and planned RD&D activities in the near future related to sealing and closure in Section 8.4.8.</i>	Nagra 2021h (NTB 21-01) Nagra 2021g (NAB 21-12) Chapter 8
5.5 Zero measurements: In the 2021 Waste Management Programme, Nagra has to document preliminary work activities concerning zero measurements. These should include a justified explanation of which processes and parameters are important for monitoring the environment and the zero measurements and how these will be recorded. <i>This condition is addressed specifically in NTB 21-01 (Nagra 2021h) and the supporting report on the integral monitoring concept. This includes an explanation of which processes and parameters are important for monitoring the environment and the zero measurements and how these will be recorded.</i> <i>The 2021 RD&D Plan contributes to answering this condition by providing a dedicated Tier 3 roadmap on monitoring activities up to the operation of the repositories around 2060 (Section 7.2) and an overview of the current RD&D state of the art and planned activities related to monitoring and monitoring concepts in Section 8.7.</i>	Nagra 2021h (NTB 21-01) Fanger et al. 2021 (NAB 20-28) Nagra 2021d (NAB 21-11) Chapter 7 Chapter 8

6. Requirements of the Federal Council for the 2021 Waste Management Programme (continued)	Addressed in
5.6 Stages of using the facilities for underground geological investigations: When updating the Waste Management Programme, Nagra has to outline the requirements for the different stages in which the facilities for underground geological investigations will be used. In addition, the type and time frame for the planned technical demonstrations have to be explained for repurposing at a later point in time. <i>This condition is addressed specifically in NTB 21-01 (Nagra 2021h) and in the supporting report on the concept of the EUU describing the different stages in which the facilities for underground geological investigations will be used. In addition, the type and time frame for the planned technical demonstrations are given.</i> <i>The 2021 RD&D Plan contributes to answering this condition by providing the context for the activities in the facilities for underground geological investigations in Chapter 6 and the integration of the demonstrations and experiments in the EUU in decision-making (respective Tier 3 roadmaps in Chapter 7).</i>	Nagra 2021h (NTB 21-01) Nagra 2021b (NAB 21-14) Chapter 6 Chapter 7
5.7 Experience gained in repository conceptual design: Within the framework of the 2021 Waste Management Programme, Nagra has to outline whether and, where applicable, through which additional feasibility-related investigations specific knowledge can be gained as early as possible to optimise the repository conceptual design. <i>The 2021 RD&D Plan answers this condition at the highest level in Chapter 3 where it captures the development and optimisation of the underground facilities in the Tier 2 Optimisation Roadmap. Chapter 6 provides an overview of the feasibility-related activities that are foreseen for the preparation of the facilities for underground geological investigations and the activities therein. It also includes the technology development. Several of the programme aspects with a significant RD&D component encompass feasibility-related investigations (e.g. thermal and gas optimisation, sealing and closure; see Chapter 7). Finally, the current state of the art and feasibility-related activities in the next years are described in Sections 8.4.1, 8.4.2 and 8.4.3.</i> <i>This condition is also addressed in NTB 21-01 (Nagra 2021h) in general and in the supporting document on optimisation.</i>	Nagra 2021h (NTB 21-01) Nagra 2021a (NAB 21-10) Chapter 3 Chapter 6 Chapter 7 Chapter 8
5.8 Interim storage capacity: When updating the Waste Management Programme, the operators of the nuclear power plants have to develop new concepts for increasing the interim storage capacity for spent fuel assemblies and vitrified high-level waste. These concepts have to consider that individual canisters have to be readily accessible for inspections and any maintenance work. <i>This condition is addressed in NTB 21-01 (Nagra 2021h) in general and in the supporting document on the various variants on interim storage capacity.</i>	Nagra 2021h (NTB 21-01) Kasemeyer 2021

7. Requirements of the Federal Council for the 2021 and future Waste Management Programmes	Addressed in
6.1 Research, Development and Demonstration Plan: Nagra has to incorporate research activities regarding the ageing of spent fuel assemblies and dry storage in future RD&D Plans. The results of the research projects as well as experiments that were listed in the previous version of the RD&D plan have to be outlined. <i>The 2021 RD&D Plan answers this condition by providing a dedicated Tier 3 roadmap on spent fuel characterisation and encapsulation up to the operation of the repositories around 2060 (Section 7.1) and an overview on the current state of the art and what has been achieved since the previous RD&D Plan in Section 8.3.4 and the references therein.</i> <i>This condition is also addressed in NTB 21-01 (Nagra 2021h) in general.</i>	Chapter 7 Chapter 8 Nagra 2021h (NTB 21-01)

Appendix A2: The Swiss radioactive waste management programme: main elements since its establishment in 1972

This appendix provides a historical overview of the Swiss radioactive waste management programme from the establishment of Nagra in 1972 up to the decision of the Federal Government on Stage 2 of the site selection process in 2018. Later developments, including Stage 3 of the Sectoral Plan and steps leading to the general licence applications, are discussed in Chapter 5.

Early legal basis and establishment of Nagra

The management of radioactive waste has been addressed by the Swiss Federal Government from the very beginning of Switzerland's nuclear programme. The fundamental aspects were defined in the Atomic Act (1959) and were further elaborated in the Federal Government Ruling on the Atomic Act (1978) and the Radiological Protection Act (RPA 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 was established in 1972 as a cooperative of the radioactive waste producers, i.e. the electricity utilities and the Swiss Confederation (represented on Nagra's Board by the Swiss Federal Department of the Interior, responsible for waste from medical, industrial and research applications). A research and development programme was initiated in the late 1970s, as well as the exploration of potential host rocks for the implementation of geological repositories for the long-term disposal of all types of radioactive waste.

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

Early activities and *Projekt Gewähr*

A broad regional field investigation programme in Northern Switzerland, as well as field investigations at several sites in the Alps, were launched in the early 1980s. In parallel, an extensive technical programme was initiated with activities in, e.g., the areas of development, testing and application of safety assessment models, waste inventory characterisation, the development of geochemical databases and the characterisation of engineered barriers. The Grimsel Test Site (underground rock laboratory in crystalline rock), managed by Nagra, started operations in 1984, while the Mont Terri Rock Laboratory (Opalinus Clay), managed by swisstopo, was established in 1996. Fig. A2-1 shows the extent of geological formations and specific sites investigated by Nagra in the period from 1980 to 2002.

To demonstrate disposal feasibility, the results of these activities were compiled in Nagra's *Projekt Gewähr* reports (Nagra 1985). In 1988, the Federal Government approved *Projekt Gewähr* for the low- and intermediate level waste (L/ILW) repository. Concerning high-level waste (HLW), the government judged that construction feasibility was given and that long-term safety was achievable, provided that the database used in the analyses could be confirmed to be applicable to a sufficiently large potential disposal area. However, at that point, the existing geological field data did not allow a confident statement that sufficiently large areas of crystalline rock with the required properties could be found in Switzerland; a specific suitable site had not been identi-

fied and thus siting feasibility was not fully demonstrated. While the L/ILW disposal programme could proceed towards site selection, as described below, additional geological studies on alternative potential host rocks had to be performed for the disposal of HLW.

L/ILW disposal investigations

For the L/ILW repository, Nagra performed exploratory investigations at the four sites shown in Fig. A2-1 (BDG: Bois de la Glaive; OBS: Oberbauenstock; PPG: Piz Pian Grand; WLB: Wellenberg), eventually leading to the selection of Wellenberg as the candidate site (Nagra 1993b). A permit for an exploratory underground tunnel had been granted by the Federal Government for the investigation. In 1994, Nagra submitted a general licence application (GNW 1994) which received a positive review by the safety authorities. However, the cantonal legislation had been recently modified and a cantonal referendum had become mandatory for a concession related to the underground, a resource belonging to the canton. The cantonal referendum took place in 1995 and the concession was rejected by a majority of approximately 51.5% (although the siting community approved it), leading to the rejection of the general licence application.

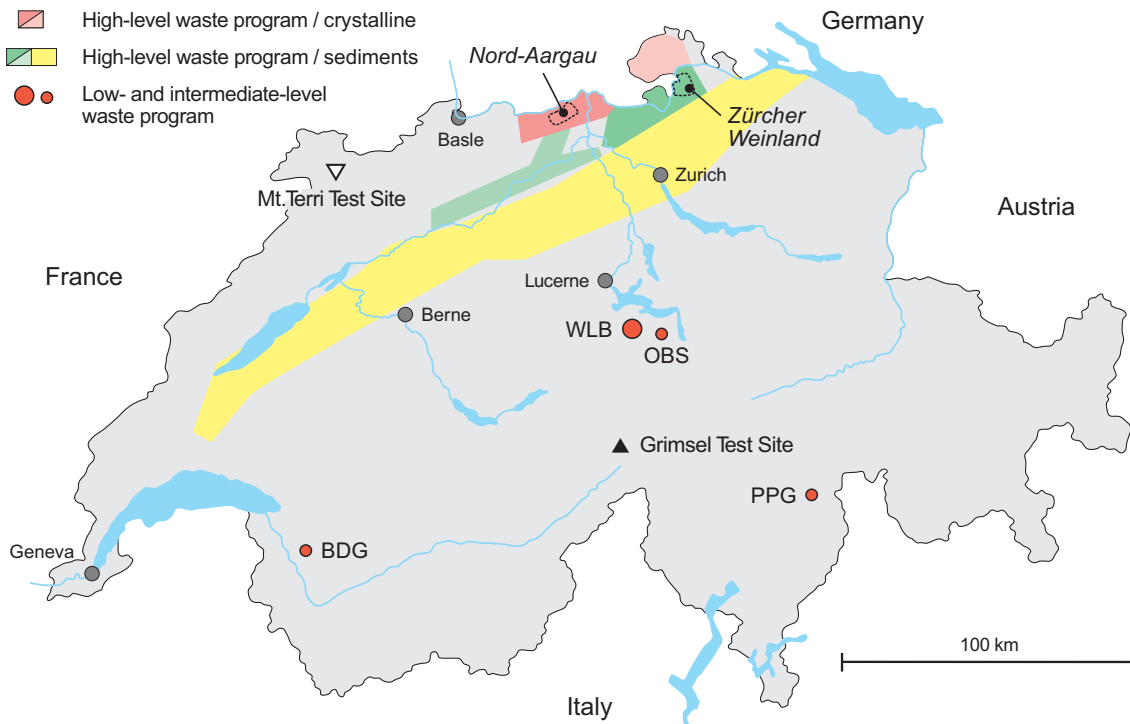


Fig. A2-1: Formations, regions and sites investigated by Nagra for the geological disposal of radioactive waste in the period from 1980 to 2002 (for acronyms, see paragraph above)

The cantonal and federal governments formed several expert groups to find a way to proceed. The Swiss Expert Group on Disposal Concepts for Radioactive Waste (EKRA) proposed adopting the concept of monitored geological disposal (EKRA 2000) as a response to societal requirements concerning monitoring and retrievability. The main features of the EKRA concept, relying on a stepwise implementation of the repository, include the construction of a monitored pilot repository and the implementation of an extended monitoring period following waste emplacement, as well as the possibility to retrieve the waste prior to the final closure of the repository.

The Wellenberg design was modified accordingly, and the new proposal was brought to a cantonal referendum in 2002 - requesting a permit and concession for exploratory tunnels. Despite the favourable evaluation of national and cantonal authorities, the requests were denied by the population for a second time, leading to a deadlock for any further steps, although the siting community of Wolfenschiessen had accepted the project in all of the public votes.

HLW investigations and Project Opalinus Clay

Meanwhile, from the mid-1980s through the 1990s, Nagra pursued studies related to evaluating sedimentary rocks for the disposal of HLW, as requested by the Federal Government. The regional investigations of the crystalline basement were ended and documented in 1994 (Thury et al. 1994, Nagra 1994a, 1994b).

For the Opalinus Clay, which was identified as the priority host rock by Nagra in agreement with the regulatory authorities and their experts, a field programme in the Zürcher Weinland potential siting region was performed, including a deep borehole in the community of Benken in Northern Switzerland and a 3D seismic campaign. With a view to demonstrating the disposal feasibility of HLW (*Entsorgungsnachweis*), Nagra submitted the "Project Opalinus Clay" reports (Nagra 2002a, 2002b, 2002c) to the Federal Government in 2002. The project included features of the EKRA monitored long-term geological disposal concept (EKRA 2000). Due to the encouraging project results, Nagra asked the Federal Government to allow future work on implementing the HLW repository to focus on the Opalinus Clay as host rock and on the Zürcher Weinland as the siting region. In June 2006, the government decided that Nagra had successfully demonstrated that the safe disposal of HLW in Switzerland was technically feasible. However, it refused the recommendation to focus further investigations on the Zürcher Weinland and stated that the search for a disposal site should be resumed following a so-called "sectoral planning" process.

Evolution of the legal framework and the Sectoral Plan for Deep Geological Repositories

In 2002, two initiatives were submitted to Parliament, requesting in essence either a moratorium for new nuclear power plants or the phasing out of nuclear energy in Switzerland. In response to these initiatives, the Federal Government launched a comprehensive revision of the Atomic Act and, on 21st March 2003, proposed the new Nuclear Energy Act, encompassing articles for nuclear energy generation as well as for the management of radioactive waste. The national referenda proposing a moratorium or the phasing out of nuclear energy were both rejected by the Swiss population. By 2005, both the Nuclear Energy Act (NEA 2003) and the corresponding Nuclear Energy Ordinance (NEO 2004) were in force.

Of particular interest in relation to the disposal programme are the following provisions:

- the concept of monitored geological disposal (based on the proposal by EKRA mentioned above, EKRA 2000), which combines passive safety with a period of monitoring and the possibility of retrievability "without excessive effort" during the emplacement and monitoring periods until final closure of the repository, is required for all types of radioactive waste (L/ILW and HLW)
- national responsibility: licensing of site characterisation work, construction, operation and closing of a repository are the responsibility of the Federal Government (general licence: approved by Parliament and subject to an optional national referendum)
- stronger commitment of the Federal Government with the approval of a Waste Management Programme prepared by Nagra on behalf of the waste producers and updated on a regular basis

- disposal in principle within Switzerland; export (and import) possible for disposal only as an exception and under stringent conditions
- site selection to be based on a "Sectoral Plan for Deep Geological Disposal" under the leadership of the Federal Government
- reprocessing: a moratorium is in place since 1st July 2006

The legislation thus introduced the need for a so-called "Sectoral Plan" for the site selection process, as defined in the Spatial Planning Act (*Raumplanungsgesetz*, RPG 1979)(RPG 1979). Sectoral plans are typically implemented when planning large infrastructure projects of national importance, such as high-voltage power lines, motorways, airports etc., where spatial planning activities have to be harmonised at the federal, cantonal and community levels. The leading role in the newly established procedure was taken over by the Swiss Federal Office of Energy (SFOE), an office of the Federal Department of Environment, Transportation, Energy and Communication (DETEC).

A Sectoral Plan includes two parts. The "Conceptual Part" is a document specifically defined for the issue at stake, in this case the siting of a deep geological repository. This part includes the description of the procedure and the roles of the stakeholders, as well as the criteria used at the various decision points and the general schedule and sequence of activities.

The conceptual part of the "Sectoral Plan for Deep Geological Repositories" was drafted by the SFOE in 2006 following consultations and intensive participatory workshops with a wide range of stakeholders. After a number of iterations, it was approved by the Federal Government on 2nd April 2008 (SFOE 2008). This allowed the initiation of the "Implementation Part" that will lead to the general licence applications for one geological repository for HLW and one for L/ILW.

Implementation of the site selection process

The Sectoral Plan process includes three stages. At the end of each stage, proposals must be approved by the Federal Government based on the results of a detailed review by the regulatory authorities and on the outcome of a broad consultation phase involving all stakeholders. Throughout the site selection process, highest priority is given to safety.

Stage 1 started with a "white map of Switzerland" (which means that, a priori, no area is excluded), resulting in the selection of several geological siting regions for each repository type. Stage 2 led to the identification of three potential siting regions for the two repository types, each of them including a site for the surface facilities. In Stage 3, the remaining geological siting regions are investigated in more detail. This leads to a further safety-oriented narrowing down to one site for each repository type for which the general licence applications will have to be prepared.

Stage 1 of the Sectoral Plan (2008 – 2011)

Stage 1 focused on a scientific screening process leading to the identification of potential siting regions. While priority was given to safety, engineering feasibility was also included in the evaluation. At this stage, societal aspects were not taken into consideration. To assess safety and technical feasibility, the conceptual part of the Sectoral Plan defines 13 criteria, grouped into four broad areas: properties of the host rock, long-term stability, reliability of geological information and suitability for construction. The identification of suitable geological siting regions was conducted in five steps. This systematic approach, summarised below, was developed to ensure that the identification and selection of the proposals for the geological siting regions are performed in a fully transparent manner; the detailed documentation was compiled 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 public acceptance and support.

In a first step, the waste inventory was defined (including reserves for future developments) and the different 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. This resulted in 49 indicators supporting the initial 13 criteria.

Steps 3 to 5 covered the evaluation of the geological siting options. The geological information base available in Switzerland is extensive and includes data and information from investigations performed by Nagra over a period of 40 years as part of its geological disposal programme – as described above – as well as from the analysis and interpretation of data gathered by other parties. The latter include, for example, deep boreholes and seismic campaigns for oil and gas prospection and for geothermal energy, shallower boreholes, surface geological and tunnel mapping, high-level precision geodetic monitoring, etc.

In Step 3, the large-scale geological-tectonic situation 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 geological-tectonic areas in Switzerland could in principle be considered 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 4 involved selecting the preferred host rock formations within the large-scale areas still under consideration. For the L/ILW repository, the Opalinus Clay with its confining units, the claystone sequence 'Brauner Dogger' with its confining units, the Effingen Beds and the marl formations of the Helveticum were proposed. For the HLW repository, the Opalinus Clay with its confining units was proposed as the preferred host formation.

The configurations of the preferred host rocks within the large-scale areas under consideration were evaluated in Step 5. Considering the presence of regional geological features that could potentially be detrimental, 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 for delimiting the geological siting regions.

In October 2008, Nagra proposed three geological siting regions for the HLW repository and six for the L/ILW repository (Nagra 2008b) (Fig. A2-2). Three of the siting regions for the latter are almost identical to those for the HLW repository, but, in two of them, other formations lying above the HLW host rock (Opalinus Clay) are included as host rock.

While Nagra's proposals were being reviewed by the authorities, under the auspices of the SFOE, the regions potentially affected by each of the geological siting regions were identified and the development of the organisation for the participatory process – to begin in Stage 2 – was initiated. The size of the regions to be involved in the participatory process took into account the areas that are, in principle, available for siting the surface facilities (the geological siting regions with an added five-kilometre radius to take into account the possible offset of the surface facility from the geological siting region when using a ramp as access from the surface site to the underground facilities) and excluding clear "no go" areas from the point of view of land-use planning.

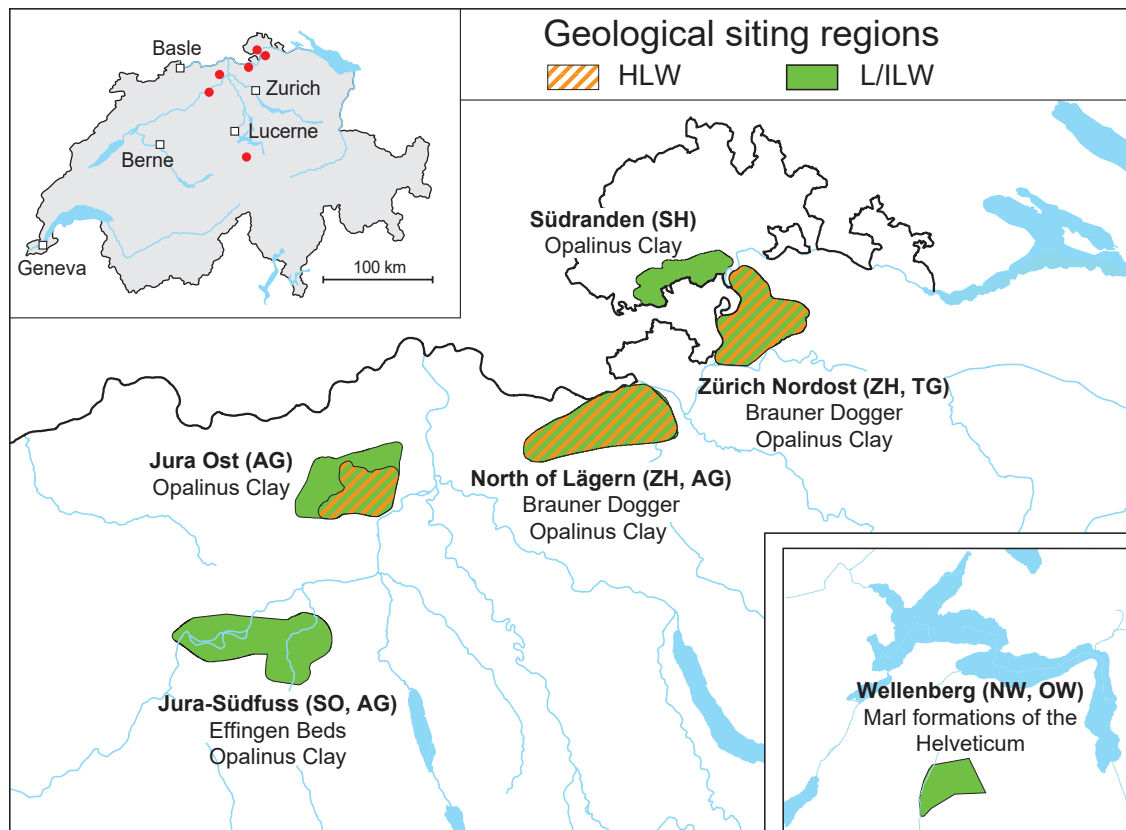


Fig. A2-2: The geological siting regions (cantons in brackets) and the respective host rocks for the HLW repository and the L/ILW repository according to the decision of the Federal Government at the end of Stage 1 of the Sectoral Plan

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

Stage 2 of the Sectoral Plan (2011 – 2018)

Stage 2 of the Sectoral Plan aimed at narrowing down the number of siting regions to at least two for each repository type. The narrowing-down process was based on safety arguments and required quantitative analyses (dose calculations according to detailed prescriptions by the safety authorities) and a qualitative evaluation (rating) of the geological siting regions according to the criteria related to safety and technical feasibility as defined in the Sectoral Plan (see Stage 1 above). Furthermore, a qualitative comparison of the siting regions was performed based on a limited number of significant safety-related features to assess whether any siting region showed clear disadvantages when compared with the others. If this were the case, this region would not be further considered in Stage 3.

The proposals for the regions to be further investigated in Stage 3 were prepared in five steps. In the first step, the methodology used in Stage 1 was adapted to address the changes in boundary conditions and to reflect 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.

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 2014b) 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 based on the relevant features specified by the Swiss Federal Nuclear Safety Inspectorate (ENSI), leading to the identification of siting regions with "clear disadvantages" in comparison with other siting regions.

In parallel, as part of the proposals submitted for Stage 2, at least one site for the surface facilities had to be selected for each region in close collaboration with the regional conferences. As a starting point for the discussions with the regions, Nagra identified twenty potential areas for surface facilities in 2012. These proposals were based on a conceptual design of the facilities and fulfilled the following primary objectives proposed by Nagra: (i) to ensure safety and engineering feasibility of the surface facilities and of the connection to the underground facilities of the geological repository; (ii) to ensure compatibility with spatial planning and environmental planning to minimise environmental impact; and (iii) to ensure an optimal integration of the facilities into the region. In the discussions, the weighing and setting of priorities for the different criteria turned out to be a critical issue, and Nagra was asked to identify alternative sites by switching priorities between different criteria. By the end of January 2014, all siting regions had issued a position statement about the sites for the surface facilities. The development of the corresponding planning studies was completed by the end of May 2014.

The proposals for underground and surface facilities were submitted by Nagra and published by the SFOE in December 2014 (Nagra 2014d, 2014c, 2014b): of the six L/ILW siting regions and three HLW siting regions identified in Stage 1, Nagra proposed to retain the two siting regions Jura Ost and Zürich Nordost for further investigation and to place the other four siting regions in reserve. Nagra stated that all six regions would meet the safety requirements, but that the regions that were temporarily placed in reserve showed clear disadvantages from a safety viewpoint compared to the two regions mentioned above.

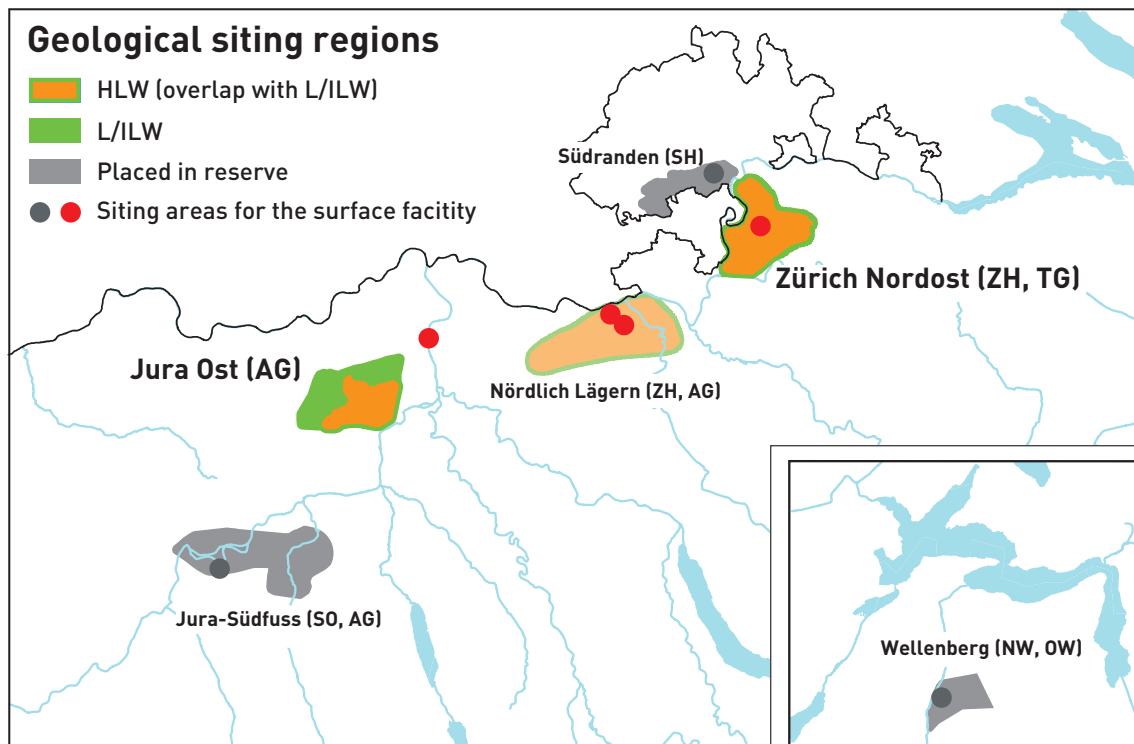


Fig. A2-3: The geological siting regions (cantons in brackets) and siting areas for the surface facility of the HLW repository and the L/ILW repository according to the decision of the Federal Government at the end of Stage 2 of the Sectoral Plan

Following its review, the regulatory authorities concluded that, in addition to the two proposed geological siting areas, Nördlich Lägern should also be further examined instead of being placed in reserve. Following a public consultation in 2017, Stage 2 was concluded with the decision by the Federal Government in November 2018. The three siting regions Jura Ost, Nördlich Lägern and Zürich Nordost were retained for further investigation in Stage 3 (Fig. A2-3). All three regions would be suitable for the disposal of L/ILW and HLW, as well as for constructing a so-called combined repository for both waste categories. The results were incorporated into the Sectoral Plan.

Appendix A3: The Nagra Disposal Programme Roadmap

A3.1 Description

Nagra has developed a Roadmap that defines all the major products (the "What?") that have been, or must be, developed over the course of the programme (the "When?") in order to deliver (design, construct, operate and close) a deep geological repository. The Roadmap covers the period from the inception of the programme (around 1980) to the expected return of the site to a greenfield state (planned for 2126). However, the primary focus of the Roadmap is the period from the present (2021) to the beginning of high-level waste (HLW) emplacement (2060) during which most of the activities will take place, including the vast majority of the underpinning RD&D. The Roadmap is structured using a tiered Work Breakdown Structure (the "How?") detailing how all programme activities feed into key decisions, key products, and the interdependence between tasks.

Terminology has been aligned to be consistent with terms used in the Nagra programme to ensure that the roadmaps can be integrated into Nagra working practices and Nagra documentation. However, certain terms that are unique to the roadmaps, or have a specific meaning in the context of the roadmaps, are defined as follows:

Programme Phase(s): Programme Phase is the term used for the timeframes across the top of the roadmap; these are aligned to Nagra planning documentation.

Programme Milestone(s): A milestone is an important point in time in the Nagra programme. Programme Milestones are either points at which Nagra must make an application to the regulatory authorities, or points at which Nagra has been authorised to conduct certain activities. The Programme Milestones have been extracted from Nagra planning documentation.

Nagra Roadmap: The Nagra Disposal Programme Roadmap (Nagra Roadmap) is the name for the entire suite of thirteen graphics which have been put together across three different "tiers". The thirteen graphics, combined, capture the entire scope of the Nagra programme. Each of the thirteen graphics is referred to as a "roadmap" and is a constituent part of the comprehensive Nagra Roadmap.

Tier (1, 2, 3): Tier 1 is a single, high-level roadmap that shows the entire scope of the Nagra programme (referred to as the "Programme Roadmap"). Tier 2 is made up of two roadmaps that cover the repository design development and optimisation from the perspective of post-closure safety and implementation (referred to as the "Optimisation Roadmaps"). Tier 3 is made up of ten roadmaps, each of which addresses an aspect of the Nagra programme with a significant RD&D component, defined as an RD&D Topic (referred to as "RD&D Roadmaps").

Programme Element(s): The Nagra programme is structured at Tier 1 using a functional breakdown of ten Programme Elements that collectively encompass all the necessary activities to support Nagra in delivering geological disposal.

Workstream(s): The repository development and optimisation scope (which is essentially a "subset" of technical scope from Tier 1) is structured at Tier 2 using workstreams that each support one of the major Programme Elements from Tier 1.

RD&D Topic(s) and Subtopic(s): Each Tier 3 RD&D Roadmap exists to show the work being carried out to address an aspect of the Nagra programme with a significant RD&D component, defined as an RD&D Topic, which is further subdivided into subtopics.

Product: A Product is a deliverable that is required for the continuation of the Nagra programme, either by the regulators, senior management or other teams within Nagra. The roadmaps feature Major Products and Subproducts:

Major Products are deliverables of high importance, which require visibility on the Tier 1 Programme Roadmap. These products are often mandated by the regulator and feed into licence applications or are central to the programme itself. They are generally aligned with the submission of licence and permit applications.

Subproducts are lower-level deliverables that bank knowledge for publication or are constituent parts of Major Products. Subproducts feature at Tier 2 and Tier 3.

Activity: Activities summarise what Nagra will be working on at a certain point in time. Activities feature at Tier 1, Tier 2 and Tier 3. The level of detail specified by Activities increases from Tier 1 to Tier 3.

Proposal: Proposals will be made by Nagra for adapting or focusing specific aspects of the Nagra programme at certain points in time. These Proposals will support Nagra in narrowing down options in accordance with the stepwise licensing process for nuclear facilities in Switzerland, allowing the programme to progress and to focus effort and resources appropriately over time. Proposals are made by Nagra at the programme level and are often strategic in nature. Proposals will be presented to the relevant authorities for assessment and, once they have been reviewed, Nagra will alter or implement the programme accordingly. Proposals feature at Tier 1 and Tier 2.

Decision: Decisions are essential components of the planning and implementation process, required for narrowing down options and making progress. They will be made based on numerous inputs, from technical feasibility to financial cost, and are supported by information gained by carrying out Activities. Decisions feature at Tier 1 and Tier 3, where the latest point by which a Decision must be made is highlighted on any roadmap featuring a Decision.

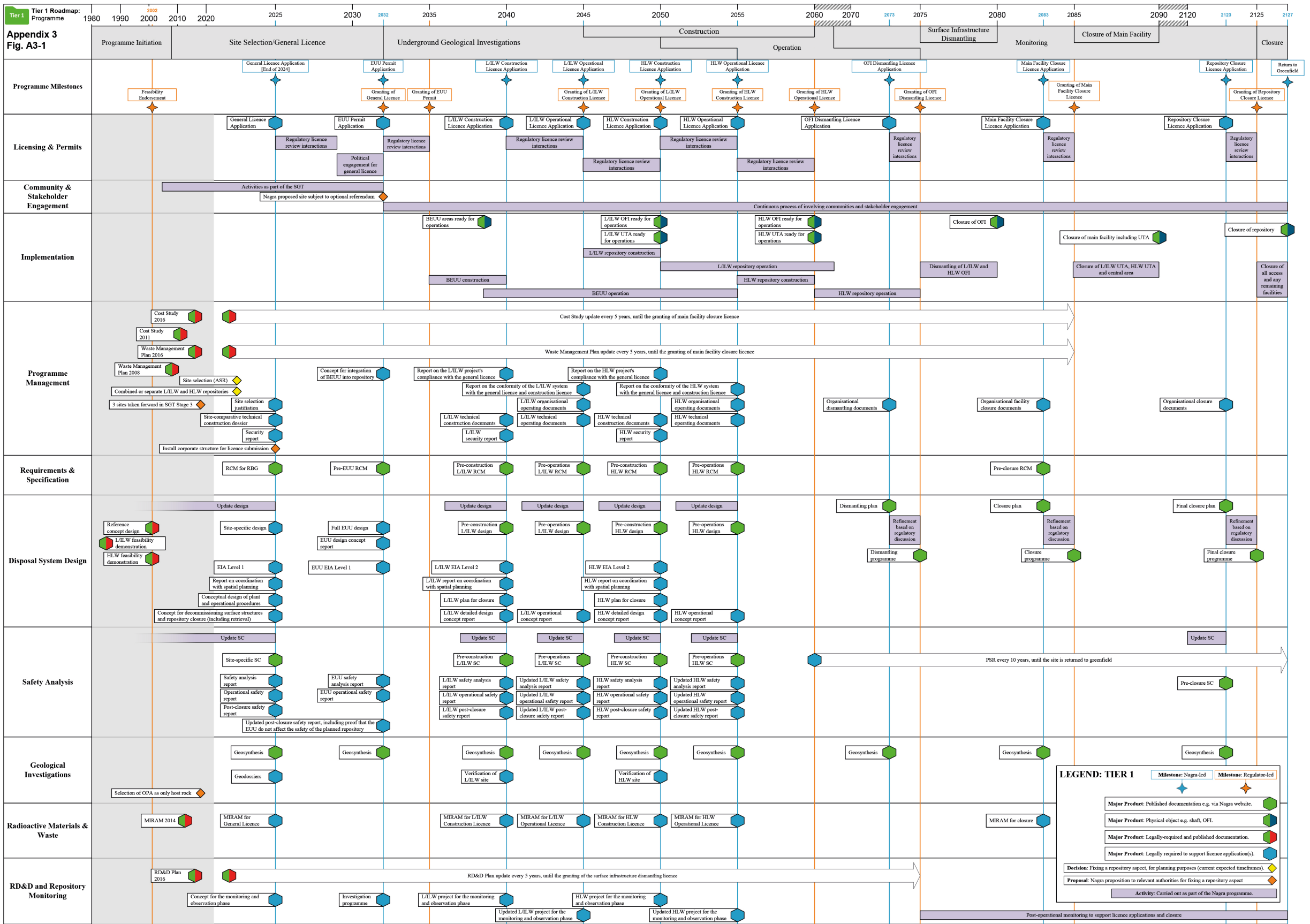


Fig. A3-1: Tier 1 Roadmap: Programme

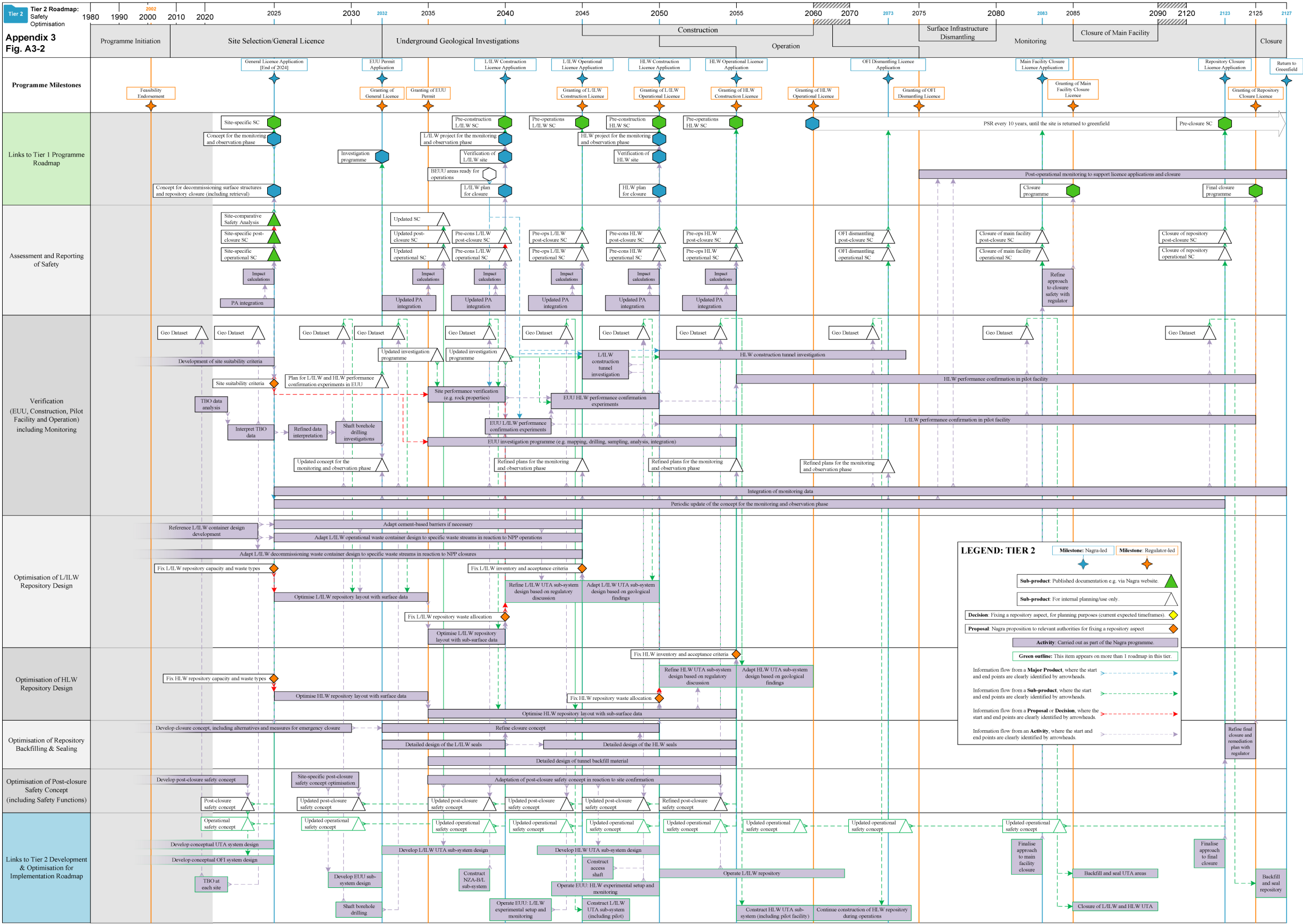


Fig. A3-2: Tier 2 Roadmap: Safety Optimisation

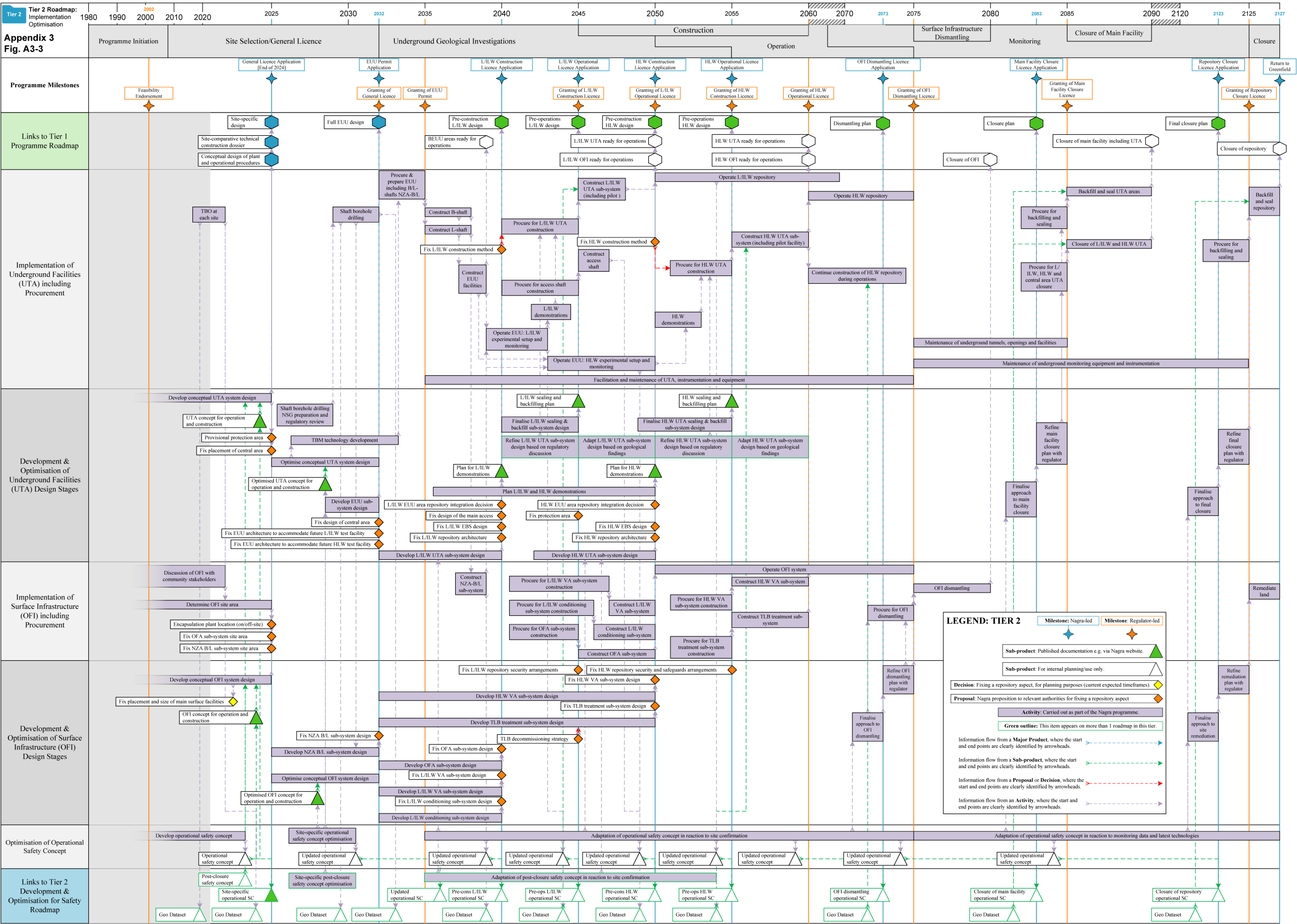


Fig. A3-3: Tier 2 Roadmap: Implementation Optimisation

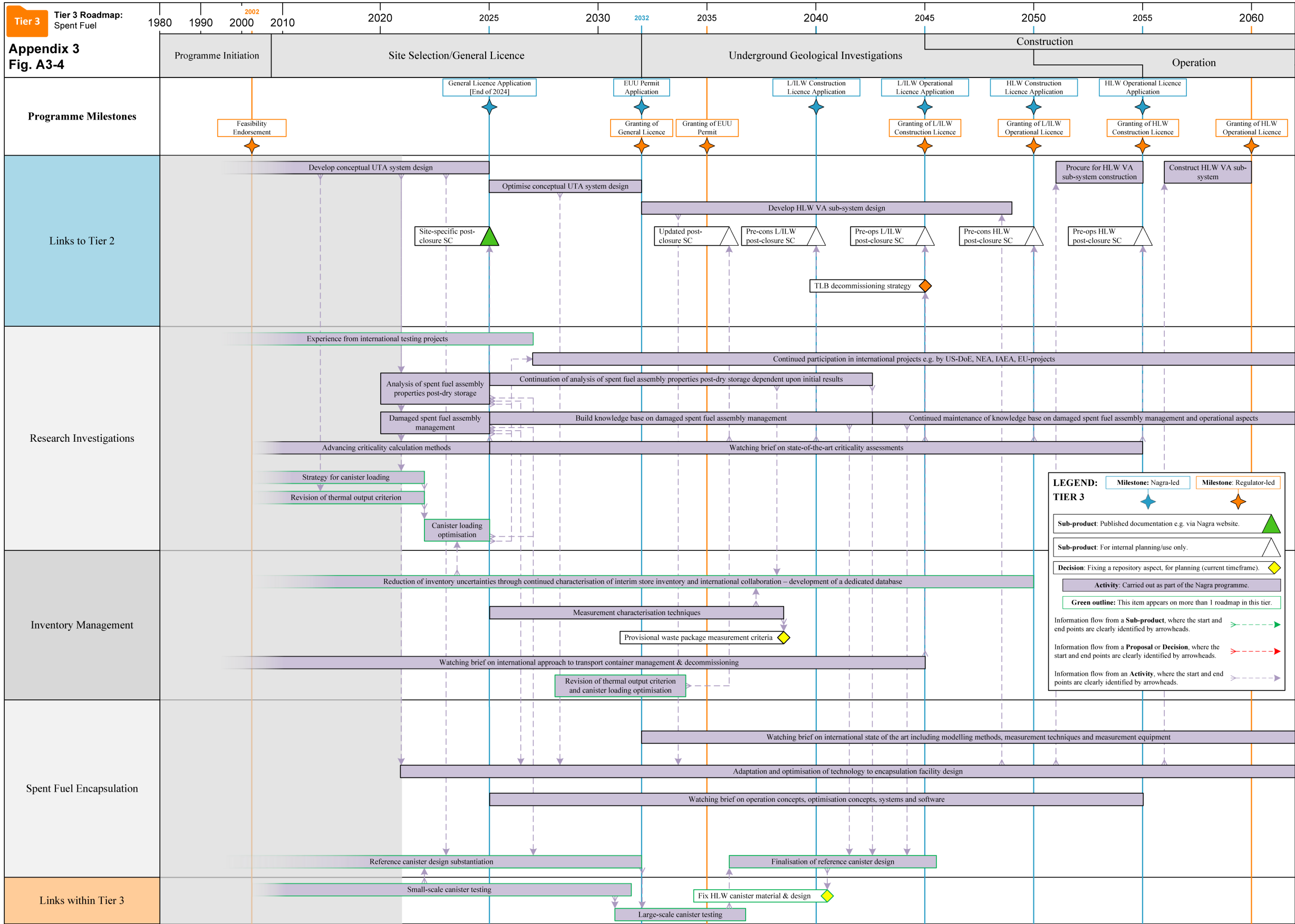


Fig. A3-4: Tier 3 Roadmap: Spent Fuel

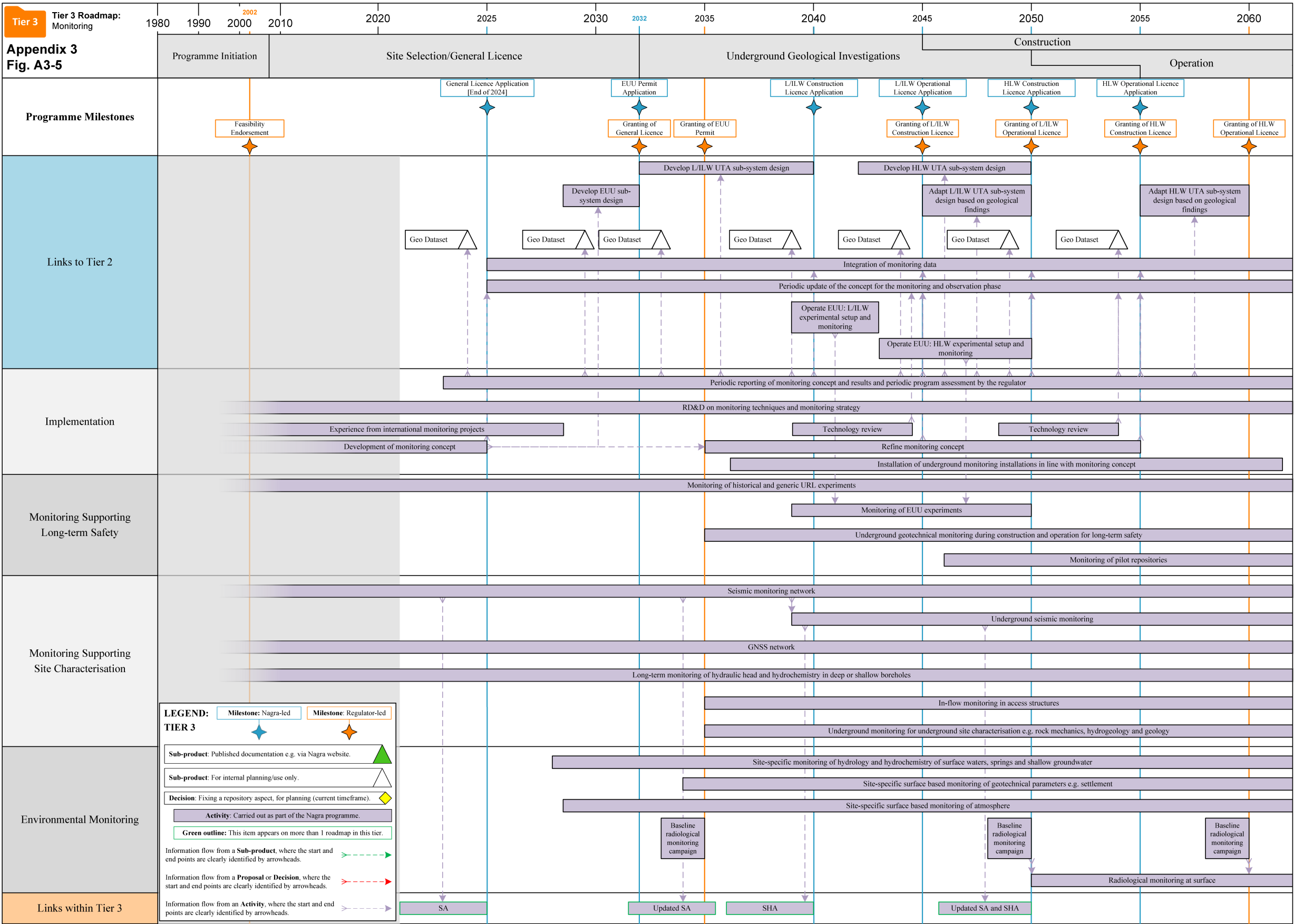


Fig. A3-5: Tier 3 Roadmap: Monitoring

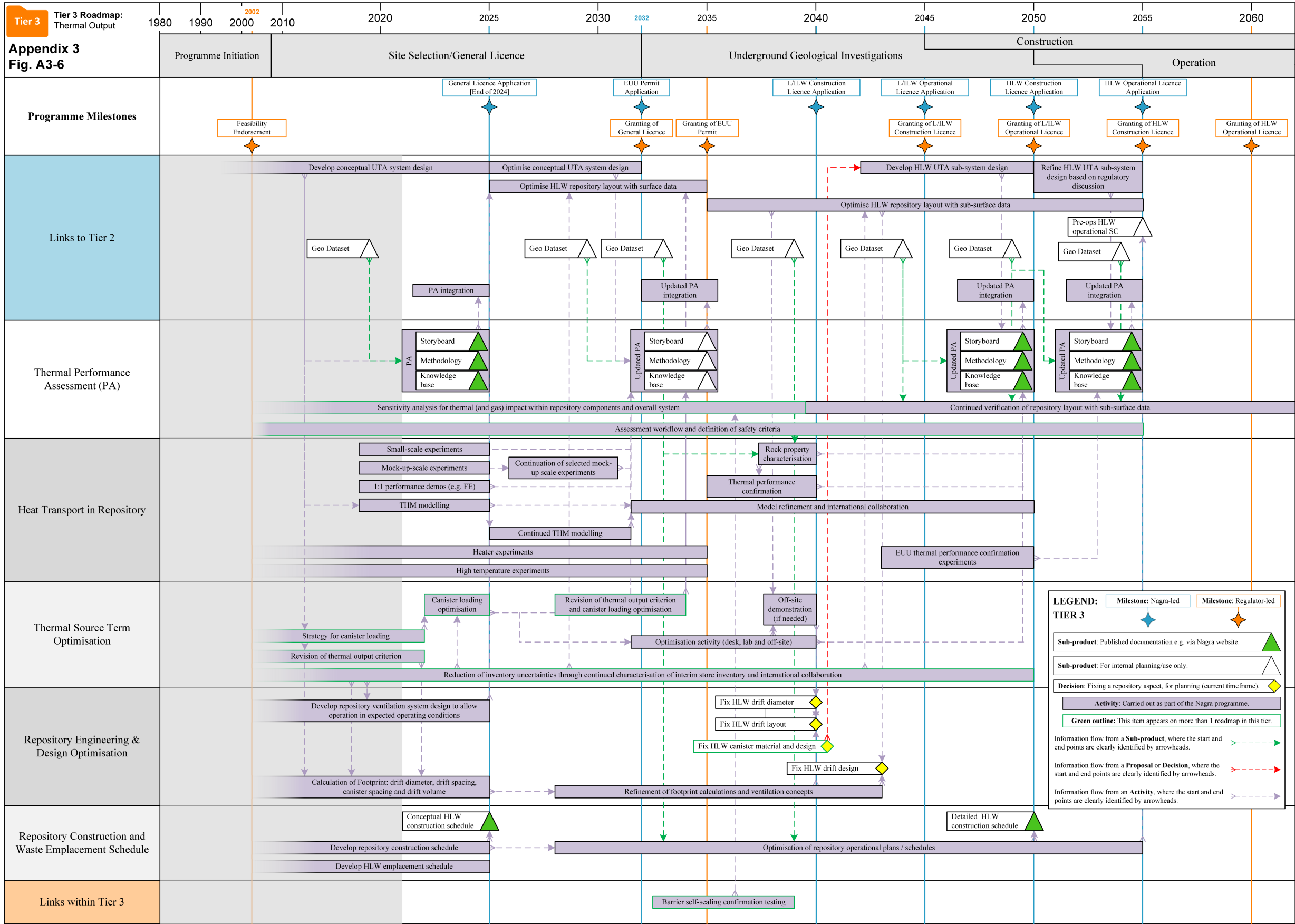


Fig. A3-6: Tier 3 Roadmap: Thermal Output

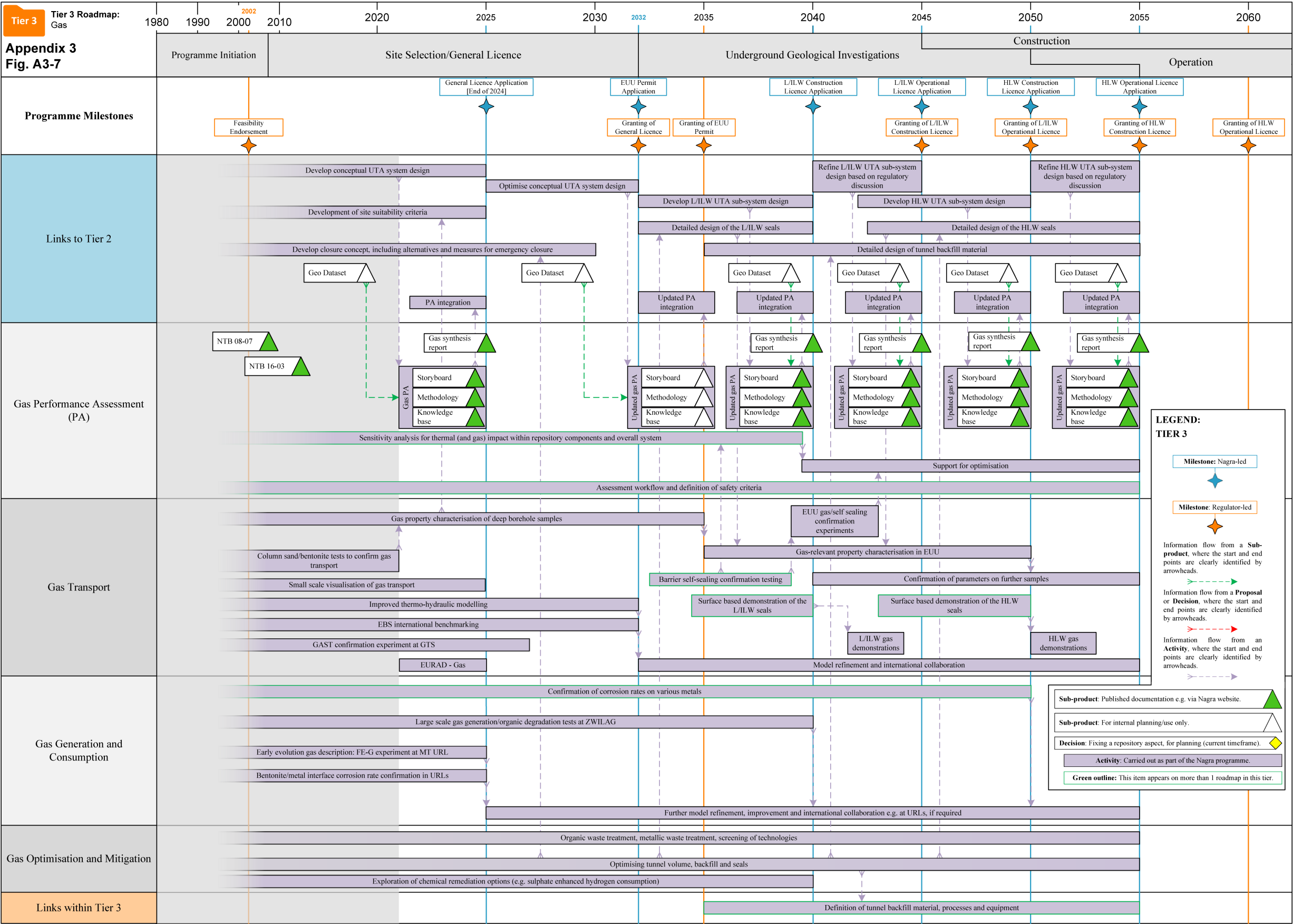


Fig. A3-7: Tier 3 Roadmap: Gas

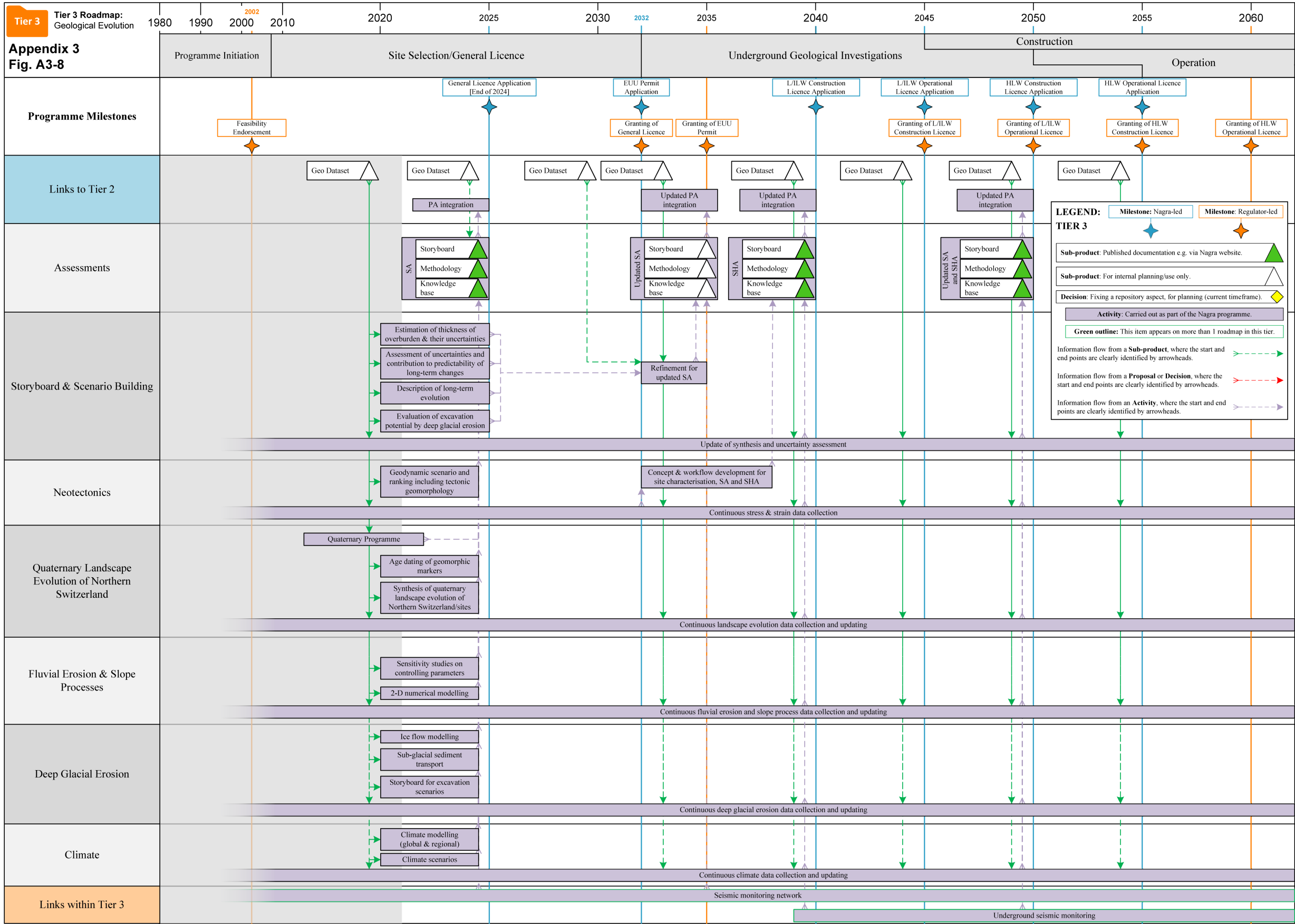


Fig. A3-8: Tier 3 Roadmap: Geological Evolution

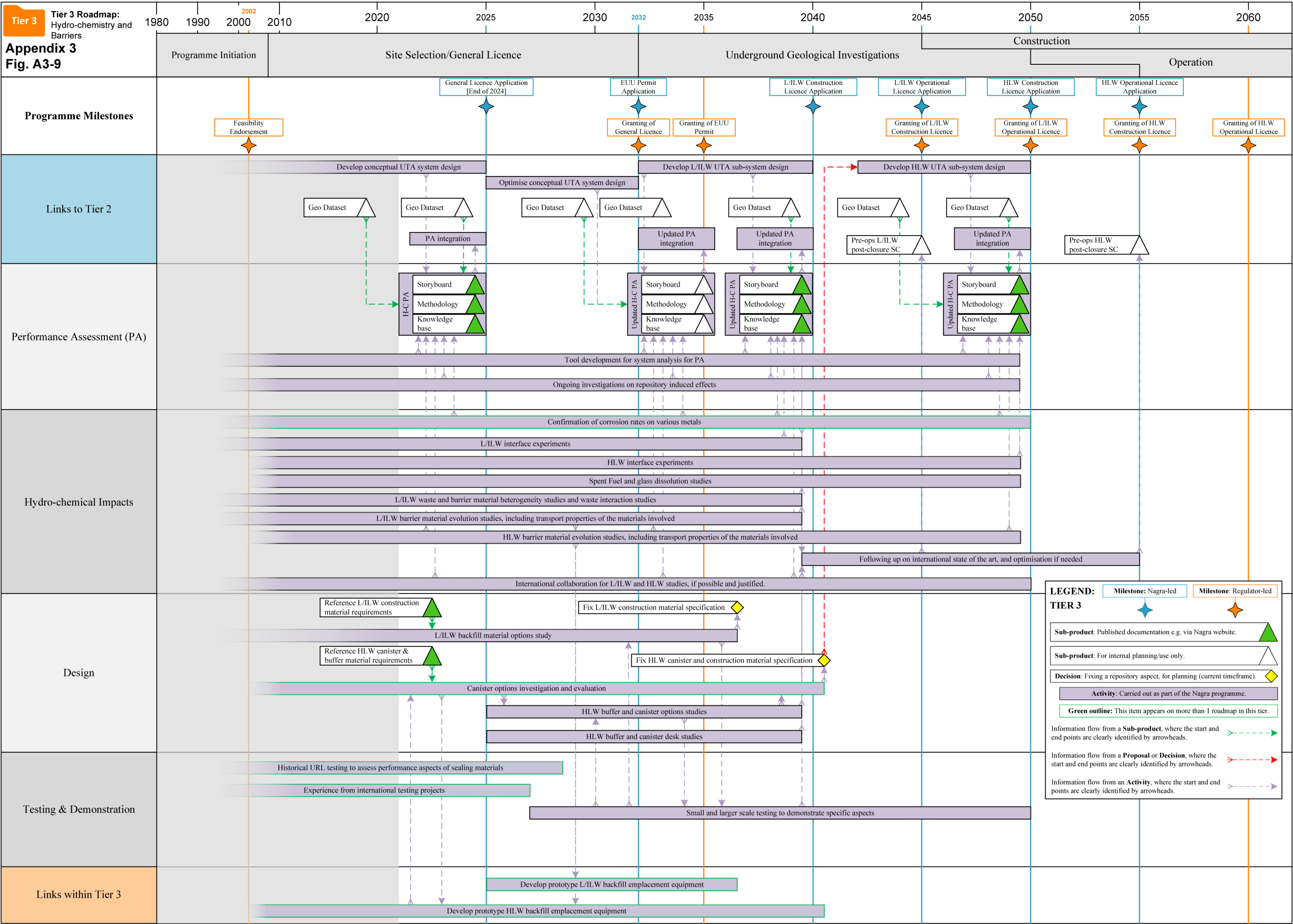


Fig. A3-9: Tier 3 Roadmap: Hydrochemistry and Barriers



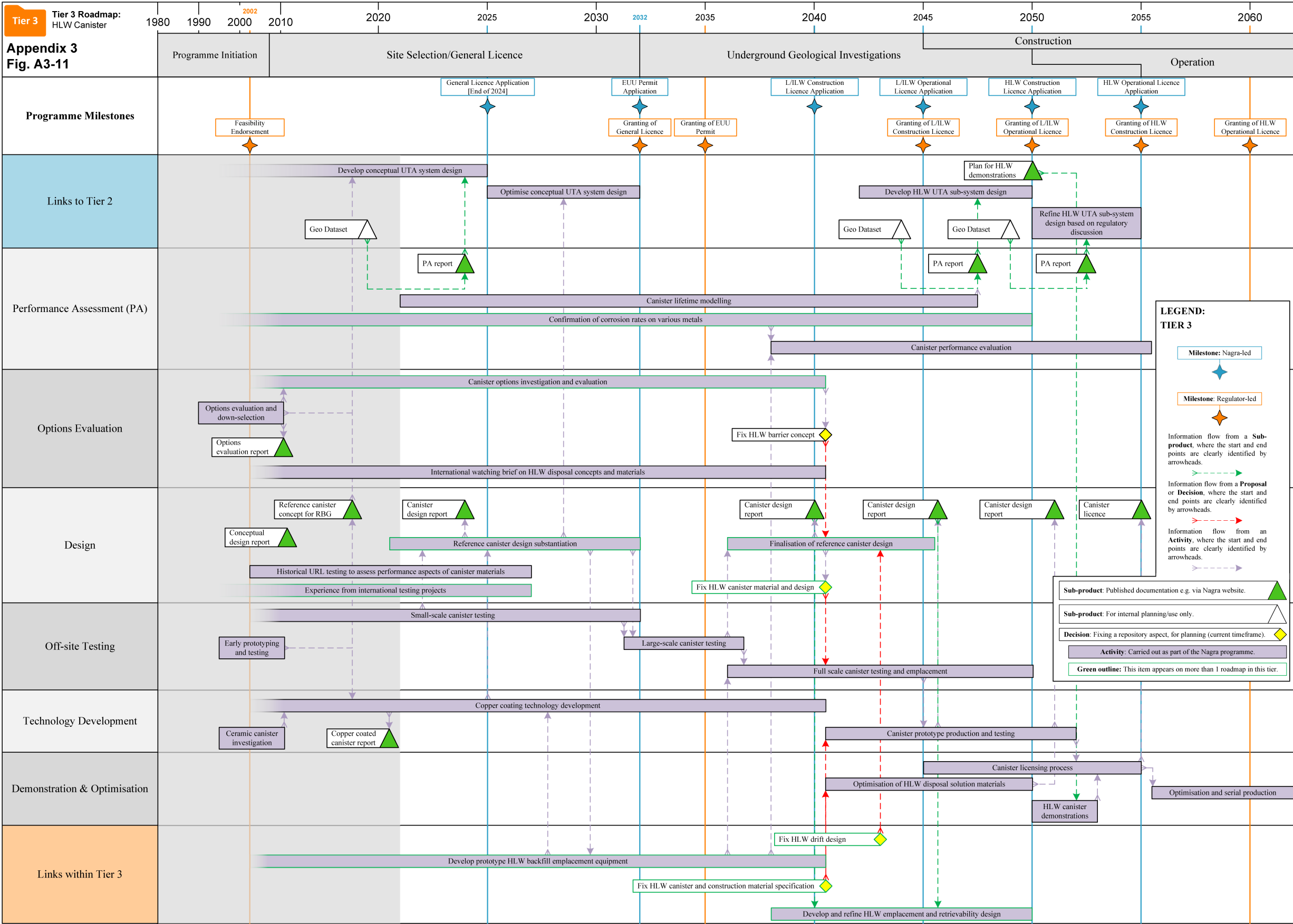


Fig. A3-11: Tier 3 Roadmap: HLW Canister

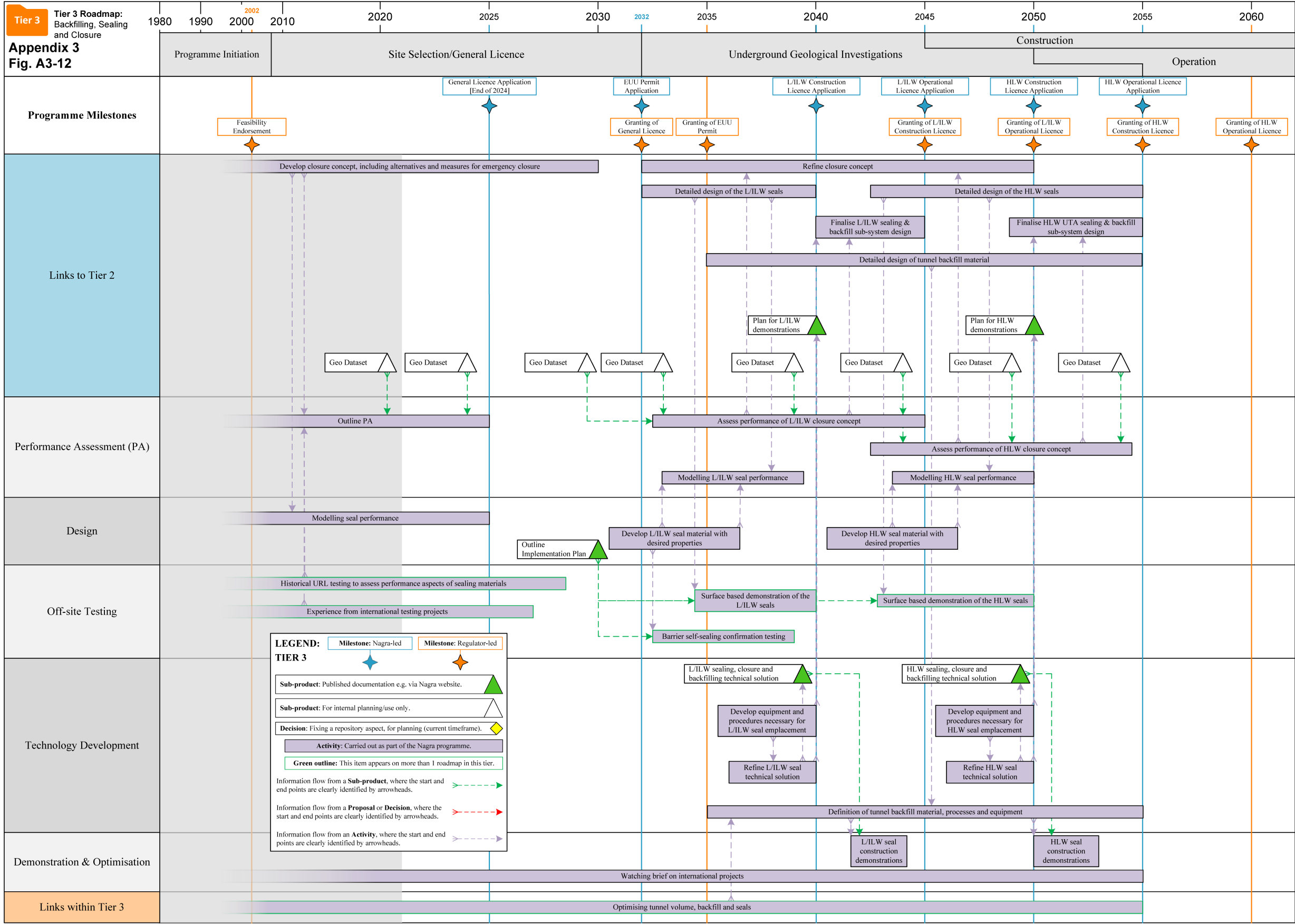


Fig. A3-12: Tier 3 Roadmap: Backfilling, Sealing and Closure

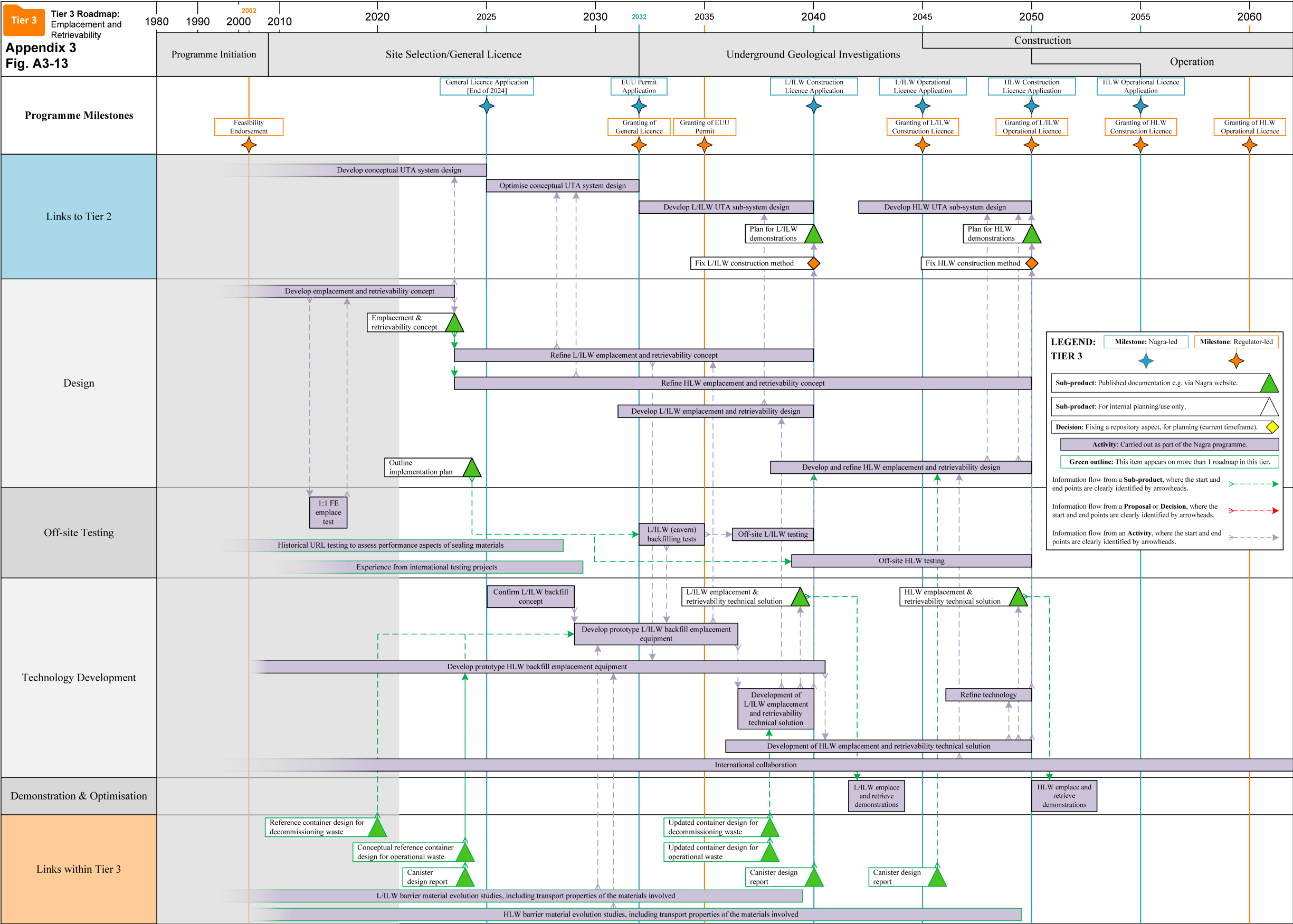


Fig. A3-13: Tier 3 Roadmap: Emplacement and Retrievability

