International Conference
Underground Disposal Unit Design & Emplacement Processes for a Deep Geological Repository
16-18 June 2008, Prague

THE SWISS CONCEPT FOR THE DISPOSAL OF SPENT FUEL AND VITRIFIED HLW

Authors: Thomas Fries, Anne Claudel, Hanspeter Weber, Lawrence Johnson, Olivier Leupin
Nagra

Abstract

Management of spent fuel (SF) and vitrified high-level waste (HLW) is based on the concept of deep geological disposal, namely long-term, effective isolation of the waste in suitable deep rock formations. The first project studies carried out by Nagra in this respect were performed more than 20 years ago when disposal in the crystalline basement and in clay were considered. The strategy developed by Nagra over the years is consistent with the concept of “monitored long-term geological disposal” as contained in the new Swiss Nuclear Energy Act of 2003 (KEG, 2003).

This paper provides an overview of the concept for facilities and operation of a deep geological repository for SF/HLW, as prepared for the disposal feasibility project and an outlook on ongoing work.

1 Introduction

Commercial use of nuclear power in Switzerland began in 1969 and by 1984, 5 nuclear power units were connected to the electricity grid: 3 PWR (Beznau 1 and 2 and Gösgen) and 2 BWR (Mühleberg and Leibstadt) at 4 sites totalling around 3,200 MWe, i.e. around 40% of the total electricity produced. The construction of new nuclear power plants (NPPs) is currently under discussion and licence applications could be submitted at the end of 2008.

Nuclear energy is governed by the Nuclear Energy Act, passed in 2003 (KEG, 2003), and several supplementary ordinances. According to the legislation, the responsibility for radioactive waste management lies with the waste producers. The National Cooperative for the Disposal of Radioactive Waste (Nagra) was therefore founded in 1972 by the NPP operators and the Swiss Federal Government, responsible for waste arising from medicine, industry and research. Nagra is in charge of preparing and implementing sustainable waste management solutions in Switzerland.

Radioactive waste is currently conditioned and stored mostly on-site and at the Central Storage Facility ZWILAG since 2001. Low and intermediate-level waste (L/ILW) consists of operational waste from the NPPs, waste from medicine, industry and research and will in future also include waste from the decommissioning and dismantling of the NPPs and nuclear research facilities. According to current estimates, the total volume of L/ILW (conditioned and packaged into disposal containers at time of emplacement in repository) will amount to 78,400 m^3 for a 50 years operation scenario for the NPPs currently in operation (all figures quoted below refer to conditioned and packaged waste). Of this, 21,100 m^3 are operational and decommissioning wastes from medicine, industry and research, 26,150 m^3 represent operational waste from the NPPs (including exchangeable reactor internals such as control rods, etc.) and 28,900 m^3 are expected from the decommissioning of the five existing NPPs and the waste treatment installations (plasma incinerator) at the ZWILAG Centralised Interim Storage Facility. Around 2,200 m^3 of waste are assumed to arise from the facility for encapsulation of spent fuel elements and high-level waste and an additional 12,000 m^3 (to be added to the above mentioned 78,400 m^3) are assumed for planning purposes (reserves mainly to cover wastes from large research facilities).

A total of around 3,400 tonnes HM of spent fuel (SF) is expected from the five reactors currently in operation, assuming a 50-year operating lifetime. The contracts between the Swiss NPP operators and reprocessing companies in France and the United Kingdom cover approximately 1,200 tonnes HM of spent fuel. For planning purposes, this is assumed to be the total amount that will be reprocessed although, in principle, reprocessing may be resumed after the current 10 years moratorium – which started on July 1, 2006 – has expired. This scenario will result in 6,600 m^3 of spent fuel elements (encapsulated in disposal containers), about 730 m^3 of vitrified high-level waste (HLW) and 1,320 m^3 of long-lived intermediate-level waste (ILW) from reprocessing.

The Nuclear Energy Act foresees disposal in geological repositories on the Swiss territory for all types of waste. The nuclear waste management concept includes two repositories, one for L/ILW and the other for SF, HLW and long-lived ILW (**Figure 1)**. Long-term safety of the repository must be assured without the need for active post-closure monitoring or control. Furthermore, nuclear energy legislation requires the demonstration of the feasibility of safe and permanent disposal of radioactive waste in Switzerland. For L/ILW, such a demonstration was formally accepted by the Federal Government in 1988. For the disposal of SF, HLW and long-lived ILW, the demonstration of disposal feasibility (*Entsorgungsnachweis*) was approved by the Federal Government in June 2006. This demonstration was based on a project for a geological repository in Opalinus Clay in Northern Switzerland.

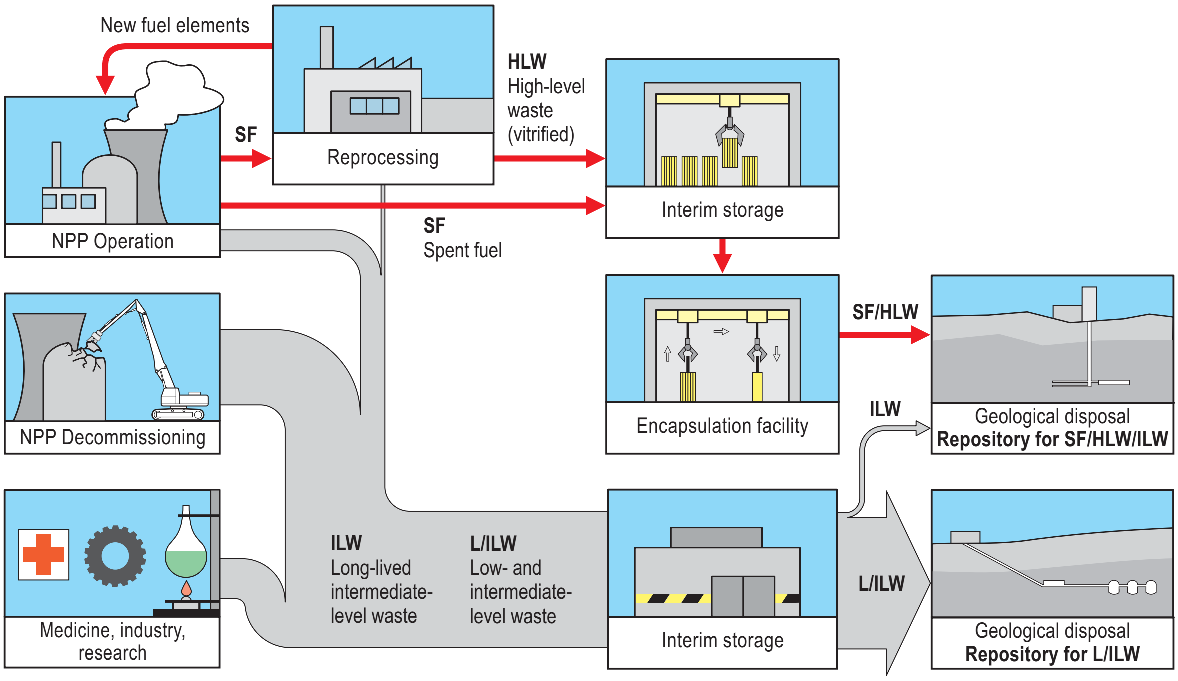


Figure 1: Swiss disposal concept

The site selection process for L/ILW as well as SF/HLW/ILW repositories is now to follow the “sectoral plan” procedure within the framework of existing land-use planning legislation. The first (“concept”) part of the sectoral plan for deep geological repositories (“Sachplan geologische Tiefenlager”) was approved by the Federal Government on 2nd April 2008. This document was prepared by the federal authorities under the lead of the Federal Office of Energy (FOE). It defines a three-stage site selection process and a series of site selection criteria related to geology and safety and will also address land-use and socio-economic aspects as well as the respective role of the parties involved. Over the past years, Nagra has compiled technical-scientific material and will submit later this year proposals for potential siting regions to the authorities.

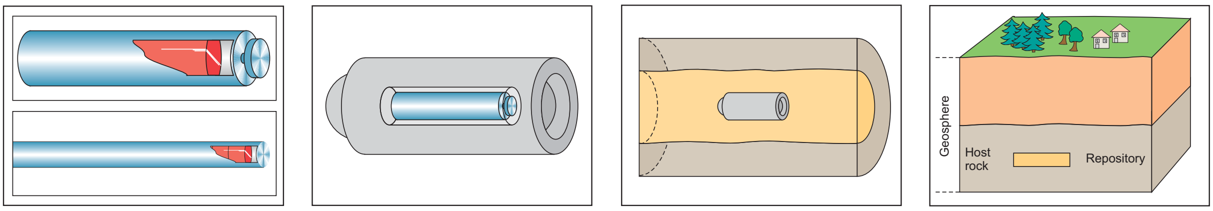
This paper will focus on the disposal of spent fuel and high-level waste. After an overview of the Swiss repository concept, recent and ongoing projects related to repository construction and operation will be briefly described.

2 The Swiss Repository Concept for SF/HLW

2.1 Disposal Principles

For the project Opalinus clay – Entsorgungsnachweis (disposal feasibility), a set of broad disposal principles were developed as part of the safety case (Nagra 2002a). Key elements directly relevant for the design are:

- The need for multiple passive safety barriers. These consist of the waste matrix, a massive long-lived disposal canister, a very low permeability backfill and seals and a suitable host rock (low permeability, good retention properties, allowing reliable construction of the repository) in a suitable geological environment (providing for long-term stability). **Figure 2** shows the multiple barrier system for SF/HLW.
- Implementation of the concept of "monitored long-term geological disposal" as described by (EKRA, 2000) and contained in the new Nuclear Energy Law (KEG, 2003). This concept consists of the main facility where the majority of the waste is emplaced and the emplacement rooms are backfilled and closed as early as possible and a pilot facility, which is in its layout exactly the same as the main facility and contains a small amount of waste that is representative for the whole inventory. The pilot facility is heavily equipped with monitoring instruments that should allow early detection of any unexpected undesirable evolution of the barrier system. The concept of "monitored long-term geological disposal" also requires that retrieval of the emplaced waste packages can be done with reasonable effort until final closure of the repository.
- Reliance on proven technology and materials to provide confidence in the feasibility of implementation. However, work is expected to continue both on the materials (including evaluation of alternatives) and on technology (periodic review of availability of optimised technology) to ensure that at time of repository implementation an optimised system will be available.



Glass matrix (in steel flask)
- Confinement
  - Containment of radionuclides in glass
- Attenuation of releases
  - Low corrosion rate of glass

or

Spent fuel assemblies
- Confinement
  - Containment of radionuclides in spent fuel pellets and Zircaloy cladding
- Attenuation of releases
  - Low corrosion rates of spent fuel pellets and Zircaloy

Steel canister
- Confinement
  - Prevents inflow of water and release of radionuclides from spent fuel or waste for several thousand years
- Attenuation of releases
  - Corrosion products act as reducing agent (giving low radionuclide solubilities)
  - Corrosion products take up radionuclides

Bentonite backfill
- Confinement
  - Long resaturation time
  - Plasticity (self-sealing following physical disturbance)
- Attenuation of releases
  - Low solute transport rates (diffusion)
  - Retardation of radionuclide transport (sorption)
  - Low radionuclide solubility in pore water

Geological barriers
Host rock
- Confinement
  - Absence of water-conducting features
  - Mechanical stability
- Attenuation of releases
  - Low groundwater flux
  - Retardation of radionuclide transport (sorption and colloid filtration)

Geosphere
- Confinement
  - Physical protection of the engineered barriers (e.g. from glacial erosion)
- Attenuation of releases
  - Retardation of radionuclide transport (sorption)
  - Dispersion

Figure 2: Multiple barrier system for SF/HLW

2.2 Geological Context

Opalinus Clay, a shale (claystone) sedimentary formation deposited about 180 millions years ago in the northern part of Switzerland (Zurcher Weinland) has been chosen as the favoured host rock for the reference project based on geological investigation including 3D seismic survey and intensive work in a 1000 m deep borehole at Benken. The investigations confirmed the remarkable homogeneity and lateral extent of the Opalinus clay. The host rock formation is approximately 100 m thick. The depth varies between 450 and 850 m. The reference repository is placed at depth of approximately 650 m. Furthermore the results from the Mont Terri underground rock laboratory, international expertise and research as well as various additional boreholes confirmed the suitability of Opalinus Clay as host rock for repositories.

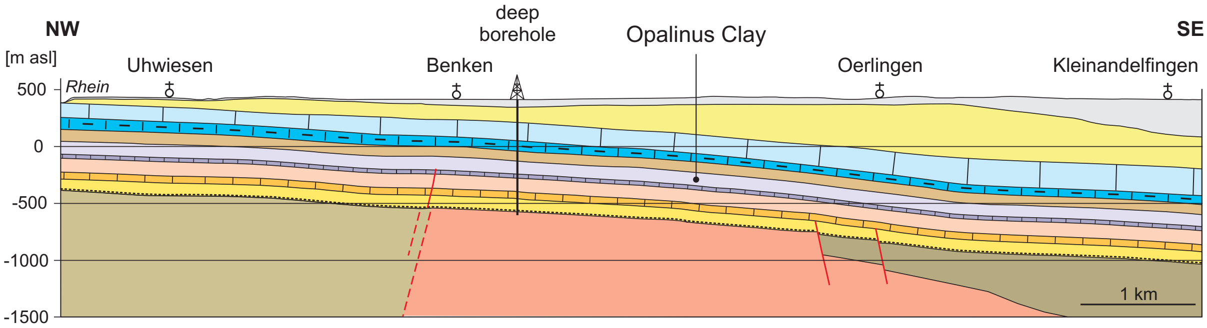


Figure 3: Geological profile Zurcher Weinland

2.3 Repository Concept

The disposal principles and the geological context were taken into account when developing the concept of the repository (Nagra, 2002b). An artist's view of the repository is depicted in **Figure 4**.

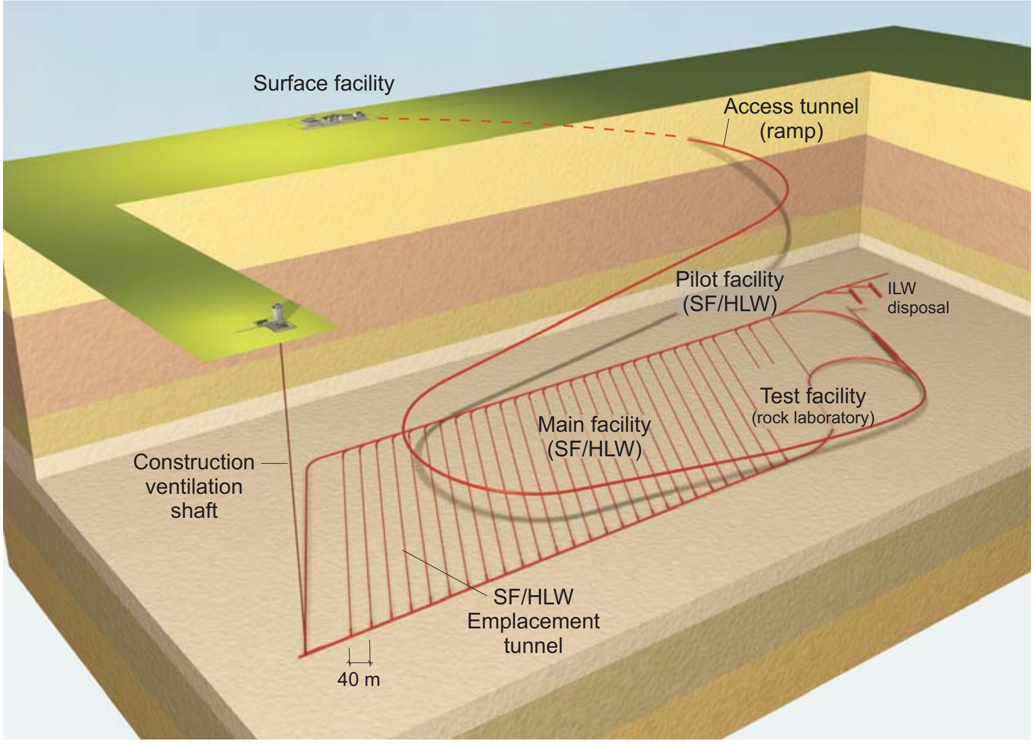


Figure 4: 3-D view on the concept of the SF/HLW repository

The main elements of the repository are the emplacement tunnels within the host rock, several auxiliary underground facilities in order to construct, operate, ventilate, observe and backfill the emplacement tunnels as well as surface facilities for encapsulation and handling the waste and all other infrastructures required to operate and maintain the repository (see **Figure 5**).

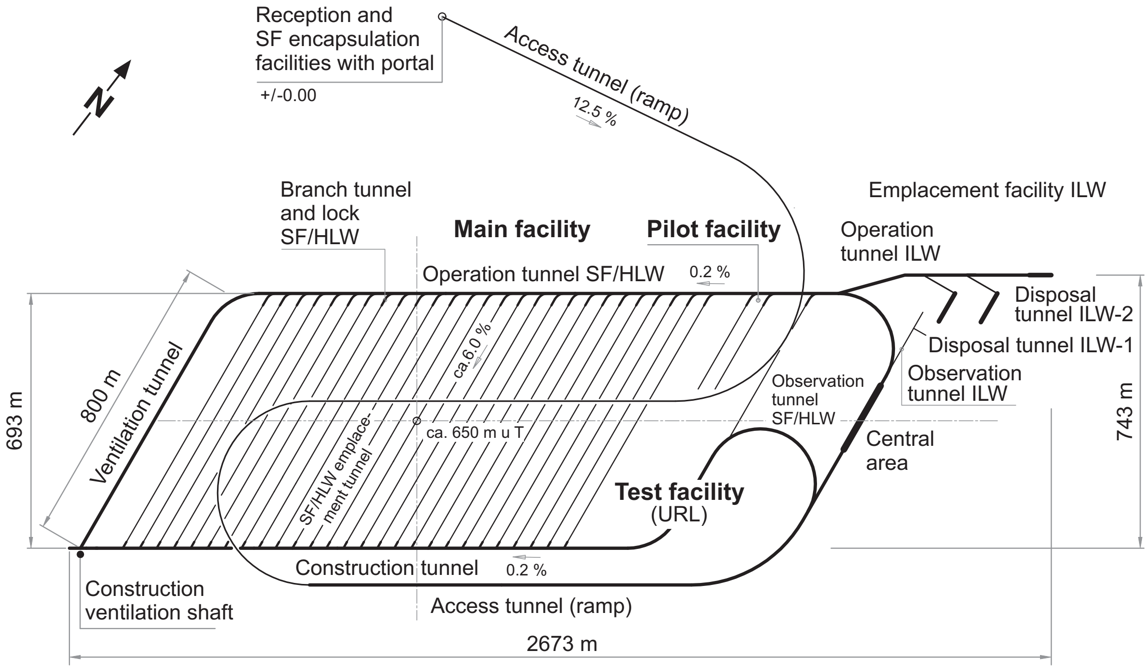


Figure 5: Overview of the underground facilities of the repository for SF/HLW and ILW

The emplacement tunnels are placed in the middle plane of the host rock formation and oriented according to the main horizontal stresses. The former maximises the transport path length, the latter mitigates unfavourable effects due to construction (instabilities, deformation, EDZ). It is obvious that the horizontal emplacement concept represents the most favourable orientation taking into account the limited thickness of the host sedimentary rock.

For the emplacement tunnels, no concrete liner is foreseen in the reference case. This will require favourable (minimally disturbed) host rock conditions, avoiding main stresses perpendicular to the emplacement tunnel axes and minimising time between excavation and backfilling. Instead of a liner a systematic pattern of rock bolts and wire mesh according to **Figure 6** are envisaged. However, for less favourable geotechnical conditions, a liner with shotcrete or by other means is considered as an alternative.

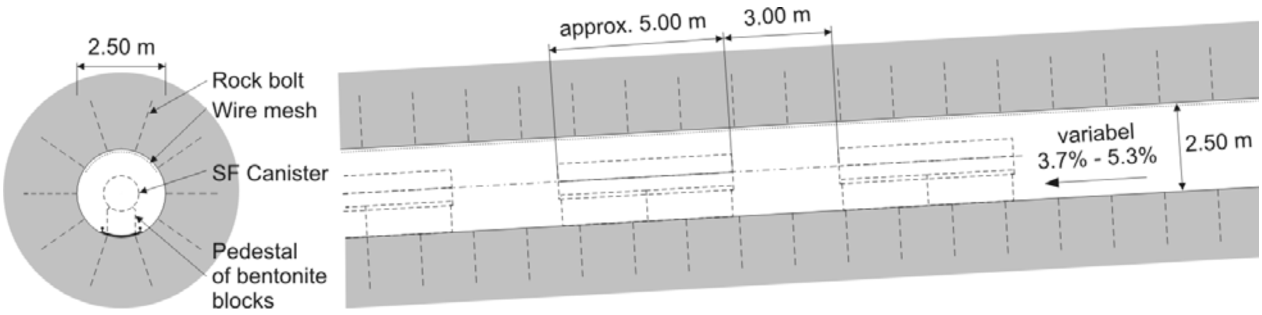


Figure 6: Cross section of emplacement tunnel

The construction of the emplacement tunnel is carried out using an open gripper type hard rock TBM (tunnel boring machine) or road header in a single shield and gripper type device in parallel to the emplacement of nuclear wastes in already excavated tunnels. Access for construction work will be established through the shaft and construction tunnel. This construction section is being partitioned off the operation tunnel and all nuclear activities with respect to ventilation, radiation protection, etc.

The engineered barrier system foresees a massive steel canister (alternatives are possible, e.g. steel insert with copper shell) and a bentonite backfill. The bentonite consists of a hybrid system: the canisters are emplaced on a pre-fabricated pedestal of bentonite blocks and the remainder of the emplacement tunnel is backfilled with a bentonite granulate (alternative materials are possible and also the use of bentonite blocks only is a possibility).

Figure 4 shows that the emplacement tunnels are reached by an access tunnel (ramp) and by a shaft; alternatives such as multiple or inclined shafts are possible. Substantial experience for both access concepts exists from the mining industry. The main reasons to prefer a ramp in the Swiss concept is the possibility to decouple the location of the surface facility from the underground deposition area and the advantages concerning transport of heavy goods.

Underground transport of the waste packages is in the reference case by rail systems using transport casks (shielding) for the disposal canisters. As many as possible of the nuclear transport activities shall be carried out with the transport casks, allowing operators to control and intervene if needed. The section along the ramp is laid out with a maximum inclination of 12.5% which requires a rack-railway system and adequate minimum curves ($R \geq 250$ m). Alternative transport systems e.g. electric driven transfer vehicle on wheels are possible which would allow spiral like access ramps with significantly smaller curves.

The emplacement is done by specially designed equipment that allows remote handling. Backfilling of the emplacement tunnels is also performed by remote handling. All of the emplacement equipment is on rail tracks and is powered by electric drive and winches since the emplacement tunnels are inclined between 4 and 6% according to the sub-horizontal host rock layer. The following figures illustrate the emplacement sequence:

- Transfer from surface to the repository level is carried out by common rack locomotives. In the central area at repository level the wagon carrying the transport cask (shielding) is shunted to a tunnel locomotive (**Figure 7, left**);
- A pedestal of bentonite blocks is positioned on the emplacement trolley at the enlarged branch tunnel of each emplacement tunnel (**Figure 7, right**). The branch tunnel is equipped with double track and a lock;
- The transport cask with a waste canister is positioned beside the emplacement trolley. After all preparations are completed operators leave the lock. All the subsequent activities will be carried out using remote operations. The canister is now pushed off the transport cask by the hydraulic device 1 (hydraulic wagon) and moved to the emplacement trolley by the transload equipment (**Figure 7, right**).

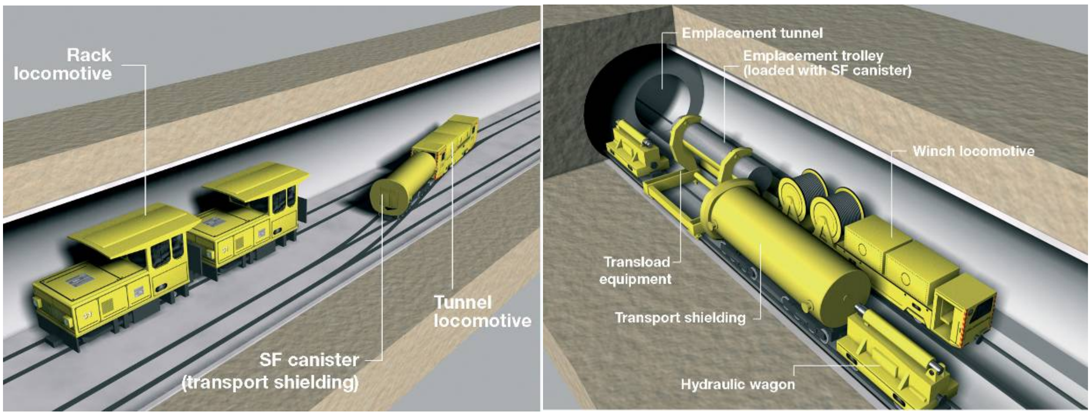


Figure 7: Emplacement of SF-Canister – Start niche and lock to the emplacement tunnel (schematic)

- The emplacement trolley is driven by gravity and controlled by a winch locomotive within the lock up to the emplacement position (**Figure 8, left**). At emplacement position pedestal and canister are lowered subsequently and the emplacement trolley is pulled back to the lock
- After a waste canister has been emplaced, the remaining tunnel is backfilled with bentonite granulate using twin augers and a wagon which is pulled back continuously by winches while backfilling (**Figure 8, right**).

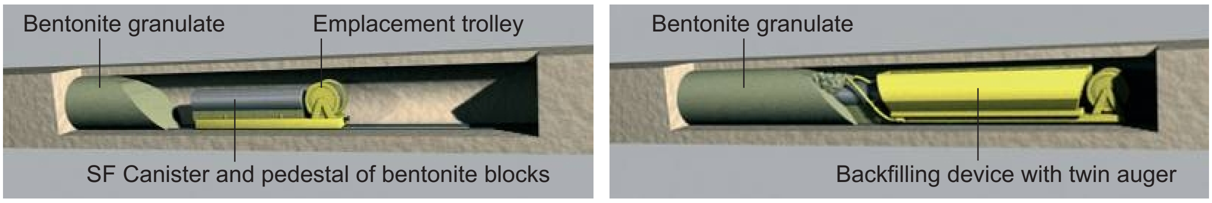


Figure 8: Emplacement trolley with spent fuel canister at emplacement position (left); Wagon emplacing bentonite granulate in disposal tunnel after a waste canister has been emplaced (right)

According to the concept of the “monitored long-term geological disposal”, closure of the repository is foreseen in a stepwise manner: in the first phase (during normal operation), all emplacement tunnels are backfilled and sealed in conjunction with emplacing the waste canisters (see **Figure 9, left**). After a period of monitoring, the access tunnels to the emplacement tunnels are backfilled; now only the pilot facility and the test facility are still accessible (see **Figure 9, right**). After a longer period of monitoring, eventually, the remaining open tunnels will be backfilled and sealed; now only the observation facilities to monitor and control the pilot facility and the test facility are still accessible. Then long-term monitoring from the surface will continue.

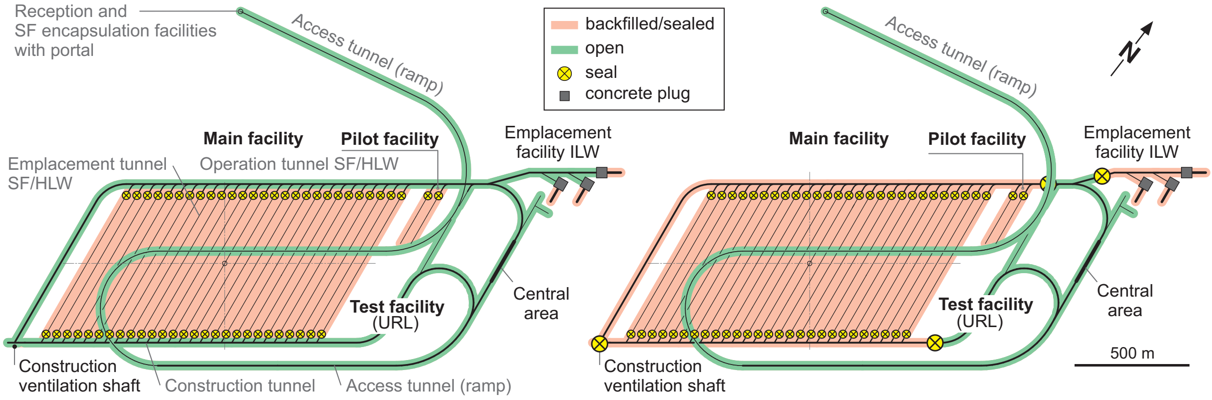


Figure 9: Left: Situation after emplacement of waste is completed and all emplacement tunnels are sealed. Right: Situation after main repository facility is closed and sealed and only the pilot and test facility are accessible during a longer period of monitoring

3 Nagra Working Programme

The following paragraphs list some examples of recent and ongoing work within Nagra’s working programme.

In order to be able to cope with the possibility of less favourable geotechnical conditions, Nagra has started some work on the use of shotcrete as liner for emplacement tunnels. Because the high pH-fluids from ordinary cement will interact with clay minerals (abundant in the bentonite backfill and also in the Opalinus clay) efforts were made with a so-called low-pH shotcrete. Preliminary experiments in an underground test facility (Hagerbach Test Gallery, Switzerland) were successful (Nagra, 2007a) and more tests are planned within the underground research laboratory at Mont Terri in the context of a mine-by test.

Because of its favourable properties with respect to emplacement, bentonite granulate is used in Nagra's reference concept. Although small-scale laboratory experiments were performed several years ago, a large scale (1:1.25) was felt to be advantageous to improve confidence that the required dry density of emplaced bentonite granulate can actually be reached. Within the EC-supported project ESDRED such an experiment was performed (**Figure 10**). The results are very promising as the required densities could be reached reliably (Nagra, 2007b).

Figure 10: Experiment testing the emplacement of bentonite granulate

One of the priorities in Nagra's RD&D program is the investigation of high temperature (> 100°C) effects on the bentonite buffer. The motivation for this stems the fact that rather high peak temperatures resulting from decay heat up to 160°C at the canister/buffer interface are expected in the current HLW repository concept. A broad international research program has been started to investigate the effects of high temperatures on the barrier properties of bentonite. The program includes in situ experiments at the Swedish underground research laboratory in Äspö, the investigation of thermal effects in natural analogues, small scale laboratory experiments and evaluation of alternative buffer material.

Studies on the development of canisters for SF and HLW presently include materials review aspects and technology assessment studies. An international review board of distinguished corrosion specialists is providing input on the corrosion behaviour of various canister materials, principally carbon steel and copper, and advice regarding appropriate future studies in relation to corrosion and other materials degradation processes. Critical reviews of hydrogen affects in steel and welding and stress relief will be performed over the next few years, in preparation for new design studies for canisters.

Other work is underway or planned and includes a re-evaluation of waste handling, especially in the surface facilities. Furthermore, work on the detailed layout of the underground structures is ongoing; this includes an evaluation of the cross-sections of the different tunnels, alternatives concerning architecture of the underground facilities in order to cope with differing host rock conditions and some more detailed design calculations on the ventilation system taking into account the climatic conditions in varying depths.

Further to this work related to design of the repository, Nagra is conducting a broad programme related to improving process understanding for key geological and geochemical aspects, including gas transport and radionuclide retention and immobilisation.

4 Summary and conclusions

The presented repository concept for SF/HLW represents the reference layout and concept for the Opalinus Clay project demonstrating disposal feasibility. The main objective was to prove the constructability of a safe repository for SF/HLW in Opalinus Clay with overburden of more than 600 m and to establish confidence in implementation taking into account all requirements in particular derived from the performance assessment (safety case) although the construction of the URL at the repository site is not expected to be launched before 2020. The main challenges from an engineering point of view have been:

- the rather unfavourable rock mechanical conditions (high overburden, low strength, swelling capacity) and the limited thickness together with sub-horizontal layers of Opalinus Clay;
- restrictions and limitations concerning rock support measures for emplacement tunnels;
- need for long-term durability and integrity of the access facilities due to the requirement for long monitoring phases;
- need for robust sealing constructions in relation to retrievability;
- demanding nuclear safety and security standards.

Taking into consideration the site selection process for repositories within the framework of existing land-use planning legislation, the need for robust and flexible repository concepts or modules respectively raises the need to develop alternative elements of the repository facility.

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