waste management programme

an insight into our work

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Waste Management Programme – an insight into our work
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Maria Schmid

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Nagra
National Cooperative for the Disposal
of Radioactive Waste
Hardstrasse 73, PO Box 280, CH-5430 Wettingen
Phone 056 437 11 11
Fax 056 437 12 07
E-mail info@nagra.ch
Internet www.nagra.ch
Blog www.nagra-blog.ch

Waste Management Programme – an insight into our work

Key points in brief

- The 2016 Waste Management Programme prepared by Nagra on behalf of the waste producers describes in detail how the disposal of all radioactive waste arising in Switzerland is being planned and implemented.

- The radioactive waste will be disposed of in deep geological repositories. Multiple passive safety barriers provide long-term protection of humans and the environment.

- The Waste Management Programme provides an overview of all the activities involved, from interim storage to the planning, construction, operation and closure of the deep geological repositories.

- The Sectoral Plan for Deep Geological Repositories regulates the search for disposal sites in Switzerland; the process is led by the Federal Government.

- Before the waste can be emplaced in the repositories, Nagra has to go through a lengthy licensing procedure at federal level, including general, construction and operating licences.

- Demonstrations of the feasibility of disposal for all waste types have been approved by the Federal Council and confirm that deep geological repositories can be constructed in Switzerland.

- Nagra has a solid scientific-technical knowledge base. The waste disposal concept is based on fundamental questions that have already been answered and the way forward will bring further optimisation.

- Nagra's research and development activities aimed at further optimisation are presented in the 2016 Research, Development and Demonstration Programme.

Waste Management Programme

Nagra prepares the Waste Management Programme on behalf of the waste producers. It outlines the work steps to be taken on the way to realising the disposal of all the radioactive waste arising in Switzerland. The Programme has to be presented to the federal authorities and updated every five years.

Purpose of the Programme

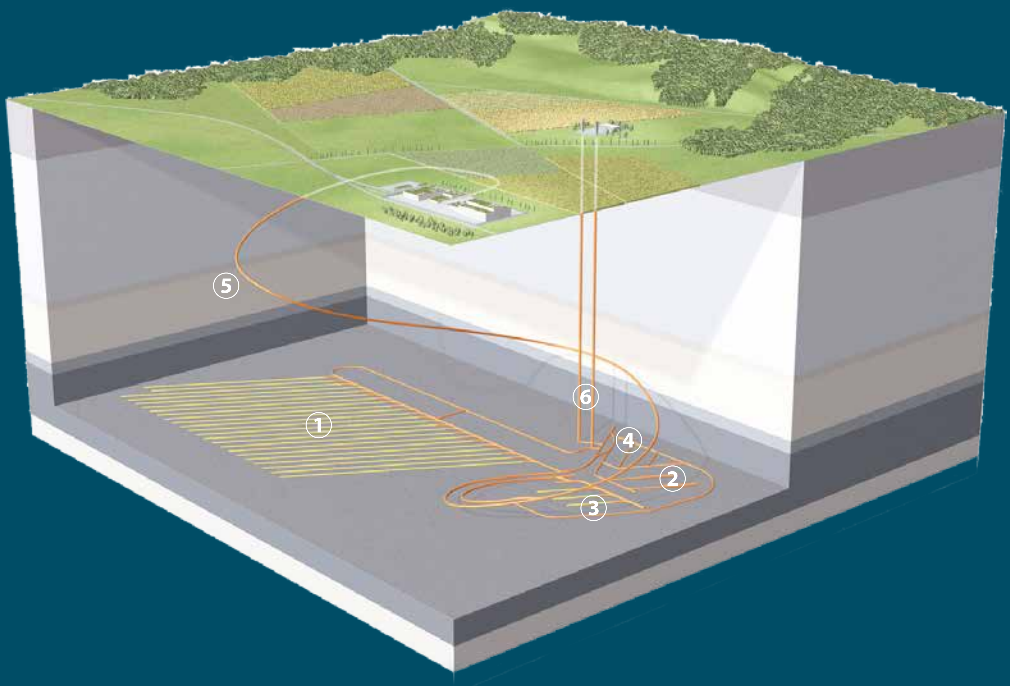
The 2016 Waste Management Programme describes Nagra´s waste disposal concept and documents the basic procedures involved in planning, constructing, operating and closing the deep geological repositories. It provides a framework for the long-term planning of the disposal facilities and indicates what decisions have to be made and when, what information they are based on and how this information is obtained. The first Waste Management Programme prepared by Nagra on behalf of the waste producers was submitted to the federal authorities in 2008 and approved by the Federal Council in 2013. In 2016, the waste producers were required to submit the updated Waste Management Programme together with the 2016 Research, Development and Demonstration Programme (RD&D Programme or RD&D Plan, see pages 22 and 23) and a Cost Study. Responsibility for the Cost Study lies with swissnuclear.

Content of the Programme

The Waste Management Programme contains information on:

- The origin, types and volumes of radioactive waste
- The deep geological repositories, including their design concept
- The allocation of the waste to the repositories
- The implementation plan for the repositories
- The duration and required capacity of centralised and decentralised interim storage
- The financial planning for waste management activities up to the shutdown of the nuclear facilities, with information on the work to be

Deep geological repository for high-level waste



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performed, the amount of the costs and the type of financing
- The public information strategy

Origin, types and volumes of waste

In Switzerland, radioactive wastes and materials arise from the production of nuclear energy in nuclear power plants and from applications in the areas of medicine, industry and research. The Nuclear Energy Ordinance defines three waste categories:

- **High-level waste (HLW)** comprises spent fuel assemblies (SF) that are not destined for further use and vitrified fission product solutions from the reprocessing of spent fuel.
- **Alpha-toxic waste (ATW)** is waste with a concentration of alpha emitters in excess of 20,000 becquerels/g of conditioned waste.
- **Low- and intermediate-level waste (L/ILW)** is all other radioactive waste.

The waste is continuously conditioned, characterised and inventoried for interim storage or deep geological disposal. Predictions of future waste volumes are made by Nagra based on a model inventory. The scenario with the largest waste volumes assumes 60-year operation for the Beznau, Gösgen and Leibstadt power plants and 47 years for the Mühleberg power plant (see table on page 8). This takes into account expected new provisions in the revised Radiological Protection Ordinance.

Deep geological repositories and waste allocation

Radioactive waste has to be managed safely on the long term without presenting any hazard to hu-

Read more

www

The 2016 Waste Management Programme (NTB 16-01, in German with an extended English summary) can be downloaded from our website www.nagra.ch.

Deep geological repository

Radioactive waste in Switzerland will be disposed of in deep geological repositories. These consist of facilities at the surface and underground.

Components of a deep geological repository for high-level waste

① **Main facility for SF/HLW:** emplacement drifts for spent fuel assemblies and high-level waste

② **ILW facility:** emplacement rooms for long-lived intermediate-level waste such as alpha-toxic waste

③ **Pilot facility:** short drifts in the repository where representative radioactive waste is emplaced and observed during the entire operational and monitoring phase

④ **Test area:** this is used to verify the data required for repository operation

⑤ **Access tunnel:** access from the surface facility to the deep disposal level; access via a shaft is also possible

⑥ **Ventilation shaft and construction shaft:** shafts for the construction and ventilation of the repository mans and the environment. Only deep geological disposal can fulfil the strict safety requirements that have to be met. The legislation in Switzerland calls for deep geological disposal and, in principle, the waste has to be disposed of in Switzerland.

Nagra's two demonstrations of the feasibility of disposing of L/ILW and HLW were approved by the Federal Council and confirm that constructing the repositories is technically feasible. L/ILW and HLW have different properties and have to be disposed of in separate emplacement rooms. These could be constructed at two different sites or realised as a so-called combined repository at the same site.

The design of a deep geological repository, i.e. the layout and arrangement of the facilities, is determined by the types and volumes of waste for disposal, the tailored safety concept, the monitoring of the repository and requirements for possible retrieval of the waste. A suitable disposal site must have sufficient space for accommodating the repository facilities at the preferred disposal depth. The Opalinus Clay host rock in which the emplacement rooms will be constructed has to be sufficiently thick and have intact barrier properties. The waste is contained by multiple safety barriers.

Implementation plan for waste disposal

Nagra has prepared implementation plans for the L/ILW and HLW repositories (see page 18). These set out the work that has to be carried out up to the time of closure of the repositories and describe the basic workflow. The framework for these time plans is provided by legal and regulatory requirements and the waste disposal concept. The time estimated for the licensing procedures and the work to be performed by Nagra are also taken into account. Following the general licence procedures, Nagra will have to submit applications for construction and operating licences. Nagra's implementation plan assumes that a valid general licence will be granted around 2031, with the start of operation of the L/ILW repository in 2050 and the HLW repository in 2060.

		Origin							Total
		SF (NPP)	WA (NPP)	BA (NPP)	RA (NPP)	SA (NPP)	MIR	BEVA	
Category acc. to NEO	HLW	1 357 (8 995)	114 (398)				8 (8)		1 479 (9 402)
	ATW		99 (414)			24 (24)	168 (634)		291 (1 072)
	L/ILW			8 326 (31 271)	478 (1 811)	18 839 (27 366)	14 222 (19 010)	651 (2 302)	42 516 (81 760)
	Total	1 357 (8 995)	213 (812)	8 326 (31 271)	478 (1 811)	18 863 (27 390)	14 398 (19 652)	651 (2 302)	44 286 (92 234)

Volumes of radioactive waste
Maximum expected volumes of conditioned radioactive waste and volumes of conditioned waste packaged in disposal containers (numbers in brackets). All numbers in cubic metres.

Interim storage of the waste

Waste already produced from the nuclear power plants (operational waste, including reactor waste) is held in on-site interim storage facilities or in the ZWILAG centralised interim storage facility in Würenlingen. These have sufficient capacity for all the radioactive waste from the Swiss nuclear power plants, including future decommissioning waste from dismantling (see table below). Waste from medicine, industry and research (MIR) destined for deep disposal is stored in a facility in Würenlingen operated by the Federal Government. An extension of this facility is planned to ensure sufficient storage capacity for all the MIR waste up to 2065.

Financial planning

According to the nuclear energy legislation, the polluter pays principle applies to the decommissioning of nuclear facilities and disposal of the radioactive waste from these facilities. The owners of the nuclear facilities are thus responsible for their decommissioning and disposal and must bear the full costs. In order to cover the costs arising after the shutdown of the facilities, the owners make annual payments into the Decommissioning and Waste Disposal Funds. These Funds are supervised by the Federal Government (see www.stenfo.ch). The waste disposal costs arising before shutdown are paid directly by the owners. The anticipated costs of decommissioning and disposal are recalculated every five years in a Cost Study (see table on page 10), which is used by the Federal Government as the basis for calculating the amount of the contributions to be paid into the Funds. In order to quantify the waste disposal project costs as accurately as possible, Nagra makes plausible exemplary assumptions that go beyond

Abbreviations

ATW	= alpha-toxic waste
BA	= operational waste from the NPPs and ZWILAG
BEVA	= waste from the operation and later decommissioning of the encapsulation plants and disposal of the transport and storage casks for SF
HLW	= high-level waste
L/ILW	= low- and intermediate-level waste
MIR	= medicine, industry and research
NEO	= Nuclear Energy Ordinance
NPP	= nuclear power plant
RA	= reactor waste from the NPPs
SA	= decommissioning waste from the NPPs and ZWILAG
SF	= spent fuel assemblies
WA	= waste from reprocessing of SF
ZWILAG	= centralised interim storage facility for NPP waste

Conditioning radioactive waste

Conditioning is defined as the activities carried out to prepare radioactive waste for interim storage or final disposal in a deep geological repository. These include mechanical chopping, decontamination, compaction, incineration, embedding in low-solubility glass or cement and appropriate packaging of the waste.

the current state of planning. This does not pre-empt any decisions that will be made during the course of the ongoing site selection process for the repositories or the subsequent licensing procedures.

Information strategy

The aim of Nagra´s public outreach activities is to inform the public about its work, ongoing projects and the results of its investigations, as well as the later construction and operation of the repositories. The reasons why radioactive waste disposal is necessary and why the waste will be disposed of on the long term in deep geological repositories are presented transparently. Society should be able to form an objective opinion and be aware of and understand the roles of the different actors in the process (see pages 16 and 17).

Sound knowledge base available

The fundamental aspects of Nagra's waste disposal concept have already been clarified and a sound scientific-technical knowledge base exists. The waste producers have also been able to build up practical experience in many areas of waste management over the years.

Stepwise approach leading to final goals

Nagra has to go through lengthy licensing procedures before the waste can be disposed of in the repositories. During this period, Nagra will further optimise its concepts, refine its knowledge and reduce remaining uncertainties (see pages 20 and 21). The work areas are defined in the 2016 RD&D Programme.

In parallel, Nagra will also continue to work on the ongoing site selection process. The input will be used by the Federal Government in the licensing procedures as a basis for the siting decision.

Topics	**Costs**
Reprocessing	2 762
Interim storage (ZWILAG), incl. centralised waste conditioning	2 686
ZWIBEZ and KKG wet storage facilities	156
Acquisition of transport & storage casks for SF/HLW	1 096
Transports	299
L/ILW repository	3 361
HLW repository, incl. encapsulation plant for SF/HLW	7 630
Total waste disposal	17 990
Decommissioning of NPPs and interim storage facilities	3 406
Total	**21 396**

Total costs of waste disposal and decommissioning
Amounts in millions of Swiss Francs; price basis 2016. The costs include outgoings already paid and outgoings to be paid via the Funds. Disposal costs for MIR waste are not presented. See also Table 7-1 in the 2016 Waste Management Programme. ZWIBEZ: interim storage facility at the Beznau NPP, KKG: Gösgen NPP

The general licence applications (see box below) prepared by Nagra present the main features of the project. Concrete planning details are required only in later licensing steps. The knowledge base must be sufficient to allow the necessary decisions to be made. This stepwise procedure, which allows variants to be kept open, is characteristic of the approach in many countries besides Switzerland. It ensures that there is sufficient flexibility to allow future information (results of detailed site investigations, advances in knowledge through R&D) or changes in the legal boundary conditions to be taken into account. Nagra can also benefit from advances in other waste management programmes.

The detailed design and layout of the facilities only have to be available at the stage of the construction licence. Considerable technological advances in underground engineering and automation of waste handling procedures are expected before the start of construction and these can be integrated into the disposal technology. Demonstrating the retrieval of the waste from the repository will also benefit from this. Up to the stage of the operating licence, Nagra has to demonstrate by means of experiments at the repository site that its concept is fully functional, in particular the emplacement of the waste.

Review of the Waste Management Programme

The Swiss Federal Nuclear Safety Inspectorate (ENSI) and the Swiss Federal Office of Energy (SFOE) review the Waste Management Programme and the RD&D Programme submitted by Nagra at the end of 2016. The Nuclear Safety Commission (NSC) will submit its review thereafter. The public consultation phase is expected for the middle of 2018 and the decision of the Federal Council on the two programmes is expected for the beginning of 2019.

What is a general licence?

Deep geological repositories are nuclear facilities and therefore require a general licence from the Federal Council. The licence applications to be submitted by Nagra describe the main features of the facilities at the proposed sites at a level appropriate for this licensing stage. The licence specifies the site and defines the size and approximate location of the main installations. Detailed descriptions of the facilities and the processes and technologies involved are a matter for the later construction and operating licences.

Safety has top priority

According to the Nuclear Energy Act, radioactive waste has to be disposed of in a way that ensures the long-term protection of man and the environment. This means disposal in deep geological repositories, isolated from our human habitat. Safety has the highest priority in the site selection process, as well as in the planning, construction and operation of the repositories.

Protection provided by safety barriers

A repository will be constructed at the 'best' site. Several successive engineered and geological safety barriers provide reliable containment of the waste in the repository. The role of the barriers is to protect the waste from impacts that would compromise safety and to retain the radionuclides in the repository until they have decayed to natural levels. To ensure the best possible protection, Nagra matches the design of the repository facilities and the technologies for its construction, operation and closure with the geology and the host rock.

The engineered barriers include the waste matrix, the disposal container and the backfilling of the HLW emplacement drifts with bentonite and the L/ILW emplacement caverns with cement mortar (see images below). All the waste is transported to the repository in a solid, low-solubility form, e.g. immobilised in cement or glass (waste matrix).

In the Swiss safety concept, the geology provides long-term stability and contributes significantly to the retention of radioactive materials in the repository. Deep beneath the earth's surface there are rock layers that remain stable for many millions of years, retain their properties and are thus suitable as a geological barrier for isolating the waste. In Switzerland, the emplacement drifts and caverns of the repository will be constructed in a very low permeability Opalinus Clay host rock. The formation is around 175 million years old.

The Opalinus Clay has a very low permeability. In Switzerland it represents the geological safety barrier for the L/ILW and HLW repositories.

A concrete disposal container filled with cement mortar contains the waste drums and forms one of the engineered safety barriers of the L/ILW repository.

What level of safety can be achieved?

Nagra has to prepare a safety demonstration for submission of the general, construction and operating licence applications. This has to show that realising a repository is feasible from the viewpoint of engineering, that it can be operated safely and offers protection over long timescales. It also defines the degree of safety that can be achieved and highlights open questions and uncertainties. In this way, Nagra can show compliance with the safety requirements set out by the authorities. Ongoing optimisation of the safety-relevant aspects will further increase the level of safety. ENSI requires such optimisation to be carried out.

Safe repositories can be constructed

Nagra has already carried out safety demonstrations, for example the two feasibility demonstrations ('Entsorgungsnachweise') for L/ILW and HLW that were approved by the Federal Government in 1988 and 2006 respectively.

The safety analyses conducted within the context of the ongoing search for sites have confirmed that safe repositories that comply with the regulatory protection objectives and criteria can be constructed in Switzerland. The maximum additional radiation dose to the population that arises from a repository may not exceed 0.1 millisieverts per year (protection criterion, ENSI Guideline G03). This corresponds to around one-fiftieth of the average annual radiation dose that a person in Switzerland is exposed to today.

A repository can only be closed when it has been shown that it is passively safe. It then fulfils its safety function without any need for monitoring of the waste or for human intervention. If passive safety cannot be demonstrated, the waste has to be retrieved from the repository.

Granulated bentonite can take up water, causing it to swell. As a tunnel backfill, it represents one of the engineered safety barriers of the HLW repository.

Model of a partly backfilled emplacement drift of a HLW repository: the disposal canister containing the spent fuel assemblies rests on a bentonite pedestal.

40 years of Nagra experience

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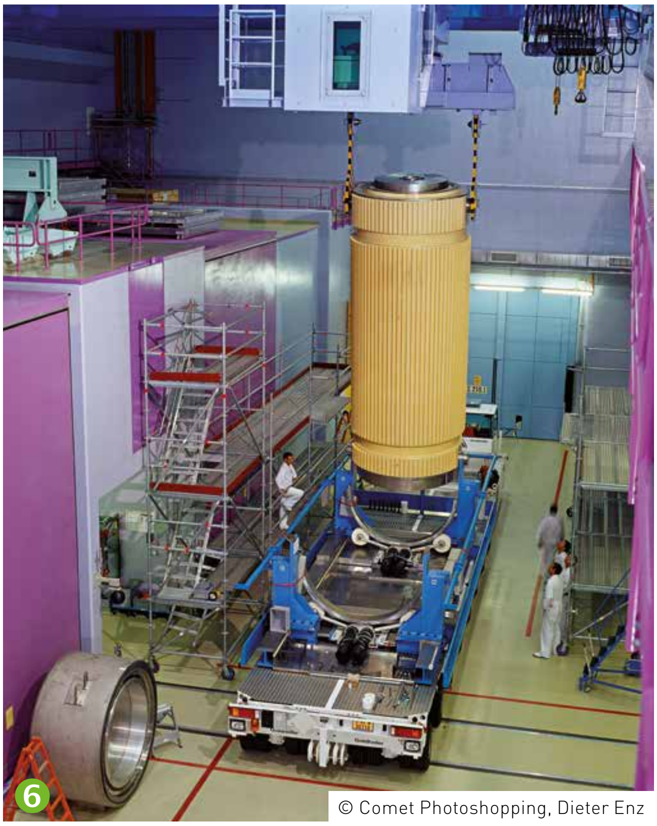
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1. Nagra deep drilling programme in Northern Switzerland (Schafisheim)
2. Boreholes for the feasibility demonstration for L/ILW disposal (Oberbauenstock, 1986/87)
3. Exploratory borehole (Wellenberg, 1992/93)
4. 3D seismics for the feasibility demonstration for HLW disposal (Weinland ZH, 1996/97)
5. Investigating gas flow (Grimsel Test Site, 2000/01)
6. Castor transport to the interim storage facility (Würenlingen, 2008)
7. Geophone array for 2D seismics (Jura Ost siting region, 2012)
8. Surveying work for 3D seismics (2015/16)

Where are we now?

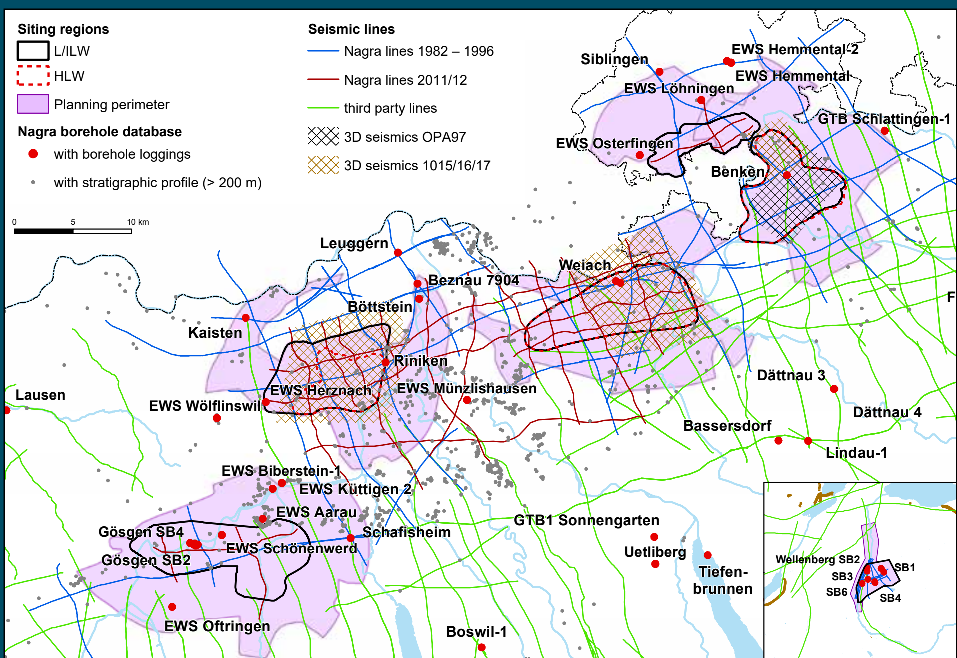
The search for sites for deep geological repositories is carried out according to the Sectoral Plan for Deep Geological Repositories led by the Federal Government. Nagra investigates the geological conditions and provides the basis for decision-making by the Federal Council.

Search for the 'best' site

In order to find the most suitable site for a repository in Switzerland, the underground geological environment has been investigated systematically using methods such as seismics and exploratory boreholes. Ongoing and future investigations will further strengthen Nagra's knowledge base.

Sectoral Plan regulates the site selection process

Site selection takes place in three stages as specified in the Sectoral Plan for Deep Geological Repositories. Knowledge increases from stage to stage, leading to a narrowing-down of the siting regions that come into question for constructing a repository. At the end of the process, one site will be selected for HLW and one for L/ILW or a single site for the two waste types (combined repository). The roles of the different actors in the Sectoral Plan process are clearly defined. In each stage, Nagra prepares the necessary scientific and technical groundwork for its siting proposals; these are submitted to the Swiss Federal Office of Energy (SFOE), which has the lead in the process. ENSI – as the regulatory authority – and the Expert Group on Nuclear Waste Disposal (EGT) review the siting proposals. Decisions are made by the Federal Council, which is supported by the Nuclear Safety Commission (NSC). The SFOE is supported by the Federal Office for Spatial Development (FOSD) and the Federal Office for the Environment (FOEN). It also secures the right of the regions to be heard in the process within the context of regional participation.



Investigating the underground geological environment of Switzerland using seismics and exploratory boreholes.

Results from Stage 1

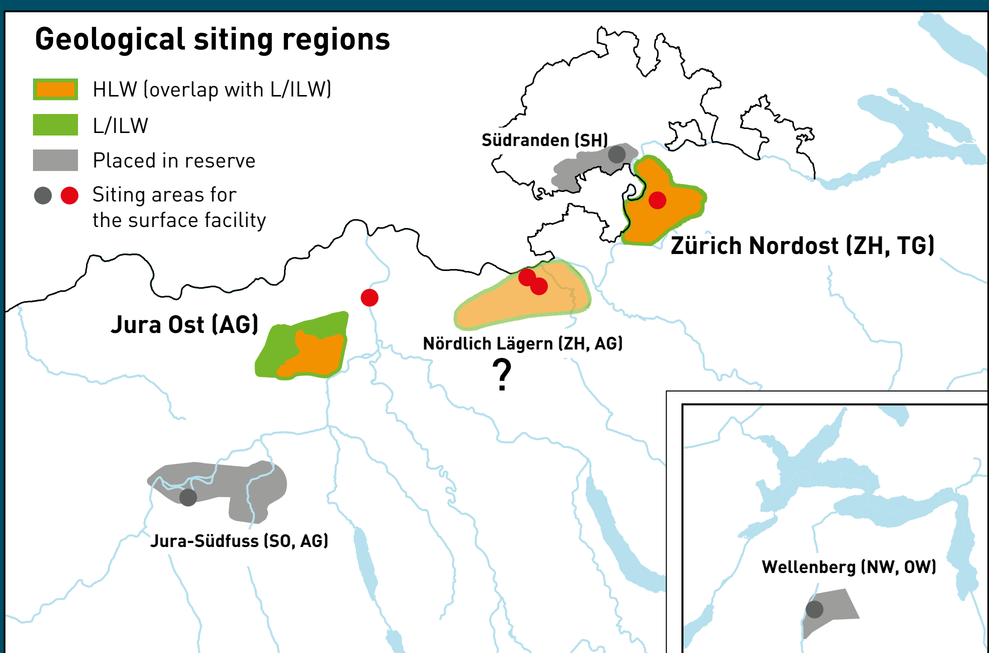
In Stage 1 (2008 to 2011), Nagra proposed potential siting regions based on legal and regulatory requirements and on the safety criteria specified by ENSI. For a HLW and L/ILW repository these were Zürich Nordost, Nördlich Lägern and Jura Ost; in addition Südranden, Jura-Südfuss and Wellenberg were proposed for a L/ILW repository. Following a detailed review, the Federal Council decided at the end of 2011 that all six regions should remain in the process.

Results from Stage 2

In Stage 2, Nagra acquired a more profound understanding through experiments in the underground rock laboratories and investigation of the geology in the siting regions – for example with seismic measurements. A provisional safety analysis was prepared for each siting region and these were compared with one another. Following the safety-based comparison, at the beginning of 2015 Nagra proposed the siting regions Zürich Nordost and Jura Ost for further investigation in Stage 3; Nördlich Lägern, Südranden, Jura-Südfuss and Wellenberg were to be placed in reserve. The Opalinus Clay was also proposed as the only host rock and, working together with the regions, at least one siting area for the surface facility of a repository was identified in each region.

Additional documentation submitted

In summer 2016, Nagra had to submit additional documentation on its siting decision to ENSI. This related mainly to the safety and engineering feasibility of a repository constructed at greater depth in the Opalinus Clay and is relevant for the question to be evaluated by the federal authorities regarding whether the siting region Nördlich Lägern should be carried forward to Stage 3. ENSI responded to Nagra's proposals in spring 2017. The decision of the Federal Council will follow after a period of open consultation and is expected for the end of 2018.



In Stage 2, Nagra proposed the siting regions Zürich Nordost and Jura Ost for further investigations in Stage 3; this proposal was based on geological investigations and the results of a safety-based comparison.

What happens next?

The siting regions remaining in the process will be investigated in more detail in Stage 3 of the Sectoral Plan process. This will be followed by the general licence procedures and then the applications for the construction and operating licences.

3D seismics and exploratory boreholes

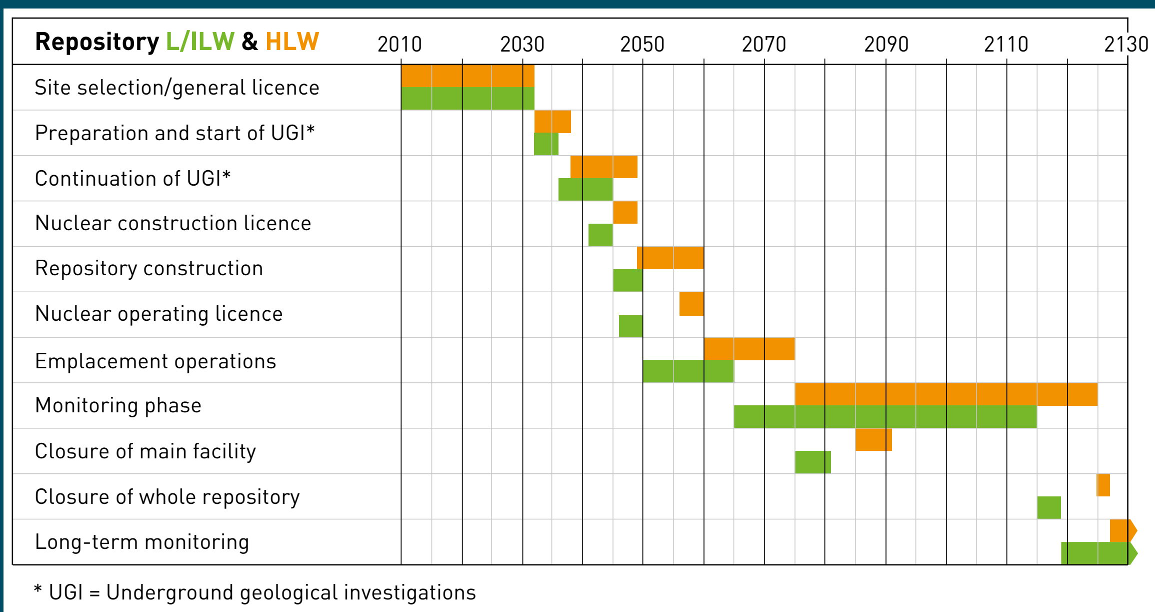
In Stage 3, Nagra will investigate the geology of the remaining siting regions using methods such as 3D seismics and exploratory boreholes. The 3D seismic measurements provide a spatial image of the underground rock layers. Seismic surveys were already carried out with a view to Stage 3 in the Zürich Nordost and Jura Ost regions in winter 2015/16. To be prepared for every eventuality and avoid potential delays, 3D seismic measurements were also carried out in Nördlich Lägern from October 2016 to February 2017.

Exploratory boreholes provide detailed data on the host rock properties and water-bearing strata and are used to calibrate seismic measurements. The boreholes require a permit from the Federal Department of the Environment, Transport, Energy and Communications (DETEC). To allow Nagra to start with drilling work after the decision of the Federal Council on Stage 2, which is expected for the end of 2018, applications were already submitted to DETEC for Zürich Nordost and Jura Ost in September 2016. Preparations have begun for applications for Nördlich Lägern.

Next target: general licences

The plans for realising the L/ILW and HLW repositories (see below) make it clear that Nagra has to go through a three-stage licensing procedure before it can emplace radioactive waste in a deep geological repository.

The general licence procedures are the first step in the process. Following analysis of the results from the 3D seismic campaigns and the exploratory boreholes, Nagra will propose the best suited



Timetable for realising the L/ILW and HLW repositories based on current planning.

(in terms of safety) repository sites around 2022. Applications for general licences will be prepared for these sites and submitted around 2024. The Federal Council and Parliament will then decide on the applications following a review by the safety authorities. The parliamentary decision is subject to an optional national referendum. If this option is taken up, the Swiss voters will decide on the general licence applications (around 2031). Once the general licences have been granted, it will be clear where the L/ILW and HLW repositories will be constructed. Safety-relevant aspects will then be verified through underground geological investigations in exploratory tunnels and shafts. Preparations will also begin for the applications for the construction and operating licences for the repositories.

Site of the Weiach exploratory borehole drilled by Nagra in 1983.

Handling uncertainties

The fundamental aspects of Nagra's waste disposal concept have already been clarified. However, some aspects still contain uncertainties and these are handled by making conservative assumptions. These uncertainties can be further reduced by targeted research and development work – there is sufficient time for this.

Irina Gaus, Project Coordinator Research & Development, explains in an interview how Nagra handles uncertainties.

How can a deep geological repository be optimised?
Irina Gaus: We have to define the safety-relevant functions of each component of a deep geological repository and the requirements they have to fulfil. Up to the stage of the operating licence, we have the possibility to go into greater detail until all the repository components, processes and technologies are recorded. We also require this information for optimisation purposes. The repository components will be constructed later in such a way that they fulfil the requirements. The better the requirements are fulfilled, the more robust a repository is against adverse influences.

How do you deal with uncertainties?
We have identified the remaining uncertainties in our waste disposal concept and are addressing these in our Research, Development and Demonstration Programme. In general, uncertainties and their potential impacts are covered by using a conservative approach with sufficiently large safety reserves. However, the multi-stage licensing process gives us sufficient time to further reduce these uncertainties through research and development. More accurate knowledge means a lower level of uncertainty that has to be addressed by making conservative assumptions. There are no longer any major uncertainties with regard to submitting the general licence applications.

Are there different types of uncertainties?
There are three different types: firstly potential uncertainties that we can avoid. Secondly, poten-

The backfilling machine is a good example of ongoing optimisation. Practical experience has shown that bentonite can be emplaced homogeneously in a tunnel using five screw conveyors. This was not always the case with previous emplacement techniques.

"With our targeted research and development work, we can optimise the safety of the Swiss repositories even further."

Irina Gaus, hydrogeologist
Project Coordinator Research & Development

tial uncertainties that cannot be avoided, but their impacts can be handled with additional development and engineering work. Thirdly, there are uncertainties that cannot be completely avoided or their impacts fully mitigated.

How do you handle the first type of uncertainty?
A forward-looking site selection process, an appropriate disposal concept and selection of tried-and-tested technologies and materials already allow us to achieve a high level of safety. In selecting the site for the HLW repository, for example, we have ruled out the Alps where the uplift rates are high. Or we avoid using materials in the repository that could have a negative effect on the safety barriers.

Why is the formation of hydrogen gas in a repository an uncertainty of the second type?
Because gas formation due to corrosion of the steel disposal canisters cannot be avoided. However, we have gas formation and removal under control: in a repository gas flows along the tunnel walls. By installing gas-permeable seals we can remove the gas directly through a backfilled tunnel and further minimise the potential risk. The production of decay heat from spent fuel assemblies is also inevitable. However, with appropriate spacing of the disposal canisters in the emplacement drifts and between the drifts themselves, the Opalinus Clay is capable of absorbing the heat without compromising its containment capability.

How do you approach the third type of uncertainty?
For this type of uncertainty, we have to investigate the impacts in particular detail and analyse the effects on the long-term safety, operational safety or technical feasibility of a deep geological repository. Based on information from additional experiments and model calculations, we can further limit potential consequences and thus show a higher level of safety. One example is glacial erosion: we have investigated what effects glacial erosion has and what measures can be taken to prevent it from compromising a repository. Construction materials cannot stop an advancing glacier; but a site can be selected to avoid it. We have also considered what would happen if, under extreme or highly unlikely conditions, the repository would nonetheless be affected.

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The materials for the disposal canisters are also being optimised. The current plan is to use steel. More on pages 28 and 29.

2016 Research, Development and

Nagra is working towards its goal of constructing deep geological repositories and continuously optimises its existing concepts. The Research, Development and Demonstration (RD&D) Programme is an important planning instrument in this respect and sets out all the relevant work priorities. Nagra maintains close collaboration with partners in Switzerland and abroad in the area of research and development.

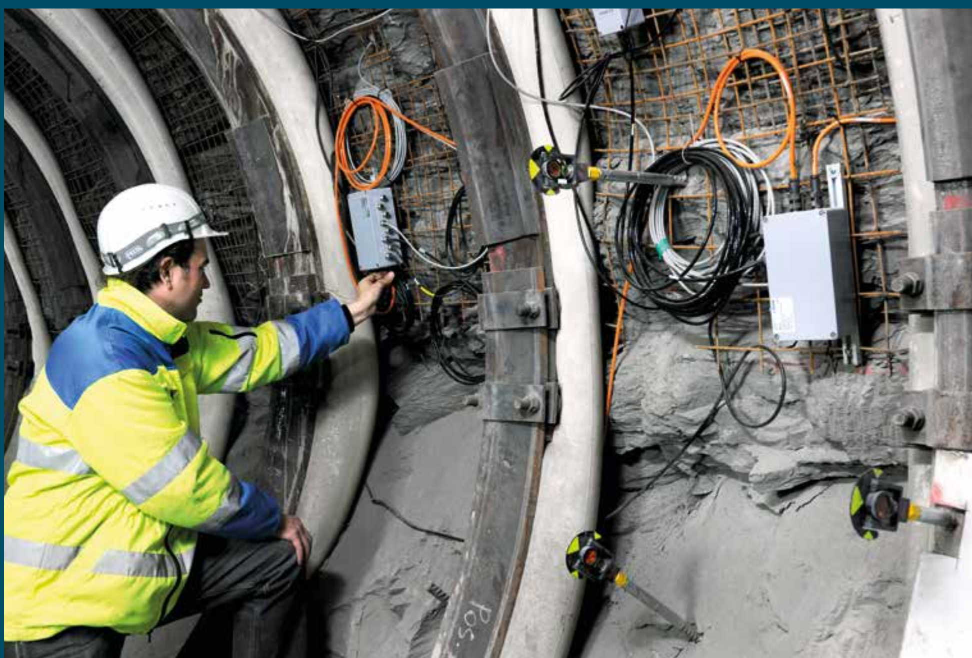
Nagra published its first RD&D Programme in 2009. It was able to demonstrate to the safety authorities that the state-of-the-art in science and technology had been taken into consideration and that its plans were goal-oriented. In 2016, Nagra had to submit the RD&D Programme together with the Waste Management Programme for the first time. In future, the two programmes have to be updated every five years.

Important planning instrument

Nagra's RD&D Programme presents the purpose, scope, type and duration of the different future work activities in the areas of research, development and demonstration in more detail. These activities are derived from the given disposal concept and implementation plan. Handling of remaining uncertainties is also described together with the research and development work aimed at investigating and reducing these further.

Focus of the work

The work covers a wide spectrum of topics, from geology to safety and safety-relevant phenomena and processes. Research and development work is also carried out on the radioactive waste itself, the engineered barriers and the technologies for the closure of the repositories. Some examples can be found in the following pages.



One of the two Swiss rock laboratories is located in Mont Terri close to the town of St-Ursanne in Canton Jura. Various experiments are being carried out in the Opalinus Clay as the host rock for a future deep geological repository for radioactive waste.

Demonstration Programme

The work addresses topics such as:

- Gas transport and removal in a repository; reduction of gas production through e.g. use of alternative canister materials
- Transport properties of selected radionuclides in the barriers of a deep geological repository
- Design and evolution of the engineered barriers; laboratory experiments and measurements to better constrain the corrosion rates of steel; influence of microorganisms
- Effects of thermo-hydro-mechanical-chemical coupled processes on the host rock
- Monitoring of a repository

Nagra is planning further geological investigations to characterise the underground geological conditions in the siting regions and to refine its understanding of safety-relevant processes in the host rock, such as the self-sealing of Opalinus Clay. Studies will also look at long-term geological evolution as affected by erosion and climate development.

Working together with our partners

Nagra assigns work to contractors who are experienced in particular technical areas, have experienced staff and the required infrastructure such as laboratories. It can look back on long-standing collaboration with established and scientifically independent competence centres such as the Waste Management Laboratory at the Paul Scherrer Institute (PSI), the Laboratory for Radio- and Environmental Chemistry at the University of Bern and at PSI, ETH Zürich, ETH Lausanne, etc. Nagra also works together with other waste management organisations, for example on experiments in rock laboratories.

Participation in international bodies

Nagra is also involved in the EU research programmes such as "Horizon 2020" and is active in international advisory bodies and working groups, for example:

- In expert groups of the International Atomic Energy Agency (IAEA)
- In working groups and projects of the Nuclear Energy Agency (NEA) on technical-scientific aspects and societal aspects of waste disposal
- In the EDRAM association (International Association for Environmentally Safe Disposal of Radioactive Materials) of leading waste management organisations worldwide.

Further reading

www

The Nagra Research, Development and Demonstration (RD&D) Plan for the Disposal of Radioactive Waste in Switzerland can be downloaded in English from our website www.nagra.ch.

Work focus: the radionuclide C-14

Dose calculations show that there is no risk to humans and the environment from a repository, even under unfavourable conditions. These calculations require measured data that describe, for example, how quickly the individual nuclides migrate through the Opalinus Clay. Such data are available for many radionuclides, including – for the first time – C-14.

Safety barriers retain nuclides

The Chinese doctoral student Yanhua Chen works in the Laboratory for Waste Management (LES) at the Paul Scherrer Institute in Würenlingen. Her investigations – looking at the interaction of specific radionuclides with Opalinus Clay – are being carried out on behalf of Nagra. The Opalinus Clay forms the natural safety barrier of a deep geological repository. Radionuclides migrate very slowly through the clay formation and, if they interact with the clay minerals in the rock such as illite and kaolinite, they are retained and migrate even more slowly.

Focus on the radionuclide C-14

"I am investigating the radionuclide C-14 that is incorporated into simply structured organic compounds such as carbonic acids and alcohols", explains Yanhua Chen. "These compounds are produced in a repository when C-14 is released as a result of corrosion of metals from nuclear reactors." C-14 is produced from nitrogen as a result of neutron irradiation during reactor operation. Because radioactive C-14 has a half-life of "only" 5730 years, it can decay almost completely in the deep underground environment before it reaches the earth's surface. "For this to happen, there only has to be a small interaction between the compounds that contain C-14 and the Opalinus Clay", says the young researcher. Up till now there were no measured values worldwide for C-14 and Nagra therefore had to assume in its dose calculations that no such interactions occurred in the case of C-14 and calculated conservatively with a large safety margin.

Yanhua Chen preparing a new experiment in the laboratory.

Weak interaction present

"Here in Switzerland I have learned a lot about safety analyses. When I return to China, I want to use my knowledge in this area to make a contribution to safe disposal of radioactive waste in my country."

Yanhua Chen, environmental engineer
Doctoral student at the Paul Scherrer Institute

"I was able to show in my experiments with the pure clay minerals illite and kaolinite and with the Opalinus Clay itself that there is a weak interaction", she summarises. This is relevant for Nagra's dose calculations which are used to show that the repository will never present a hazard to the population. "If the values I have measured for the radionuclide C-14 withstand an independent review, they will be used as input to Nagra's dose calculations", says Yanhua Chen proudly. This means that Nagra will be able to use the values measured by Yanhua Chen and will no longer need to make conservative calculations in this case.

Yanhua Chen (right) shows Jens Mibus (Project Manager Safety Analyses, Nagra) the test installation she is using to carry out research on the Opalinus Clay.

Work focus: production and rem

Investigations on gas production and removal in a deep geological repository are a focal point of Nagra's R&D activities. The results show that gas can be removed effectively into the surrounding rock. Other aspects such as gas formation due to the degradation of organic wastes are still under investigation.

Gas is produced in a repository

Gas is produced in a closed repository for HLW or L/ILW. It consists mainly of hydrogen generated by the corrosion of metals under anoxic conditions. Deep repositories contain a wide range of different metals and alloys in the radioactive waste itself, in installations such as rock bolts and supporting arches and as a container material. Steel is the most common metal and corrodes very slowly under repository conditions (see pages 36 and 37). Other gases such as methane can be produced in a L/ILW repository due to the degradation of organic wastes such as ion-exchange resins and various plastic materials.

Investigating the effects of gas

The ability of a repository to retain radionuclides depends on the safety barriers remaining intact and factors that could affect the integrity of the barriers have to be investigated. These include the formation and removal of gas. Opalinus Clay forms the natural safety barrier that is particularly important for the long-term safety of the repository. It can self-seal fissures and contains many small fluid-filled pores. Material transport through the clay occurs very slowly by diffusion between pores. An intact pore system supports the long-term containment of radionuclides. In the Mont Terri Rock Laboratory, Nagra has investigated how the Opalinus Clay and the bentonite tunnel backfill react under different gas pressures. Experiments and model calculations were also used to estimate the expected gas volumes and pressures.

Gas can be removed safely

The analyses have shown that – even with very pessimistic assumptions – the expected gas pressures lie below values that could result in damage to the barriers. The gas flows along the tunnel walls from the repository into the surrounding Opalinus Clay. Under the expected pressures, the gas then dissolves in the porewater of the clay and is transported away through the pores. To prevent the pressures building up excessively in the tunnels, the gas can be removed directly through the tunnels and into the surrounding rock using specially engineered measures. These include tunnel seals that retain the radionuclides but allow gas to pass through. Intensive international research efforts have gone into optimising these seals, including at the Grimsel Test Site where a site-generic 1:1 experiment is currently underway.

In a comprehensive study on gas production and removal carried out in 2016, Nagra also showed options for further reducing gas generation, if necessary. A very large component of the gas could, for example, be reduced in a HLW repository by using alternative canister materials (see pages 28 and 29).

oval of gas

Degradation of organic wastes

"What I enjoy about my work is that it brings together different disciplines such as chemistry, microbiology and physics."

Dr. Mario Stein, chemist
Project Manager Radioactive Materials

Mario Stein is responsible for inventorying and characterising radioactive materials at Nagra. He makes predictions of future waste arisings and carries out experiments. "Experimental data on the degradation of organic wastes under the conditions that prevail in a L/ILW repository are rare", he says. "For this reason, we are investigating the microbial degradation of ion-exchange resins and other organic materials ourselves." Ion-exchange resins are used in nuclear power plants to clean water circuits and spent resins arise as radioactive waste for conditioning. Mario Stein carries out experiments with inactive waste stored in gas-tight, sealed drums that are heated slightly. He can continuously measure temperature, pressure and the carbon dioxide, methane and oxygen content in the gas phase of the drums. In order to analyse all the gas components, gas samples are taken directly from the drums. The experiment has been running since September 2015. "After one year we could see no clear degradation of the ion-exchange resins resulting in gas formation", says Stein.

If required, the amount of gas from organic wastes in a repository could be reduced. One possible method is pyrolysis – a controlled incineration of organic waste. As the corrosion of steel produces larger volumes of gas than the degradation of organic waste, Nagra is also focusing increasingly on alternative canister materials.

Mario Stein is using this test facility to investigate the degradation of organic compounds. It is located at the ZWILAG interim storage facility in Würenlingen. The ion-exchange resins being investigated are contained in five heatable drums.

Work focus: alternative container

Disposal containers form one of the engineered barriers of a deep geological repository. The canisters for spent fuel assemblies and vitrified high-level waste from reprocessing are an important focus of Nagra's work.

Carbon steel disposal canisters

Spent fuel assemblies (SF) and other high-level waste are packaged in disposal canisters and transported to the HLW repository. The canisters must be stable on the long term and have slow corrosion rates. Switzerland has selected low-permeability Opalinus Clay as the repository host rock; the canisters are embedded in a bentonite backfill in the emplacement drift. ENSI requires the canisters for SF and HLW to remain tight under these conditions for at least 1000 years. At present, Nagra is planning gas-tight welded cylindrical canisters made of carbon steel with a wall thickness of 14 centimetres. Calculations show that these canisters will remain completely intact for around 10,000 years. How quickly a canister corrodes under exclusion of oxygen depends on humidity, temperature, pH and salinity in the emplacement drift. Laboratory experiments indicate that the measured corrosion rates of carbon steel in compacted bentonite decrease after a few months to a value of less than one-thousandth of a millimetre per year. This agrees well with values obtained in the Mont Terri Rock Laboratory.

Different countries, different materials

To ensure safe waste containment, the canister material has to be adapted to the conditions of the host rock. Given the geological boundary conditions, granite is the only host rock in Sweden and Finland and, in fractured granite, the containment time has to be much longer than is required in the Opalinus Clay. Sweden and Finland therefore use slowly corroding copper with a cast iron insert for their disposal canisters for spent fuel.

A granite host rock may contain water-bearing fractures. For this reason, Sweden and Finland are using more corrosion-resistant copper canisters with a cast iron insert.

materials

Nagra is testing alternative materials

Nagra has to specify the canister material when applying for a construction licence. Up till then, variants of the tried-and-tested carbon steel will be kept open. Developments in the area of materials science are being monitored and research carried out on alternative materials together with other organisations. Nagra is looking at corrosion resistance as well as the mechanical stability of the materials and will consider the potential effects on the safety barriers of a repository. It should also be possible to manufacture large numbers of containers simply and economically.

Stainless steel does not come into question as a canister material as the uncertainties surrounding it are too large. It has a natural protective layer that makes it more corrosion-resistant than carbon steel but this is never perfect and is susceptible to damage. This could result in uncontrollable local corrosion phenomena that could cause deep holes in the steel.

Ceramics have also been discussed as canister materials but, at present, there is no option available as the lid of the canister cannot be welded tightly and ceramics are brittle.

Canisters made completely of copper would make little sense in the Swiss concept with very low permeability Opalinus Clay. Together with its Canadian sister organisation NWMO, Nagra is therefore developing a carbon steel canister with a 3 to 10 mm thick copper coating. The copper coating is a good solution as it provides the benefit of the increased corrosion protection of copper without using too much of the valuable metal. Other metal coatings, for example nickel and titanium, are being evaluated together with the Swiss Federal Laboratories for Materials Science and Technology (EMPA).

Prototype of a steel canister with a copper coating.

Impressions from the Swiss rock

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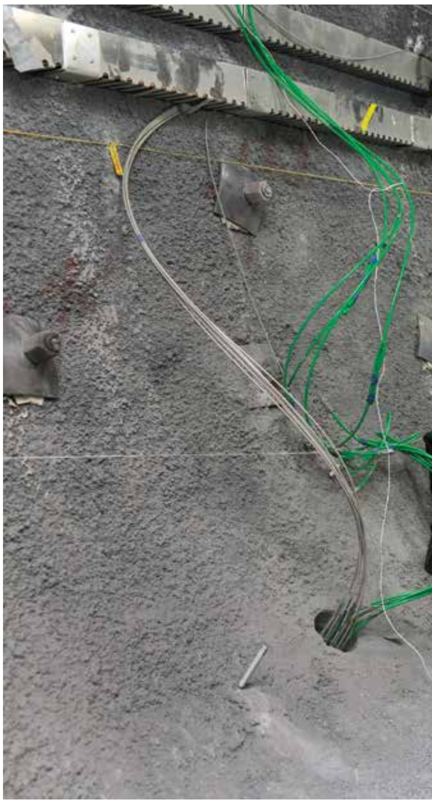

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laboratories


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In the two Swiss rock laboratories, experiments can be conducted directly in the rock under realistic conditions. The Grimsel Test Site is operated by Nagra and the Mont Terri Rock Laboratory by the Federal Office of Topography swisstopo.

Register for a free guided tour:

fuehrungen.nagra.ch


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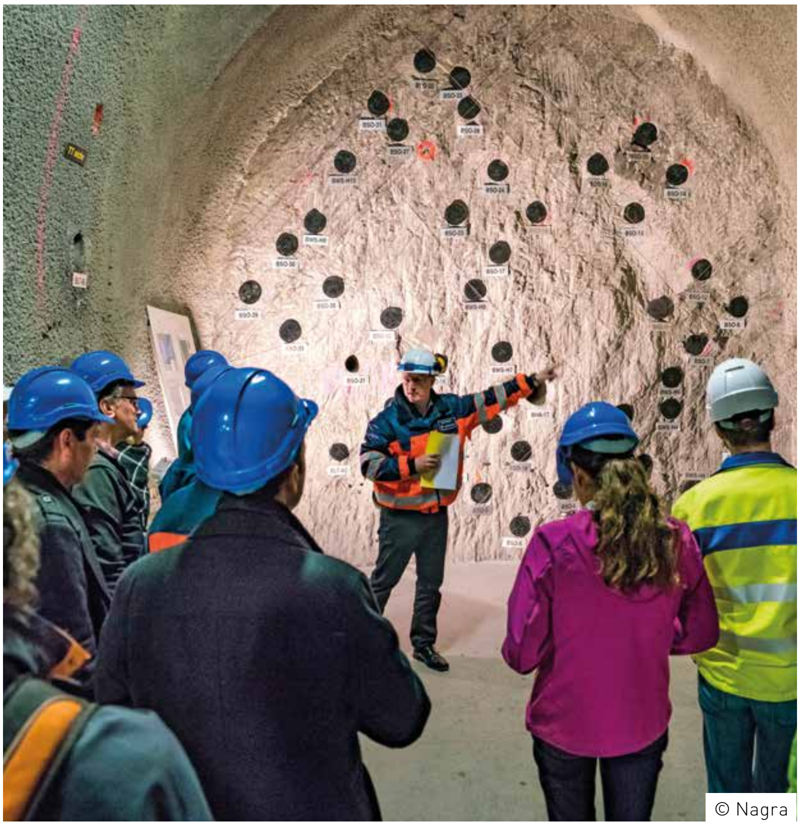
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Investigations in the two Swiss

With the Grimsel and Mont Terri underground rock laboratories, Switzerland has two international centres for research on deep geological disposal. Hundreds of metres beneath the earth's surface, Nagra and its partners are carrying out experiments on the safe disposal of radioactive waste.

Rock laboratories allow experiments to be carried out under realistic conditions directly in the potential host rock. Important information on the engineering feasibility and safety of repositories can be acquired and this flows into the planning and construction of the facilities. The Grimsel Test Site is operated by Nagra and the Mont Terri Rock Laboratory by the Federal Office of Topography swisstopo.

Valuable data and know-how

Nagra tests and optimises its concepts with experiments in the two laboratories. Geological, chemical and physical processes that will occur later in a repository under similar boundary conditions are investigated. In particular, the effectiveness and long-term behaviour of the engineered and geological barriers are evaluated for a wide range of potential influences: corrosion of the disposal canister, migration rates of radionuclides in the Opalinus Clay, removal of gas and heat, etc. The experiments help to improve process understanding, develop models for making predictions and provide data for model calculations. Drilling technology can also be optimised for the Opalinus Clay, which is challenging in terms of construction.

Experiments on a 1:1 scale

Procedures for emplacing waste containers are investigated on a large scale over several years under a wide range of influences in so-called demonstration experiments. The Full-Scale Emplacement Experiment in the Mont Terri Rock Laboratory is such a 1:1 scale experiment which simulates the concept for disposal of spent fuel in an emplacement drift.

The Mont Terri Rock Laboratory is located in the Opalinus Clay around 300 metres below the earth's surface.

rock laboratories

Sensor tests and new measurement methods

A sealed repository will be monitored for a period of at least fifty years. Sensors for monitoring parameters such as temperature, humidity and pressure are therefore being tested and suitable measurement methods developed.

Measured data are important for predictions

A deep repository will safely contain spent fuel for at least one million years. This can be shown in the context of safety analyses using dose calculations. Migration rates of radionuclides measured in rock laboratories also provide input for these calculations. Nagra was able to show that the radiation dose from a deep repository at the surface is far below the level of natural radiation and the prescribed limit of 0.1 millisieverts per year. This is true even under unfavourable conditions and over the entire containment time of the waste.

"The Grimsel Test Site is the only underground laboratory worldwide where researchers can carry out experiments under controlled conditions on the behaviour of radionuclides in fractured rock. Under realistic conditions, we use traces of radioactive substances to investigate how they migrate slowly through small fissures and fractures in the rock or how their transport is retarded. Our internationally recognised research centre offers our partners optimum research conditions with full infrastructure."

Dr. Ingo Blechschmidt, geoscientist
Head of the Grimsel Test Site

The Grimsel Test Site lies 450 metres beneath the Juchlistock (left) in the granitic rocks of the Aar Massif in the Bernese Alps.

Long-term diffusion experiment

Long-Term Diffusion Experiment (DR-B), Mont Terri Rock Laboratory

The diffusion of radionuclides in Opalinus Clay has been studied in situ for at least ten years. A new mobile probe that allows non-destructive measurements is being used to detect the radionuclides.

Detecting radionuclides using simple methods

When determining the migration rates of radionuclides, Nagra had to end its diffusion experiments up till now with recovery of a drillcore which is sent to the laboratory for analysis. This type of sampling is destructive to the experiment site. Now, for the first time, Nagra is using a mobile probe that can measure the smallest concentrations of certain elements (e.g. iodine, caesium, uranium) non-destructively in the Opalinus Clay. Migration rates can then be derived from the measured concentration curves. The measurement principle is based on X-ray fluorescence: the probe, which is height-adjustable and can be rotated, is installed in a monitoring borehole in the Opalinus Clay and emits X-rays. If these encounter one of the elements mentioned at the borehole wall, the elements emit a characteristic X-ray radiation. The probe captures this and provides the element concentrations.

Diffusion of iodine in Opalinus Clay

The diffusion of iodine in Opalinus Clay is being investigated in the DR-B Experiment. Iodine is produced in nuclear power plants during nuclear fission and is contained in the radioactive waste. There are two forms: radioactive iodine-129 and stable iodine. As they both have practically identical chemical properties, stable iodine is used in the experiment and the results are transferable.

The test setup consists of a central borehole into which iodine is injected and three monitoring boreholes which accommodate the measuring probe (see image on the right). The experiment started in summer 2016, with iodine in the form of a sodium iodide solution being injected into the lowermost

The mobile XRF probe being tested in the monitoring borehole.

in Opalinus Clay

section of the central borehole. From there it migrates through the Opalinus Clay until it can be detected after a few years by the measuring probe in the monitoring boreholes.

"Nuclear waste management is a cross-generational project. Not only do we have to acquire knowledge – we also have to document it and pass it on."

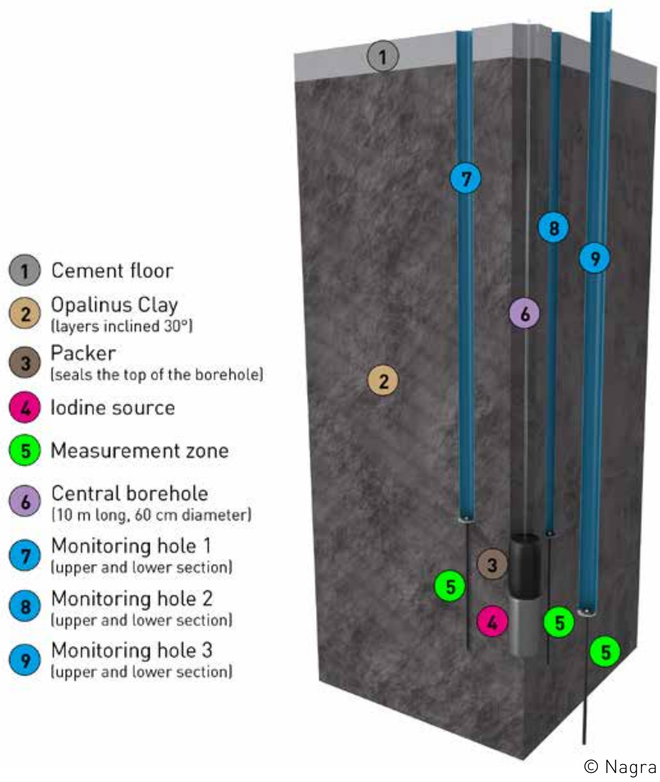
Dr. Veerle Cloet, chemist and environmental engineer
Project Manager Materials Performance

The migration rate of iodide through the Opalinus Clay is determined by slow diffusion. The iodide is negatively charged and will be repelled by the negatively charged surface of the clay. This means that sorption is very low to non-existent, i.e. iodide is not additionally retained due to this mechanism. Compared to positively charged radionuclides, it thus migrates "quickly" through the Opalinus Clay and, for the purpose of dose calculations, it therefore belongs to the relevant nuclides.

The importance of knowledge management

Veerle Cloet is investigating interactions between cement and clay safety barriers and material transport in the barriers. "Material transport from a deep geological repository occurs exclusively by diffusion in the Opalinus Clay and is very slow", she explains. "As a natural safety barrier, the Opalinus Clay makes an important contribution to the safe containment of the waste." These interactions are also being studied in the laboratory at PSI, the University of Bern and EMPA.

For a cross-generational project such as nuclear waste disposal, it is not only important to build up knowledge – it also has to be documented and passed on, believes Veerle Cloet. The scientific exchange with her Nagra colleagues is very important in this respect. "We make decisions together on the basis of scientific and technical investigations – aspects of safety are most important for us. But I am also aware that radioactive waste disposal is an emotional issue for many people and is linked with societal and political considerations."



Sketch of the long-term diffusion experiment: the different boreholes, for example the monitoring boreholes for the mobile probe, are clearly visible.

Experiment on corrosion in bent

Corrosion in Bentonite (IC-A), Mont Terri Rock Laboratory

This experiment is investigating the corrosion of metal components consisting of steel and copper. In both the L/ILW and HLW repositories, there is a wide range of metals and alloys in the waste itself, in facility installations and as a container material. Steel is the most common metal.

Realistic test conditions

Nikitas Diomidis has been investigating the corrosion of carbon steel in bentonite under anoxic conditions in the Mont Terri Rock Laboratory since the beginning of 2013. Similar conditions will prevail in a future HLW repository. Several stainless steel cylinders are inserted in a 16-metre deep borehole in the Opalinus Clay (see image below) and porewater enters the cylinders through openings. The steel cylinders themselves are not the target of the investigations but rather hold the bentonite inside together. "Each of the cylinders contains small pieces of carbon steel embedded in compacted granulated bentonite mixture or in bentonite blocks", he explains. His aim is to find out how high the corrosion rates of the carbon steel samples are under in situ conditions and what influence microbial activity has. "There will be bacteria in a deep repository and, in the worst case, these could accelerate the corrosion of steel", says Diomidis. "This can be prevented by selecting suitable conditions, for example by using a tight bentonite backfill."

"The aim is to extend the lifetime of the containers and reduce the amount of gas produced by iron corrosion."

Dr. Nikitas Diomidis, materials scientist
Section Head Materials Performance

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onite

Agreement with laboratory tests

In 2014, around one year after the start of the experiment, the first three cylinders were removed from the borehole in order to determine the corrosion rates of the samples and to see whether bacteria had any influence. "The analyses show that bacteria have no significant influence on corrosion." However, it is too early for final conclusions. Further cylinders will be removed in the coming years and their content analysed. "Nevertheless, we can already say that the corrosion rates of carbon steel measured in situ in the Mont Terri Rock Laboratory agree well with values from laboratory experiments in tightly compacted bentonite", explains the Nagra researcher. At the moment, the corrosion rate is less than one-thousandth of a millimetre per year and will decrease further as the experiment progresses.

Copper is also being investigated

The three cylinders that have been removed have been replaced with new cylinders that additionally contain three different types of copper samples. This will allow Nagra to investigate the extremely slow corrosion of copper under repository conditions and to see whether there are differences between the different copper samples.
The copper samples are:

- Oxygen-free copper with traces of phosphorus such as that used by the waste management organisation SKB for its containers
- Samples of the copper spray coating applied to carbon steel containers
- Samples of electrolytically deposited copper

The information from this experiment will help to construct more robust disposal containers.

Image left:
Removing the stainless steel cylinders from the borehole.

Image centre:
Twelve such cylinders are placed in the borehole.

Image right:
Each steel cylinder contains small samples embedded in compacted bentonite.

Experiment on the engineered ba

Full-Scale Engineered Barriers Experiment (FEBEX), Grimsel Test Site

Tests already began in the 90s on the feasibility of constructing emplacement drifts for spent fuel. The long-term behaviour of the engineered barriers was investigated under realistic conditions and models for predictions were verified.

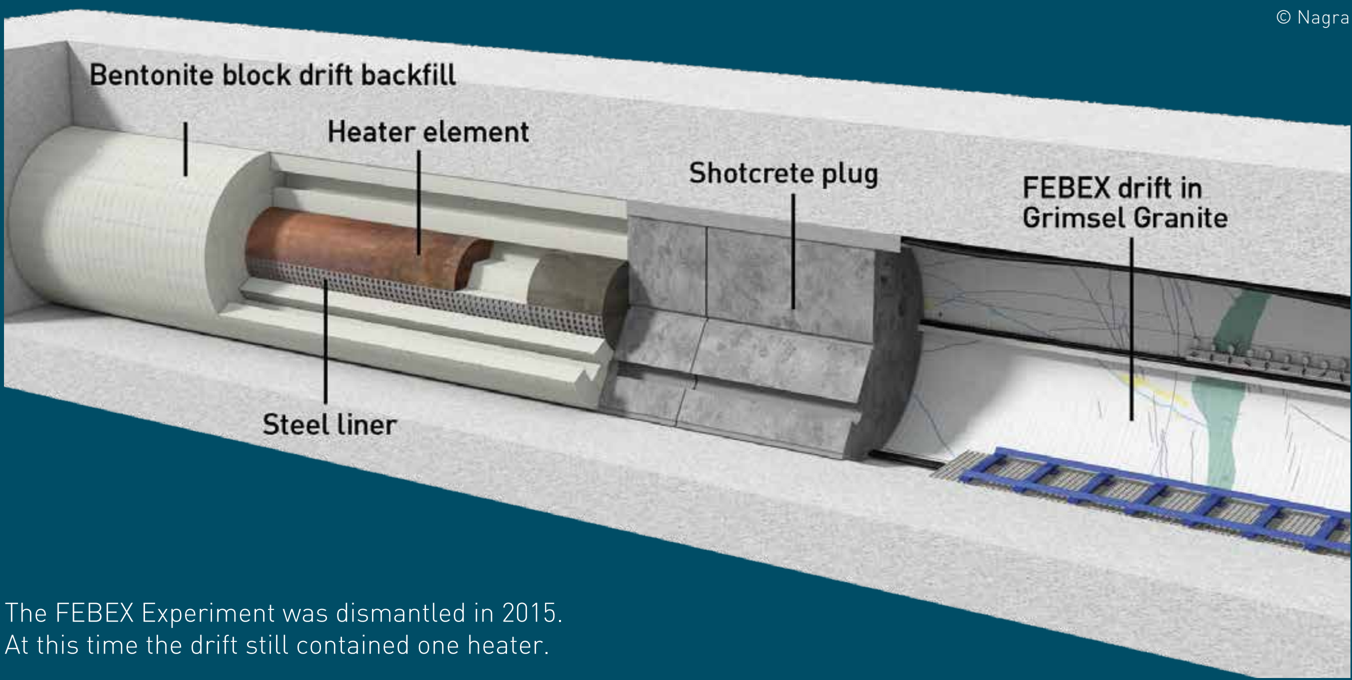
Studying the effects of heat

In this 1:1 scale demonstration experiment, an emplacement drift for spent fuel based on the Spanish disposal concept was constructed in granite. Nagra was able to acquire practical experience in the construction of the engineered barriers, with the focus on bentonite blocks to be used as a backfill material. It was also possible to study the effects of heat on the bentonite blocks and the surrounding rock. As radioactive waste cannot be used in the experiments at the Grimsel Test Site, two containers with heaters were used to simulate the heat production of the spent fuel assemblies. The heaters were placed in the drift in 1997, surrounded with bentonite blocks and the drift sealed with a concrete plug. The experiment then began.

After 5 years, the first of the two heaters was excavated in 2002 and numerous samples were collected. As the majority of the measuring instruments for monitoring the experiment were still functioning, the test continued with one heater up to 2015. This allowed Nagra to collect valuable measured data on the long-term behaviour of the engineered barriers.

"The FEBEX experiment is the only one of its kind to date in research into deep geological disposal that has run over such a long time period. Nagra was able to show that the system of engineered barriers is fit for purpose."

Dr. Florian Kober, geoscientist
Project Manager FEBEX Dismantling Project



The FEBEX Experiment was dismantled in 2015.
At this time the drift still contained one heater.

rriers

Bentonite behaved as expected

During the 18-year duration of the experiment, Nagra researchers were able to collect a wealth of measured data, for example on temperature, water content and the swelling pressure of the bentonite. "The measuring instruments proved to be much more robust than expected", explains Florian Kober, "I found this particularly impressive." In 2015, around 70 percent of the installed instrumentation was still functioning. "This is not a matter of course", says Kober, "as the conditions in the drift are extreme, with temperatures of 80 to 100 °C, high pressures and high humidity."

Numerous samples were collected when the heaters were dismantled and sent to laboratories in Switzerland and abroad for analysis. "The measured data and the rock samples collected during dismantling have shown that the engineered barriers have generally behaved as expected", explains Kober. All the small gaps present after the installation of the bentonite blocks have also been sealed through the uptake of water from the surrounding granite and swelling of the bentonite. Not all the samples have been analysed yet, but it can already be seen that there will be a good agreement between the results of laboratory analyses of the samples and the measured values from the Test Site, says Kober. "The experiment allows us to collect data on the mechanical, physical and chemical behaviour of the bentonite", he explains. The data will be used to verify the predictions of computer models. "Generally, the predictions – for example of temperature – agree with the measured data." Only the saturation of bentonite with water took longer than expected. "We use the models to make predictions that are as accurate as possible for planning new experiments – also in the Opalinus Clay – and, ultimately, for a future repository."

Numerous samples were also collected when excavating the second heater in 2015.

Emplacement experiment for hig

Full-Scale Emplacement Experiment (FE Experiment), Mont Terri Rock Laboratory

In the FE Experiment, practical experience is being gained with the emplacement process for a future repository for high-level waste. The main objective is to measure the effects of heat on granulated bentonite mixture and Opalinus Clay.

Test run for the deep repository

The Swiss emplacement concept for a HLW repository is being tested on a 1:1 scale under realistic conditions. The first part of the test was carried out between 2010 and the beginning of 2015, also as part of the EU project LUCOEX "Large Underground Concept Experiments". Using similar working procedures to those in a future repository, a test drift was excavated in the Opalinus Clay, three containers (heaters) emplaced and the drift backfilled with granulated bentonite mixture and sealed with a concrete plug. A wealth of know-how was available from earlier experiments: for example for the development of a new backfilling machine (see page 20) that can emplace the granulated bentonite more evenly and with a higher density. A high density maximises the swelling pressure of the bentonite and optimises the removal of heat.

Heat continues to be emitted from spent fuel after emplacement in the repository and has to be removed without damaging the rock. The heat causes the porewater and the Opalinus Clay to warm up. Because water expands more strongly than clay, this leads to a build-up of stress. In the second part of the FE Experiment, Nagra will therefore be looking in the coming years at such thermo-hydro-mechanical coupled processes and the effects of heat on the granulated bentonite and the Opalinus Clay. Around 1700 sensors will be used to monitor temperature, humidity and water content, pressure, deformation, etc.

The last settings for the heater sensors are made in the FE drift, which is already partly filled with granulated bentonite.

h-level waste

“It’s a good feeling to see that something planned on paper actually functions.”

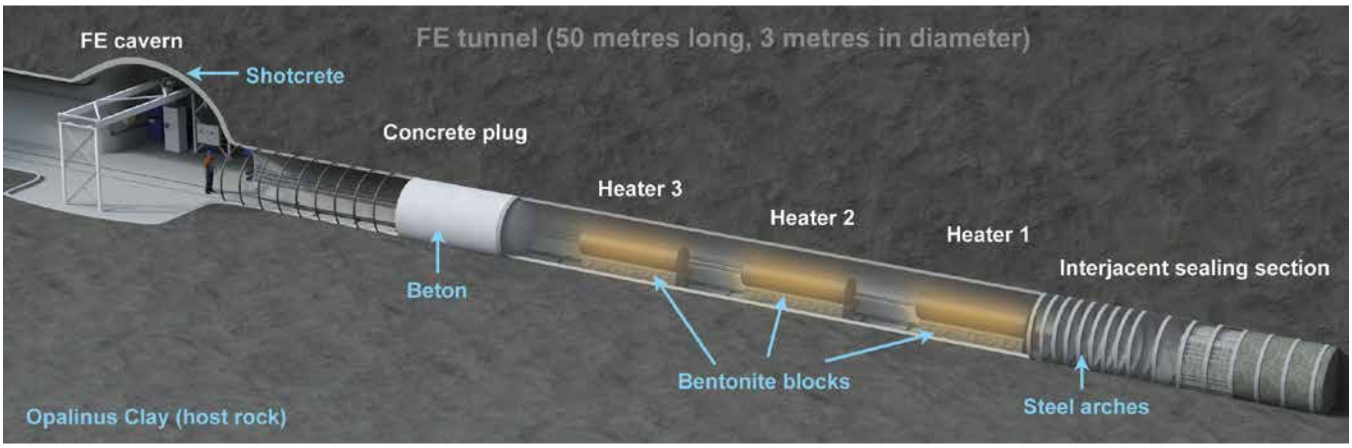
Herwig R. Müller, engineering geologist
Project Manager

“The numerous sensors in and around the drift record around one million data-points – every day!”

Benoit Garitte, civil engineer
Project Manager

A unique prototype

“Many years of theoretical planning lie behind the FE Experiment and now we have implemented it successfully in practice”, says Herwig R. Müller, who was responsible for realising the experiment from the stage of planning to the start of the heating phase. “Just two years after the start of measurements, everything is looking good and the measured data are very promising”, explains Benoit Garitte, who is now responsible for the collection of data and data analysis. Not a straightforward task: “We are recording around one million measured values per day”, explains Garitte. It is important for him and his team to be able to visualise the enormous amount of data. “The analysis of the measured values shows that temperatures behave as predicted by the models. The experiment provides us with valuable measured data and allows us to reconcile existing models and computer simulations. We will use these later to perform calculations for a deep geological repository”, adds Garitte. Herwig R. Müller also emphasises the significance of the FE Experiment for research on deep disposal: “What we are dealing with here is a prototype that has never been built before.” The experiment provides Nagra with important hands-on experience for the emplacement and backfilling processes in a repository, says Müller.



The waste disposal programme is

Nagra is well on the way to ensuring that all radioactive waste arising in Switzerland can be disposed of safely in deep geological repositories and that no unacceptable burdens are placed on future generations.

Deep geological repositories already exist

Not only Switzerland but also many other countries have opted for deep geological disposal and research in this field is a mature science. Deep geological repositories for low- and intermediate-level waste are already in operation in countries such as Finland, Sweden, South Korea and Hungary. Following decades of research and development, disposal projects for high-level waste are also far advanced in countries such as Finland, France and Sweden and a repository for spent fuel is currently under construction in Finland. Close international collaboration also allows Switzerland to benefit from such progress.

Taking responsibility

Deep geological disposal of radioactive waste is a challenging task, both technically and societally. Nagra undertakes its work towards cross-generational protection of humans and the environment with the necessary respect and with a sense of responsibility. Key waste management steps have already been implemented in Switzerland and the search for repository sites according to the Sectoral Plan of the Federal Government continues to make progress. The financing of all the work required for decommissioning the nuclear facilities and disposing of the radioactive waste is also secured; the waste producers make annual contributions to decommissioning and waste disposal funds. Nagra is approaching the remaining steps in the Waste Management Programme with great care and using the best available technologies.

At the end of 2015, the Finnish waste management organisation Posiva was granted a construction licence for Onkalo, the deep repository for spent fuel on the Olkiluoto peninsula. The lower half of the photograph shows the underground accesses that have already been constructed.

on track

Further reading

Nagra (2016): Entsorgungsprogramm 2016 der Entsorgungspflichtigen. NTB 16-01 (in German)

Nagra (2016): The Nagra Research, Development and Demonstration (RD&D) Plan for the Disposal of Radioactive Waste in Switzerland. NTB 16-02

Nagra (2016): Production, consumption and transport of gases in deep geological repositories according to the Swiss disposal concept. NTB 16-03

Nagra (2015): Siting regions for deep geological repositories – Nagra's proposals for Stage 3. Brochure 7

Nagra (2008): Entsorgungsprogramm 2008 der Entsorgungspflichtigen. NTB 08-01 (in German)

Nagra (2002): Projekt Opalinuston; Konzept für die Anlage und den Betrieb eines geologischen Tiefenlagers; Entsorgungsnachweis für abgebrannte Brennelemente, verglaste hochaktive sowie langlebige mittelaktive Abfälle. NTB 02-02 (in German)

These documents are available under www.nagra.ch in the section "Publications" where they can either be downloaded or ordered in printed form.

Nationale Genossenschaft für die
Lagerung radioaktiver Abfälle

(National Cooperative for the Disposal
of Radioactive Waste)

Hardstrasse 73
P.O. Box 280
CH-5430 Wettingen

Tel +41 (0)56 437 11 11
Fax +41 (0)56 437 12 07

info@nagra.ch
www.nagra.ch
www.nagra-blog.ch

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