THE REGULATORY PERSPECTIVE: ROLE OF REGULATORY REVIEW OF THE SAFETY CASE AND FEEDBACK TO SITE INVESTIGATION

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Abstract

Swiss Legislation requires for all types of radioactive waste the safe and permanent disposal in deep geological repositories within Switzerland by stipulating a step-by-step procedure for site selection and licensing of the disposal facilities. Each step requires safety considerations or safety analyses which are reviewed by the Swiss Federal Nuclear Safety Inspectorate. The principle steps of radioactive waste disposal include:

(i) Demonstration of disposal feasibility for all types of radioactive waste in Switzerland.

(ii) Site selection process in three phases to narrow down the number of suitable sites to one for realisation ("Sectoral Plan for Geological Repositories").

(iii) Construction, operation and closure of the repositories according to Swiss legislation in five steps (licence for geological investigations, general licence (decision-in-principle), construction licence, operation licence, closure order).

Step (i) has been completed in 2006 when the Swiss Federal Council approved the demonstration of disposal feasibility for high level and long-lived intermediate level waste submitted by the implementer in 2002. Currently the Swiss waste disposal programme is starting the site selection procedure according to (ii). This paper describes the safety requirements, presents examples of regulatory reviews and elucidates its feedback to site investigation.

Introduction

Geological information played a key role in former assessments of the demonstration of disposal feasibility in Switzerland. For each demonstration, the Swiss implementer, Nagra, presented a safety case based on geological information. We here focus on two examples regarding the disposal of high level (HLW and long-lived intermediate-level waste (ILW-LL), Nagra projects "Gewähr" and "Opalinus Clay". We show how geological information influenced the regulator's assessment process applied to the safety cases submitted by Nagra (Chapter 2). After illustrating the lessons learnt from the past, we then outline how we will in the future use the geological data base for safety analysis in the siting process,[1] and how different sites will be compared to reduce the number of sites on the basis of regulation limits and safety considerations (Chapter 3).

In 2005, the Nuclear Energy Act came into force in Switzerland (together with a supplementary Ordinance), replacing the former Atomic Energy Act of 1959. The new legislation addresses the issue

1. This process was started on April 2, 2008, by the approval of the "sectoral plan for geological repositories" by the federal government of Switzerland.

of radioactive waste management more specifically. The regulatory guidelines on geological waste disposal are currently revised to conform to the new legislation.[2]

In Switzerland, the producers of radioactive waste are responsible for the safe management and disposal of the waste they generate and have to bear the costs for its disposal. According to the new legislation, all radioactive waste will undergo final disposal in repositories situated in suitable geological formations. The producers of radioactive waste, i.e. the nuclear power plant operators and the Federal Office of Public Health (responsible for the waste arising from medicine, industry and research) have in 1972 formed the National Cooperative for the Disposal of Radioactive Waste (Nagra) which is responsible for the disposal of all kinds of radioactive waste. Two repositories are foreseen by Nagra, one for low and intermediate level waste (LILW) and the other for high level waste (HLW, including spent fuel, SF, if not reprocessed) and long lived intermediate level waste (ILW-LL).

The nuclear energy legislation requires the demonstration of the feasibility in Switzerland of safe and permanent disposal of radioactive waste. For this purpose, Nagra undertook the project "Gewähr", which they completed in 1985 (Nagra, 1985). The report presented a demonstration of the feasibility for the disposal of all waste types in Switzerland. Concerning HLW and ILW-LL,[3] the study was based on a repository in the crystalline basement of Northern Switzerland, but failed to provide the required demonstration of siting feasibility. In line with the recommendations by HSK, the federal government ordered that research for a HLW repository must be extended to sedimentary rocks. After a broad selection process, Nagra chose the Opalinus clay formation, an indurated mudstone, in an area 30 km north of Zürich, for further geological investigations (including deep exploratory drilling at Benken and a 3-D seismic survey). The project "Opalinus Clay" was submitted to the authorities in December 2002 (Nagra, 2002), and approved by the federal government in 2006.

According to the new Nuclear Energy Ordinance, the site selection process for radioactive waste repositories will be defined in a sectoral plan, i.e. within the framework of the existing national land use planning legislation. Site selection will be based primarily on safety criteria, but must also address socio-economic aspects. While the demonstration of the feasibility of all waste types focused on a site chosen by Nagra an found suitable to fulfil the regulatory limits, the siting procedure according to the "sectoral plan for geological repositories" will include a systematic search, with safety having first priority, including a comparative approach intended to compare among potential sites and to apply socio-economic aspects among those sites that are considered as equally safe.

Including the site selection process, the principle steps of radioactive waste disposal in Switzerland include:

(i) Demonstration of disposal feasibility for all types of radioactive waste in Switzerland (which was achieved for all waste types in 2006).

(ii) Site selection process in three phases to narrow down the number of suitable sites to one for realisation, which started on April 2, 2008.

(iii) Construction, operation and closure of the repositories according to Swiss legislation in five steps (licence for geological investigations, general licence, construction licence, operation licence, closure order).

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2. The requirements for radioactive waste disposal are summarized in HSK guideline R-21 (HSK 1993). In the near future it will be replaced by the new guideline G03.
3. As part of project "Gewähr", Nagra demonstrated also the disposal feasibility for LILW with a model repository in marly sediments at Oberbauenstock. The feasibility demonstration was approved by the federal authorities in 1988.

Due to the cooling time required for spent fuel prior to disposal, a repository for HLW/ILW-LL is needed only several decades from now. Current estimations suggest that operation of such a repository will not start before 2040.

Swiss experience in regulatory reviews and feedback to site investigation

Two important reviews of safety cases to demonstrate the feasibility of the safe geological disposal (as required by the Atomic Energy Act and its addendum of 1978) for HLW and ILW-LL have been performed in Switzerland:

- For project "Gewähr" (Nagra 1985), the review of HSK concluded that the feasibility for HLW (excluding SF[4]) based on a repository in crystalline basement rocks in northern Switzerland was only partly proven. In 1988 the Federal Council ordered implementers to extend their investigations to sedimentary rocks.
- The second review by HSK dealt with project "Opalinus Clay" (Nagra 2002), submitted to demonstrate the disposal feasibility of SF, HLW and ILW-LL in the Opalinus clay in order to meet the requirements defined by the federal government in its judgement on Project "Gewähr" in 1988. A broad technical review by HSK (HSK, 2005) came to positive conclusions.

Both feasibility studies had to meet the safety requirements defined in HSK guideline R-21 where a basic deterministic approach is requested. The results of the radiological consequence analyses had to demonstrate that calculated doses do not exceed the individual dose limit of 0.1 mSv/year (HSK/KSA, 1993). In addition to this quantitative individual dose limit for probable scenarios, a complementary total risk criterion is applied to the sum of scenarios of low probability.

Project "Gewähr" of Nagra

Content and aim of Project "Gewähr"

Project "Gewähr" covered the management and safe disposal of vitrified HLW and ILW-LL. The feasibility study considered the disposal of the waste at 1 200 m below ground in a stable very low-permeable granite block in the crystalline basement of northern Switzerland. An essential part of the study was the safety analysis, which focused on the long-term aspects of the post-closure phase. The data used for the safety analysis were mainly based on experimental results, especially those obtained from laboratory measurements, geological field investigations and several exploratory drillings.

Using a multiple barrier concept, the vitrified HLW was proposed to be enclosed in massive cylindrical steel containers emplaced horizontally along the axis of tunnels and surrounded by a 1.4 m thick backfill of highly compacted bentonite. The ILW packages would have been placed in caverns with concrete lining and cementitious grout backfill.

The project report concluded that the technical feasibility of disposal of HLW and ILW-LL was demonstrated, that the technical safety barriers showed a high level of efficiency, and that a suitable geological environment to ensure long-term safety in Switzerland as defined by the regulatory requirements was available. The safety analysis showed that the disposal concept would provide adequate protection of mankind and the environment under all realistically anticipated conditions.

4. In 1985, it was planned that all spent fuel (SF) elements will undergo reprocessing. SF was thus not considered part of the waste to be disposed.

Implementation of the review

For its review, HSK developed generic models of the geological settings of the crystalline basement of northern Switzerland. The geological investigations conducted by Nagra were closely supervised by HSK and its experts. Independent compilations of geological, hydrogeological and hydraulic data of the crystalline basement were compiled, water-conducting features identified and conceptual models for nuclide transport evaluated. Processes and events which could possibly act on the disposal system were analysed and relevant scenarios defined for consequence analysis. Dose calculations with independent computer codes were done for enveloping scenarios and as parametric studies.

Overview of review results

The geology of Northern Switzerland is characterised by a pre-Mesozoic crystalline basement, covered with Mesozoic and younger sediments. The basement is crosscut by a number of deep E-W trending graben structures filled with permo-carboniferous sediments that are difficult to detect by seismic means. Taking into account the restricted knowledge accumulated so far from the exploratory drillings, the question concerning the disposal feasibility of HLW was split into three parts by HSK:

- The first part (*safety of the disposal concept*) concerned the demonstration of long-term safety of the multi-barrier system under the condition that the assumed host-rock properties used for safety assessment are representative for a volume of rock large enough to host the repository. This part was assessed positively by HSK.
- The second part (*engineering feasibility*) addressed questions whether construction, operation and closure of a repository are practicable under such conditions. This part, too, was assessed positively by HSK.
- The third part (*siting feasibility*) dealt with the question whether a suitable volume of granitic rock having the requested size and properties could be found in northern Switzerland by the exploration techniques available today. In its review HSK came to the conclusion that siting feasibility could not be proven because of the strong heterogeneity of the crystalline basement in northern Switzerland and the unfavourable tectonic and hydrogeological situation (deep permo-carboniferous graben-structure, intensive fracturing of the crystalline basement and artesian discharge of hot thermal springs in the area). Due to several hundred metres of sediment cover, the exploration and characterisation of the basement was (and still is) difficult. HSK therefore recommended to extend research and field investigations to sedimentary rock formations with minor tectonic overprint and more favourable exploration properties (e.g. by reflection seismic methods).

These recommendations were accepted by the federal government and integrated into the federal decree on project “Gewähr” in 1988.

Review of important geological safety aspects

In order to characterise the water flow around and through the repository in project “Gewähr”, Nagra used a set of three hydrodynamic models, the regional model, the local model and the block model for the repository site. Among those, the block model is the most essential one to describe how radionuclides may be transported away from the repository by groundwater. Two questions need to be addressed before migration through the geosphere can be calculated: (i) where and how does the groundwater flow? and (ii) what is the retention capacity for radionuclides along the flow path?

Flow system: Water flow in the northern Switzerland crystalline basement is observed to predominantly follow various types of discontinuities related to brittle deformation. Even after measurement of hydraulic transmissivities at various depths in a vertical borehole, it is difficult or even impossible to infer 3-D-flow systems from a single test drilling. Six boreholes were drilled into the crystalline basement in northern Switzerland, however they were far apart and their hydraulic properties differed so strongly that a consistent picture of ground water flow could not be established. Careful analysis of inflow points along these boreholes suggested two prime candidates of flow systems to be considered in the safety analysis:

- **The kakirite-quartz vein model**: Vuggy to porous water-bearing quartz veins embedded in kakirite (fault breccia) zones of varying thickness (cm to m) were found in the reference boreholes. The kakirites showed hydrothermal alteration by the selective breakdown of Ca-rich feldspar into clay minerals. The model assumes that water flows along quartz tubes (one tube of 10^{-2} m diameter per m^2) and that matrix diffusion into the kakirite material of up to 1 m thickness is possible.
- **The dyke rock model:** Water bearing zones in fractured dykes (aplites, pegmatites, less common ore-veins) were observed in the boreholes. This model assumes that water flows in open fractures along the dyke rocks (one parallel open fracture with aperture 10^{-4} m per metre of dyke thickness) while matrix diffusion is limited to the 1 mm thick coating material of the fractures. Due to the paucity of Ca-rich feldspar in these dyke rocks, hydrothermal alteration to clay minerals is mostly absent.

In its review of the crystalline synthesis report (Nagra, 1994), HSK (2004) re-analysed the inflow points in the Nagra boreholes and correlated them to lithological aspects and to relative transmissivity. To clarify which inflow points dominate water flow, the relative proportion of each inflow point to the total transmissivity was analysed. Single inflow points show high to moderate hydraulic transmissivities ranging from $5x10^{-5}$ m^2/s to less than 10^{-9} m^2/s. 65% of the total transmissivity is provided along single open fractures, while cataclastic zones do not represent the dominant water flow system (only 21%). 55% of the total transmissivity is linked to the occurrence of quartz-rich rocks (incl. dykes) and mineralised veins, which by their enhanced brittle behaviour during deformation, markedly enhance the permeability of the crystalline basement.

Sorption: Along the flow paths, radionuclides may sorb onto mineral surfaces on the channel or fracture walls. If the rock matrix is accessible to matrix diffusion, additional surfaces are available for sorption processes. Nagra compiled two sets of sorption coefficients, (i) a set of values derived from realistic estimates, and (ii) a set of conservative values. The two sets primarily referred to values from granitic rocks, whereas little was known about sorption in dyke rocks. HSK therefore argued that as long as the level of knowledge is so poor, calculations should be based on conservative sorption values for the dyke model, and the “realistic” sorption values should be applied for comparison purposes only. HSK called the two data sets as “sorption high” and “sorption low”, thus avoiding the terms “realistic” and “conservative” (Table 1).

Table 1. **Maximum annual individual doses from a HLW/ILW-LL repository calculated for two different flow models and two sorption data sets. The regulatory safety criterion is 0.1 mSv/year**

Model	kakirite-quartz model	dyke rock model
“sorption high”	$1.2 \cdot 10^{-8}$ mSv/year	$4 \cdot 10^{-5}$ mSv/year
“sorption low”	$5 \cdot 10^{-5}$ mSv/year	$2 \cdot 10^{-3}$ mSv/year

Dose calculation: Safety analyses were performed by HSK for both water flow models, assuming the same hydraulic conductivity (10^{-9} m/s) and flow path length (500 m, reference case scenario). The calculation results of HSK are shown in table 1 using Nagra reference case scenario assumptions for all other safety parameters. The different models and sorption data sets cause large differences in the results: the calculated doses of the two flow models (kakirite-quartz model with low sorption values and dyke rock model with high sorption values) differ by more than five orders of magnitude.

Two individual types of uncertainties have to be distinguished, i.e. the uncertainty in the parameters (sorption coefficients, hydraulic conductivities) and the uncertainty of the flow model. The flow systems in kakirite and in dyke rocks cannot simply be called “realistic” and “conservative” only based on the higher annual doses for the dyke model. The lack of detailed geologic information does not support such terminological distinction: either of the models could be true, or both could be wrong. Assessing the safety of a HLW repository becomes uncertain if nuclide migration though a single safety element – the geospheric barrier – differs by five orders of magnitude.

Due to the paucity of the field data (no outcrops, only few boreholes), and due to the tectonic complexity and inherent heterogeneity of the investigated crystalline basement, the question of the dominant flow paths in the crystalline remained open. Considering in addition that much higher hydraulic transmissivities (by up to a factor of 10^4) were measured in fractured dyke rocks and ore-veins in the Nagra boreholes in the crystalline basement of northern Switzerland (but not considered in Table 1), the safety margin with respect to the regulatory dose limit seems uncomfortably small or even absent in the case of the dyke model with conservative sorption values.

Lessons learnt and feedback to site investigations

The crystalline basement in northern Switzerland is almost completely covered by sedimentary rocks and therefore difficult to explore over wider areas from the surface. Many geological and tectonic models on these rocks are therefore speculative in their nature. The only data sources are drill cores and test results from boreholes.

The understanding of the water flow system in the host rock is a key element for any safety assessment. Field evidences from crystalline rocks at the surface north of the Swiss border (Black Forest) indicate that water in the crystalline rocks flows along different types of discontinuities such as single open joints, fault, shear, and fracture zones, discontinuities along lithological contacts such as leucocratic and quartz-rich rocks, dyke rocks, mineral and ore veins. Fractures may be sealed by hydrothermal alteration or widened by dissolution processes enhancing the complexity and heterogeneity of the flow paths.

The review of project “Gewähr” showed that the inherent heterogeneity and the tectonic complexity of the crystalline basement may lead to an incomplete or inadequate characterisation of the geological barrier. The spatial arrangement of highly water conducting features turned out to be one of the most sensitive geological parameters, capable to by-pass most of the barrier function of the rock. A key issue for site investigations is therefore the capability to identify such features and quantify their impact. It was in particular the combination of a very sensitive parameter (hydraulic conductivity) and the inability to explore the 3-D variability of this parameter that led to a rejection of the siting feasibility by HSK.

Project “Opalinus Clay”

Content and aim of the project

The project “Opalinus Clay” 2002 (Nagra, 2002) describes the post-closure safety assessment of a repository for SF, vitrified HLW and ILW-LL in the Opalinus clay in northern Switzerland. The main objective of the project was to demonstrate disposal feasibility in order to fulfil the requirements defined by the Swiss federal government in 1988 in its judgment of project “Gewähr”. As before, the three aspects of the siting feasibility, the engineering feasibility and the safety feasibility were addressed.

The proposed model repository is located at a depth of 600-700 m in a 115 m thick clay layer (Nagra, 2002). The passive multi-barrier concept includes durable waste forms (SF, HLW) in steel canisters surrounded by bentonite buffer emplaced co-axially within a system of parallel tunnels in the host rock. ILW-LL was proposed to be placed into concrete containers in caverns backfilled with cementitious grout.

The implementer's safety assessment demonstrated safe disposal of SF, HLW and ILW-LL to be feasible. The long-term safety assessment showed that the radionuclides would be retained within or near the repository for very long times. Long-lived radionuclides that eventually reach the biosphere would be present only at concentrations well below the required safety limits and pose no harm to humans and the environment. Due to the very low permeability and the favourable sorption capacity of Opalinus clay the geosphere was expected to be a strong barrier to nuclide migration. Diffusion was shown to be the main process for the transport of dissolved radionuclides. The salinity of the measured Opalinus clay pore water still reflects one-third of old original seawater composition.

Implementation of the review

HSK reviewed the project "Opalinus Clay" with the support of six groups of external national and international experts and with a contribution of the KNE (Commission on Nuclear Waste Management) expert group (KNE, 2005).

The main objective of the review was to provide an independent evaluation of the quality of the post-closure safety assessment presented by Nagra. The focus of the review was on:

- The understanding of the multi-barrier system and its safety functions.
- The geological situation and the evaluation of the long-term stability.
- The isolation capacity of Opalinus clay and the surrounding confining rock units.
- The physical and chemical properties of the different barriers and the scientific understanding of processes and barrier functions.
- The comprehensiveness of features, events and processes (FEPs) affecting the disposal system.
- The derivation and comprehensiveness of scenarios identified for performance assessment.
- The reliability of mathematical model calculations for consequence analysis.
- The treatment of data and model uncertainties.
- Traceability and quality of the documentation.

HSK tested and complemented selected model calculations by independent modelling (temperature evolution, groundwater flux through repository, sorption data, radionuclide release and migration through the barrier system to the biosphere and dose calculations, sensitivity studies by parameter variations). Additionally, HSK reviewed the engineering feasibility of the repository (not discussed in this paper).

The criteria by which HSK assessed the safety case were based on the quantitative safety criteria in the guideline HSK-R-21. For siting feasibility demonstration, HSK (1999) defined a set of qualitative criteria which a site has to fulfil. The most important properties are:

- Low permeable host rock.
- Sufficient volume of host rock for locating a repository.
- Long-term geological stability.
- Predictability of long-term behaviour.
- Explorability.
- Favourable rock mechanical properties.
- No conflicts with other utilisation (e.g. ore, coal, water geothermal resources).

Overview of review results

The review of HSK came to generally positive results and concluded that the project "Opalinus Clay" has successfully demonstrated the disposal feasibility of HLW/ILW-LL in Switzerland. With respect to the geological data density provided for this demonstration, HSK concluded that the geological data base of the safety assessment is clear and comprehensive, so that features, events and processes can be analysed carefully and in a comprehensive manner (including the data and model uncertainties).

At the same time, HSK formulated a number of "open questions", which should be further evaluated by Nagra before undertaking further steps towards the realisation of a repository in Opalinus clay. HSK concluded that these "open questions" do not call into question the demonstration of disposal feasibility of HLW/ILW-LL. In particular, HSK recommended that Nagra should further evaluate:

- The corrosion behaviour of the SF-HLW steel canisters including mechanical stability, the influence of corrosion induced changes and the influence of sulphide on corrosion.
- The gas production rate due to corrosion and decomposition of organic compounds in the repository, and gas transport processes in bentonite and Opalinus clay.
- The thermal stability of bentonite buffer at temperatures above 100°C.
- The saturation behaviour of bentonite pellets during the thermal phase.

Lessons learnt and feedback to site investigations

The review of project "Opalinus Clay" provided a number of important qualitative and quantitative arguments for the isolation capacity of Opalinus clay: (i) the very low hydraulic conductivity measured in boreholes (m-scale experiments) and in the underground rock laboratory at Mont Terri (100 m-scale experiments) demonstrating that solute transport in Opalinus clay is diffusion-dominated and very slow, (ii) the presence of saline pore water reflecting old marine origin and stagnant hydraulic conditions, (iii) systematic concentration profiles of natural element concentration and isotope ratio in porewater showing that solute transport is diffusion controlled and (iv) diffusion experiments on rock samples in the laboratory or on a larger scale in the Mont Terri underground rock laboratory confirming the diffusion coefficients as deduced from the distribution profile of the natural tracers. The measured rock properties of Opalinus clay allowed modelling of the clay host rock as a diffusion-retention-barrier with sound scientific understanding of the safety relevant processes. In summary, Opalinus clay proved to be a most effective long-term component of the barrier system.

The simple geological structure of the site, with tectonically nearly undisturbed horizontal sediment layers, resulted in a good explorability by high resolution 2-D and 3-D seismic methods. In addition, the homogeneity of the Opalinus clay and the observed narrow range of the rock properties (e.g. porosity, permeability) allow for the extrapolation of borehole data over larger areas. Predictability and explorability are paramount for adequate site characterisation.

The past geological evolution of the Opalinus clay was reconstructed by Nagra by detailed analysis of thermal parameters within the rock sequence and by basin modelling providing important information on the range of potential evolution scenarios of the site area over the next million years. The geological setting enhances HSK confidence that no geodynamic processes or events conceivable today will lead to unacceptable radiological consequences in the future.

Site selection according to the sectoral plan: learning from the past

The "Sectoral Plan for Geological Disposal" (SGT[5]) defines a step-by-step procedure for site selection. In phase 1 of SGT, the implementer has to derive a set of quantitative requirements for potential host rocks for the planned repositories (e.g. dimensions of the repositories, thickness and

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5. The "Sectoral Plan for Geological Disposal" has recently been published by the Swiss Federal Office of Energy (BFE) in its final version (see at: www.bfe.admin.ch). It is available in German, French and Italian ("Sachplan geologische Tiefenlager"; Plan Sectoriel – Dépôts en couches géologiques profondes", and "Piano settoriale dei depositi in strati geologici profondi", respectively).

hydraulic conductivities of host rocks). Based on these requirements, the implementer has to identify suitable large-scale geological areas for hosting a repository. Then, potentially suitable host rock formations within these areas are identified by excluding regions with enhanced tectonic complexity or probable occurrence of deep glacial erosion.

Safety criteria for the selection of potential siting regions (phase 1 of the sectoral plan)

The long-term stability and the retardation properties of the host rock and the geosphere are important qualities which have to be considered in the selection process of a disposal site. In Phase 1 of the sectoral plan, criteria for the selection process are of *qualitative* nature.[6]

HSK experience from past reviews of feasibility studies and the requirements of the Swiss legislation lead to a list of 13 safety criteria to gauge suitable sites. These criteria are united in four criteria groups:

1. Properties of the host rock (including additional surrounding strata).
2. Long-term stability.
3. Reliability of geological statements.
4. Suitability for construction.

HSK will base its review of the implementer's proposal of siting regions on these criteria groups.

Criteria group 1: properties of the host rock

Criteria of group 1 consider nuclide-retarding aspects of technical and natural barriers. HSK formulated four criteria to judge the suitability of potential formations: *Spatial extent (1.1)* requires that the host rock dimensions are sufficient to contain the main fraction of radionuclides. *Hydraulic conductivity (1.2)* requires that transport of radionuclides is sufficiently slow, *Geochemical conditions (1.3)* look for favourable geochemical conditions which ensure radionuclide retardation, and *Migration paths (1.4)* consider transport processes favourable to retard nuclide migration.

Criteria group 2: long-term stability

Typical time scales for the demonstration of safety are of the order of 10^5 years for LILW and of 10^6 years for HLW/ILW-LL. Criteria of group 2 consider the long term stability of natural and technical barriers. HSK defined four criteria to evaluate the suitability of possible formations: *Durability of the properties (2.1)* requires that the rock formation is sufficiently stable during the time frame considered in the safety analysis. *Erosion (2.2)* evaluates whether the long-term stability of the geosphere is hampered by erosion. *Repository induced effects (2.3)* consider whether the chosen host rock formation is insensitive to repository induced processes such as increased temperature, gas formation due to corrosion processes or formation of new water conducting path ways. In order to reduce the likelihood of inadvertent human intrusion into the repository, *Conflicts with other utilisation (2.4)* avoid areas with exploitation potential for resources within or below the host rock formation.

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6. One reason is that HSK guideline R-21 states that radiological consequences from a repository must not exceed a yearly individual dose of 0.1 mSv but does not specify how this safety criterion has to be fulfilled. By choosing an adequate combination of natural and technical barriers, the implementer must comply with the safety criteria. HSK refrained thus from setting specific values for quantities such as thickness of the host rock layer or hydraulic conductivities since the overall retardation of nuclide transport at a given site is dependent on many parameters.

Criteria group 3: reliability of the geological statements

Safety assessments rely on data gained from geological investigations of the host rock and surrounding geological formations. Criteria of group 3 evaluate the reliability of geological characterisation, exploration and predictability. HSK uses the criteria *Characterisation of the rocks (3.1)* and *Ability for spatial exploration (3.2)* to test the suitability of rock formations. Characterisation of the rocks should be feasible as far as possible from the surface. Geological investigations of the host rock must not damage its barrier function. Homogenous host rock formations have therefore a two-fold advantage: a smaller amount of penetrative investigations will enable more reliable data and modelling. The predictability of long-term developments of processes such as climate change or geodynamic activity is an additional element to make safety assessments reliable (*Prediction of long-term changes, 3.3)*.

Criteria group 4: suitability for construction

The selection procedure for a repository must also consider the feasibility of underground engineering. HSK listed two criteria *Rock mechanical properties (4.1)* and *Underground configuration (4.2)*. The implementer has to demonstrate that construction and operation of a repository (including any shafts, ramps or access tunnels) in the chosen regions will face no fundamental geotechnical or hydrogeological problems.

HSK will review the implementer's proposal of regions by focusing on safety related issues:

- Are the implementer's requirements for the choice of the host rock formations/geosphere correctly derived and sufficient to comply with the dose limit of 0.1 mSv/year (HSK/KSA, 1993)?
- Did the implementer use all relevant geological information, and is the quality of the data adequate for the choice of the site regions?
- Did the implementer take the 13 criteria into account for the choice of the siting regions?
- Is the implementer's procedure to choose these regions transparent and plausible?

Quantitative safety analysis for site evaluation (phase 2 of the sectoral plan)

In each of the identified siting regions, the implementer has to choose a site for which he has to carry out a provisional safety analysis. In addition to the safety assessment for the individual sites, aspects such as land planning and socio-economical issues are taken into account to find at least two sites for each repository.

The choice of these sites must be transparent and plausible. In order to achieve this objective, the implementer has to show the contribution of the technical and natural barriers to overall safety and the compliance with the safety criteria (annual dose of less than 0.1 mSv, HSK/KSA, 1993). Any provisional safety analysis must be based on adequate knowledge of the host rock properties, the local geosphere and the geochemical conditions, but site specific data are not required in this phase. HSK may request additional investigations if the quality of the data base for the safety analysis is considered insufficient.

In a first step, the implementer has to define a reference scenario for the provisional safety analysis which should correspond to a realistic description of the expected evolution of the repository including realistic assumptions for the development of the waste forms, the near-field, the far-field, the geosphere and for the radionuclide transport to the biosphere. Within this reference scenario, the implementer has to define a reference case and reference values for the transport relevant parameters to calculate the expected radiological consequences of a potential repository at each chosen site.

In a second step, the implementer has to vary key parameters relevant for nuclide migration such as the water-flow, nuclide specific diffusion parameters, geochemical parameters (solubility, K_d values) according to a procedure to be developed by HSK. The results of these calculations will provide a measure for the robustness of each site. For spent fuel elements, additional variations such as increased dissolution rates for the fuel elements or a limited canister life time will have to be taken into account.

The sites will then be categorised according to the maximum annual dose obtained in the parameter variation procedure: The best category entails all sites with a maximal yearly dose of less than 0.01 mSv. The next category comprises sites with a maximum annual dose between 0.01 mSv and 0.1 mSv. Sites with a maximum annual dose higher than 0.1 mSv are excluded from further considerations.

Based on an assessment of the remaining sites according to the safety criteria, the implementer will propose at least two sites for repository type. This proposal will be reviewed by HSK. If approved by the Swiss government, the site selection enters the final phase (phase 3) of the sectoral plan, in which the implementer collects site-specific data at all the sites, prepares an updated safety assessment and chooses the sites for the realisation of the two repositories. HSK will review the safety assessments. The choice of the sites leads to the general licence application which will be granted by the Swiss government, and must be approved by Parliament: The approval is subject to a facultative national referendum.

Conclusions

The example of the crystalline basement of northern Switzerland, covered by several hundred metres of sediments and characterised by a complex pattern of water conducting discontinuities, illustrates that the availability of geologic data may strongly influence or, in this case, even question the results of the safety assessment. The mostly subvertical discontinuities are invisible in refraction seismic profiles, and their hardly predictable water flow could not be understood by a series of boreholes, leading to uncertainties in the radiological consequences. Next to realistic models, models with conservative parameters had to be used, increasing the resulting annual doses by several orders of magnitude. The combination of a process that turned out to be of high importance and the lack of quantification for the key parameters of this process led to a partial rejection of the submitted safety assessment.

The demonstration of the feasibility of safe disposal in Switzerland was later achieved in an area of very simple geology, as shown by the application of a high-resolution 3-D seismic survey. The ability of spatial exploration has evolved into a prime criterion in the recently started siting procedure.

The doubts about the suitability of the crystalline basement as a host rock by the authorities and the recommendation to extend the search of a suitable host rock into sedimentary rocks has markedly influenced the RD&D programme of the implementer in Switzerland. The establishment of the Mont Terri rock laboratory has to be seen as a result of this recommendation. This rock laboratory has provided a large number of relevant data sets on Opalinus clay and has thus contributed to the successful demonstration of the feasibility of safe disposal by the “Opalinus Clay” project of Nagra.

Accordingly, the repository design had to be adapted to sedimentary host rocks, including a series of alternative FEPs (such as e.g. the influence of the thermal pulse on clay mineral stability, the influence of corrosion gas, the impact of a pH plume on clay mineral stability, the characterisation of an extended deformation zone around disposal tunnels) that had to be investigated and considered in the safety assessment.

The new siting procedure is strongly relying on the geological information available. Lack of geological knowledge will lead to enhanced uncertainties about the radiological evolution and to the exclusion of sites by direct comparison of the site-specific annual doses. In the final phase of the siting procedure, equivalent geologic knowledge among the remaining site candidates will be required as a basis for a final siting decision.

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