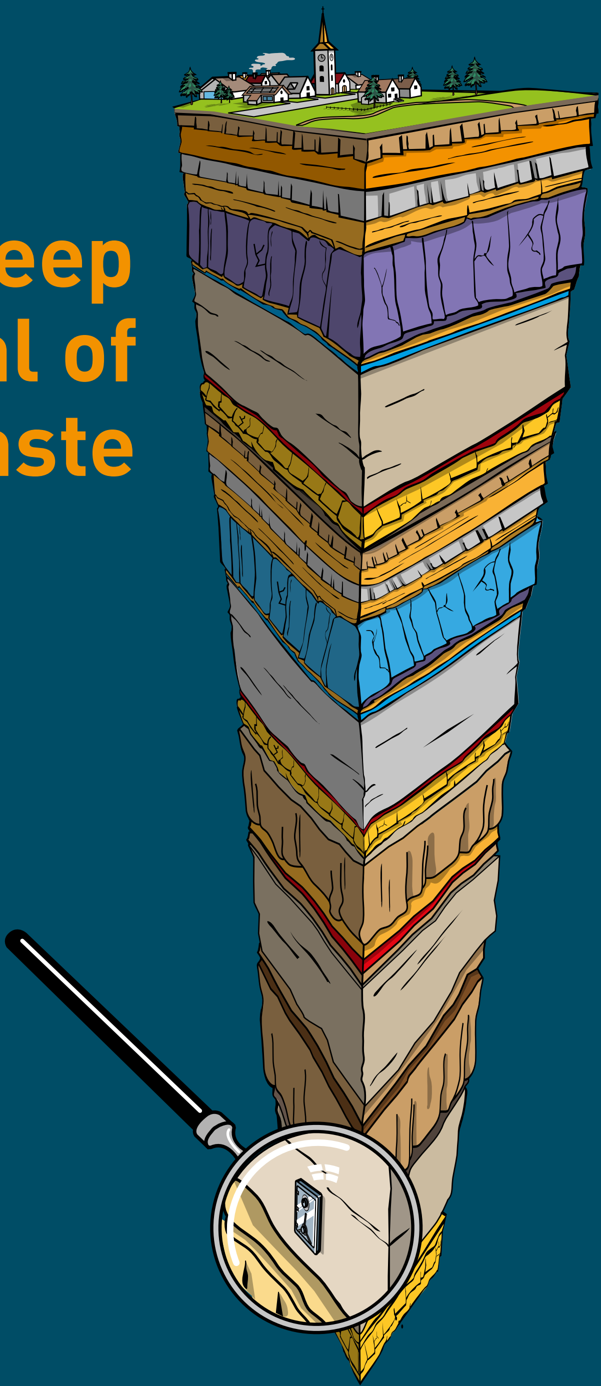
long-term safety

the main goal of deep geological disposal of radioactive waste



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About this brochure

This brochure looks at disposal systems, engineered barriers, the host rock and natural analogues of a deep geological repository for high-level waste arising from the operation of a nuclear power plant.

Visitors attending exhibitions, presentations or other events have questions regarding the long-term safety of a deep geological repository. They are particularly interested in the long-term protection from radioactive substances. Geological challenges such as earthquakes and long-term measures to ensure the safety of future generations are also discussed. This brochure explains the most important aspects of these questions.

A selection of the terminology used in this brochure is explained in the Glossary starting on page 32.

Long-term safety – the main goal of deep geological disposal of radioactive waste
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The most important poi
Long-term safety – an introduc

Switzerland's radioactive waste must be disposed of safely, which means isolating it from the human environment for a very long period of time.

Protection against radioactivity

Natural radiation is part of our habitat (see Figure 1). Humans must be protected against excessive exposure to radiation because it can damage their health. It is easy to protect against a radiation source outside the body (external radiation) by using suitable shielding, keeping a safe distance or by limiting the exposure time. Internal radiation is caused by absorbing radioactive substances (radionuclides) that decay inside the body. It is possible to protect against this radiation type by avoiding the ingestion of radionuclides.

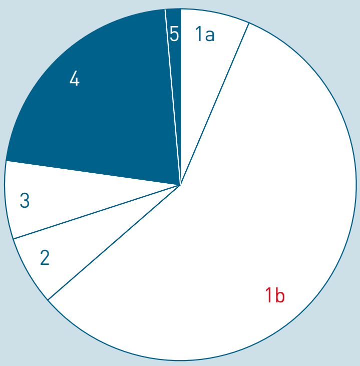
Radioactive waste must be safely confined and isolated from the human habitat to prevent radionuclides being taken up into the human body.

Consensus on deep geological disposal

As opposed to chemical waste, the toxicity of radioactive waste decreases with time due to decay. However, long containment periods are needed until the radiation level of radioactive waste has decreased to a level equivalent to that found in nature (see Figure 7, pages 12-13).

At the earth's surface, within the sphere of human influence, conditions do not remain stable over long periods of time. World history is marked by social and political upheavals. A repository at the surface would have to be actively monitored the entire time. Safe containment would depend on a well-functioning society.

Underground geological processes occur extremely slowly and are unaffected by what is happening at the earth's surface. Earth's history shows us that many rock formations can remain stable over millions of years and barely alter their properties. Compared to the timescales over which these geological processes occur, the necessary contain-



natural	1 Internal radiation	
	a) caused by ingesting food	0.35 mSv
	b) caused by air breathed indoors (radon and decay products)	3.2 mSv
	2 Radiation emanating from soil and rock	0.35 mSv
	3 Cosmic radiation	0.4 mSv
synthetic	4 Medical applications	1.2 mSv
	5 Others: industrial applications including atom bomb tests, Chernobyl, nuclear installations, research	< 0.1 mSv
	Total	5.5 mSv
	Radiation doses from medical applications and radon show a large scatter.	

Figure 1
Average annual radiation exposure for a Swiss resident according to the Swiss Federal Office of Public Health (2014): Further data are available in Figure 6 on page 11.

nts at a glance

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ment period for high-level waste is relatively short. In a deep geological repository, impermeable rock formations confine the waste passively – without human intervention. Today, there is international consensus that high-level waste should be disposed of in stable underground rock formations. The waste solutions discussed have not only included deep geological disposal or disposal at the earth's surface. Other options that have been considered and, in some cases, even carried out include dilution, deep sea disposal or even disposing of radioactive waste in outer space. However, some of these concepts carry high risks for humans and the environment and they have been abandoned. The Swiss Nuclear Energy Act stipulates deep geological disposal (see text-box below). The radioactive waste must remain retrievable after emplacement.

Barriers provide safety

In deep geological repositories, the radioactive substances are safely enclosed by containers, tunnel backfill, repository installations and by the surrounding rock. These engineered and natural barriers (so-called safety barriers, see page 17) prevent unacceptable amounts of radioactive substances from being dissolved by water and migrating through the surrounding rock to the earth's surface where they can reach our habitat. They ensure that the strict protection objectives for humans and the environment will be reliably complied with over long time periods.

Scientists around the world agree that deep geological disposal of high-level waste is the safest solution. Underground, the waste can decay over millennia until it has reached a harmless level.

Several engineered and natural safety barriers in a deep geological repository ensure that the high-level waste is isolated from the human habitat at the earth's surface for a very long period of time.

Nuclear Energy Act

The Swiss Nuclear Energy Act stipulates deep geological disposal for all types of radioactive waste:

Art. 31 Obligation to manage and dispose of radioactive waste

1 Anyone who operates or decommissions a nuclear installation is obliged to safely manage all radioactive waste arising from that installation at their own cost. The obligation to manage and dispose of radioactive waste shall encompass the necessary preliminary activities such as research and geological investigations, as well as the timely provision of a deep geological repository.

Art. 37 Operating licence

1 An operating licence for a deep geological repository is granted if […]:
a. the findings obtained during construction confirm the suitability of the site;
b. it is possible to retrieve the radioactive waste without undue effort until closure of the repository.

Safe containment in the future

While the radioactivity is decaying, slow processes are taking place inside the deep geological repository: The bentonite backfill becomes saturated with water and the disposal canisters corrode. The behaviour of the bentonite and the Opalinus Clay host rock has been thoroughly researched. It is thus possible to make detailed statements about the future evolution of the repository until the radioactivity has decayed to natural levels (see pages 18-25).

Learning from nature

The materials intended for use in the engineered barriers of a deep geological repository can be found in similar form either as natural ore deposits or as archaeological relics, or even both. These "natural analogues" can be regarded as a type of long-term experiment and offer valuable examples of the long-term behaviour of deep geological repositories (see pages 26-27).

By conducting experiments in underground rock laboratories in Switzerland and using models, scientists investigate the future behaviour of the safety barriers in a deep geological repository.

Studies on natural processes that extend over very long periods of time help us to understand the long-term evolution of deep geological repositories.

Figure 2
More than 100 people are working for Nagra on radioactive waste disposal in Switzerland.

Safety has the highest priority

The correct site selection and layout of the repositories ensure long-term safety. Nagra conducts extensive safety analyses to investigate the functioning of the engineered and natural barriers after the repository has been properly sealed. Increasingly detailed safety analyses are stipulated in all stages of the Sectoral Plan for Deep Geological Repositories, as well as for the following licensing procedures. These analyses must demonstrate that the population at the earth's surface is not exposed to potential additional radiation doses exceeding a specified level, namely the protection criterion of 0.1 Millisievert annually. This is equivalent to one fiftieth of the average annual radiation exposure of a resident of Switzerland.

Information for the future

The topic of how to mark a deep geological repository is frequently discussed. The purpose is to avoid unintentional intrusion into the repository. There are different options for preserving information on a repository over long periods of time.

Nagra conducts extensive safety analyses and models the performance of the engineered and natural barriers after the closure of a deep geological repository.

Many countries around the world are occupied with the question of how to safeguard knowledge about deep geological repositories for future generations. One possibility is to keep the information in several archives.

Long-term safety – why?

The effect of radioactivity on hu

Radioactive waste must be safely confined and isolated from the human habitat to prevent the radionuclides contained in the waste from entering the human body.

Radiation is a natural component of our environment, coming mainly from soil and rocks. This includes the radioactive noble gas radon that can escape from below ground and accumulate in basements and cellars. Various other sources also contribute significantly to natural radiation exposure (see Figure 1, page 4, and Figure 6, page 11).

Radioactive substances emit ionising radiation. There are three types: alpha, beta and gamma radiation. All of these have the ability to expel electrons from the atomic shell. This can lead to the breaking up of chemical compounds, which is why these radiation types are termed ionising. Alpha and beta radiation consists of particles. They are made up of helium nuclei and electrons. Like light or radio waves, gamma waves are electromagnetic waves, but their wavelengths are much shorter, and they therefore have higher energy.

How to protect against radiation?

Three principles apply to protection against external radiation:

- Using shielding
- Maintaining a safe distance
- Limiting exposure time

It is possible to shield radiation sources. Depending on the radiation type, materials of differing thickness are needed. To retain alpha rays, a piece of paper or a few centimetres of air already suffice. Alpha rays do not penetrate the body's uppermost layers of skin. To shield beta rays, a sheet of aluminium with an approximate thickness of two millimetres is needed. This radiation type can

Figure 3
Spent fuel assemblies in the Swedish interim storage facility CLAB in Oskarshamn: The radiation from the spent fuel assemblies is shielded by water.

mans

penetrate human tissue. Dense materials are needed to stop gamma rays. For example, to halve the gamma radiation emitted from the radionuclide caesium-137 (unstable isotope of the element caesium), seven millimetres of lead or 1.5 centimetres of iron are needed (see Figure 4). In nuclear power plants, water is used to shield against the radiation emitted by spent fuel assemblies (see Figure 3).

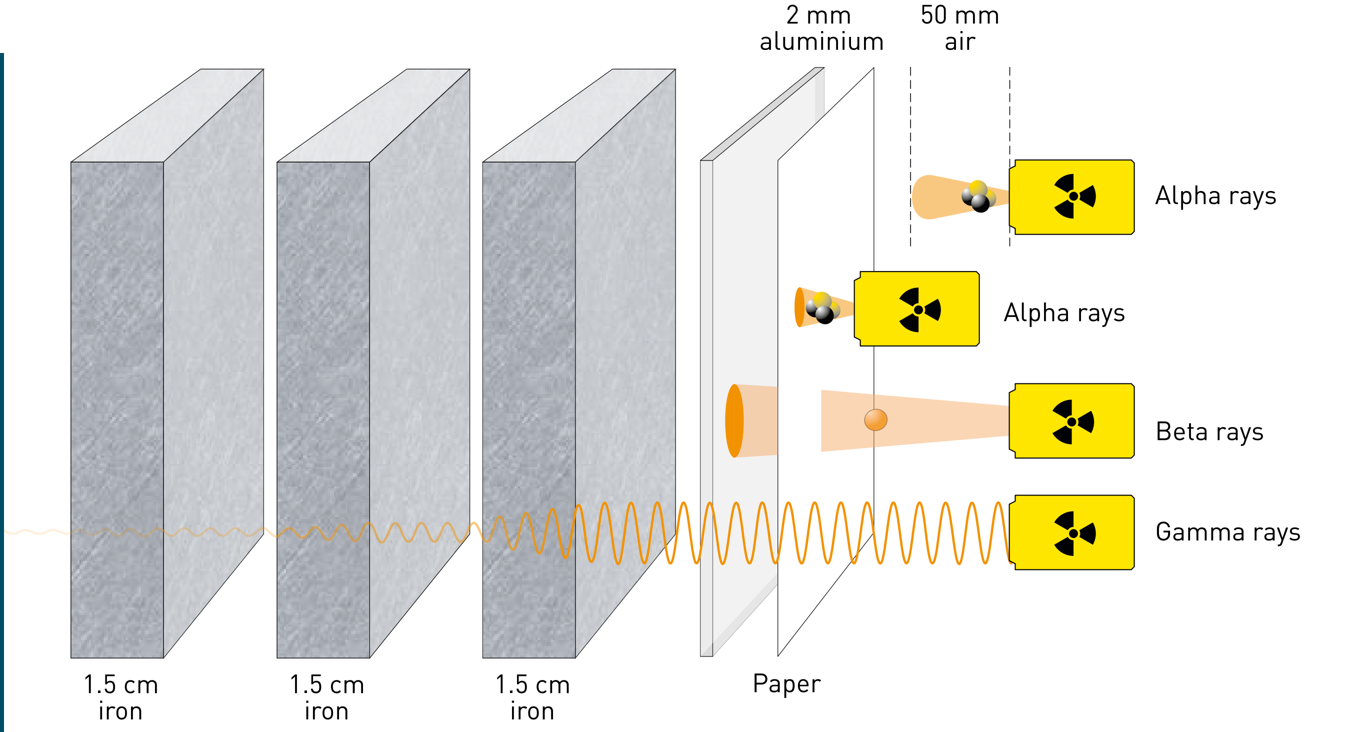
The effect of radioactive substances on human health is greater when they are ingested than when they impact the body externally.

Unit

Sievert (Sv)
The dose caused by ionising radiation (alpha, beta, gamma and X-rays) is measured in Sieverts (so-called dose equivalent), which is a measure of the biological effect of radiation. The same dose in Sieverts represents an equivalent radiation dose.

1 Sv = 1 000 mSv (Millisievert)

Figure 4
Shielding of different radiation types



Avoiding radiation exposure

It is possible to protect against internal radiation by avoiding the ingestion of radioactive substances through food, drinking water or air (see Figure 5). Filter masks, for example, are a possible protective measure when working with volatile radioactive substances in research or industry. In a private environment, it can be useful to air out the basement regularly to avoid exposure to radon. Surface contamination with radioactive substances can be washed off.

Inside the body, ingested radioactive substances decay, which can directly damage cells, tissue or organs. The duration of the radiation exposure depends on the half-life and the biological residence time of the radionuclides in the body.

Dose: a measure of effect

The effects of radiation depend on the ingested dose. If a dose of approximately 250 Millisieverts is ingested within a short period of time, the first signs of radiation sickness appear. This amount is more or less equivalent to the radiation exposure of 20 computer tomography scans from stomach to pelvis (see Figure 6). If the dose increases further, nausea, vomiting and headaches can occur. Excessive radiation exposure can lead to long-term damage such as cancer.

Ensuring safe containment

Radioactive waste must be safely enclosed and isolated from the human habitat (biosphere) to avoid the uptake of radionuclides into the body. To ensure this, Switzerland's radioactive waste will be disposed of in a deep geological repository.

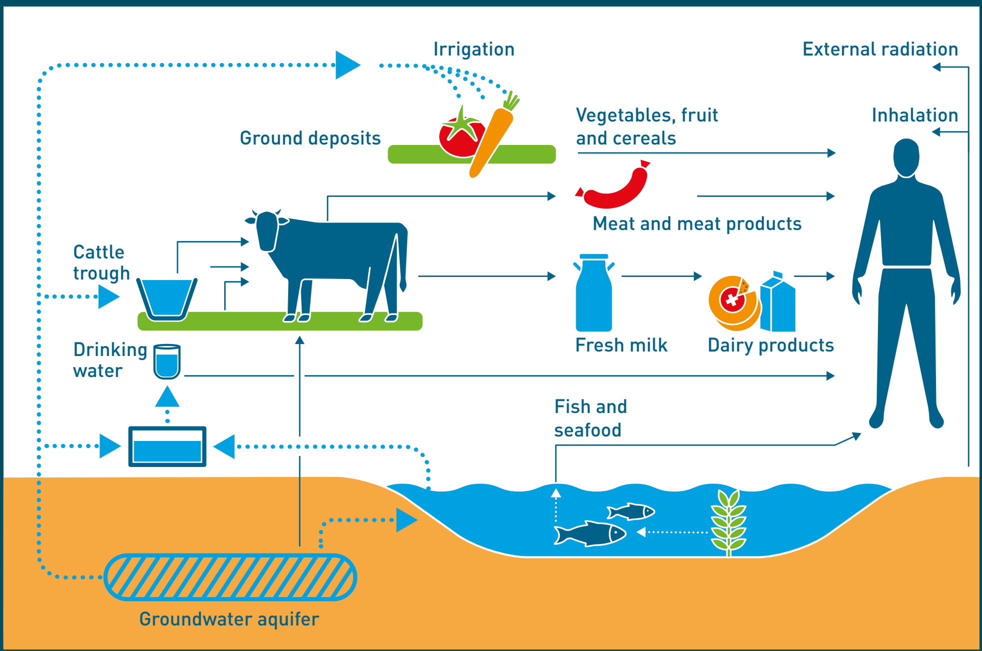


Figure 5
Absorption of radionuclides by the human body

Radiation doses from natural and artificial sources

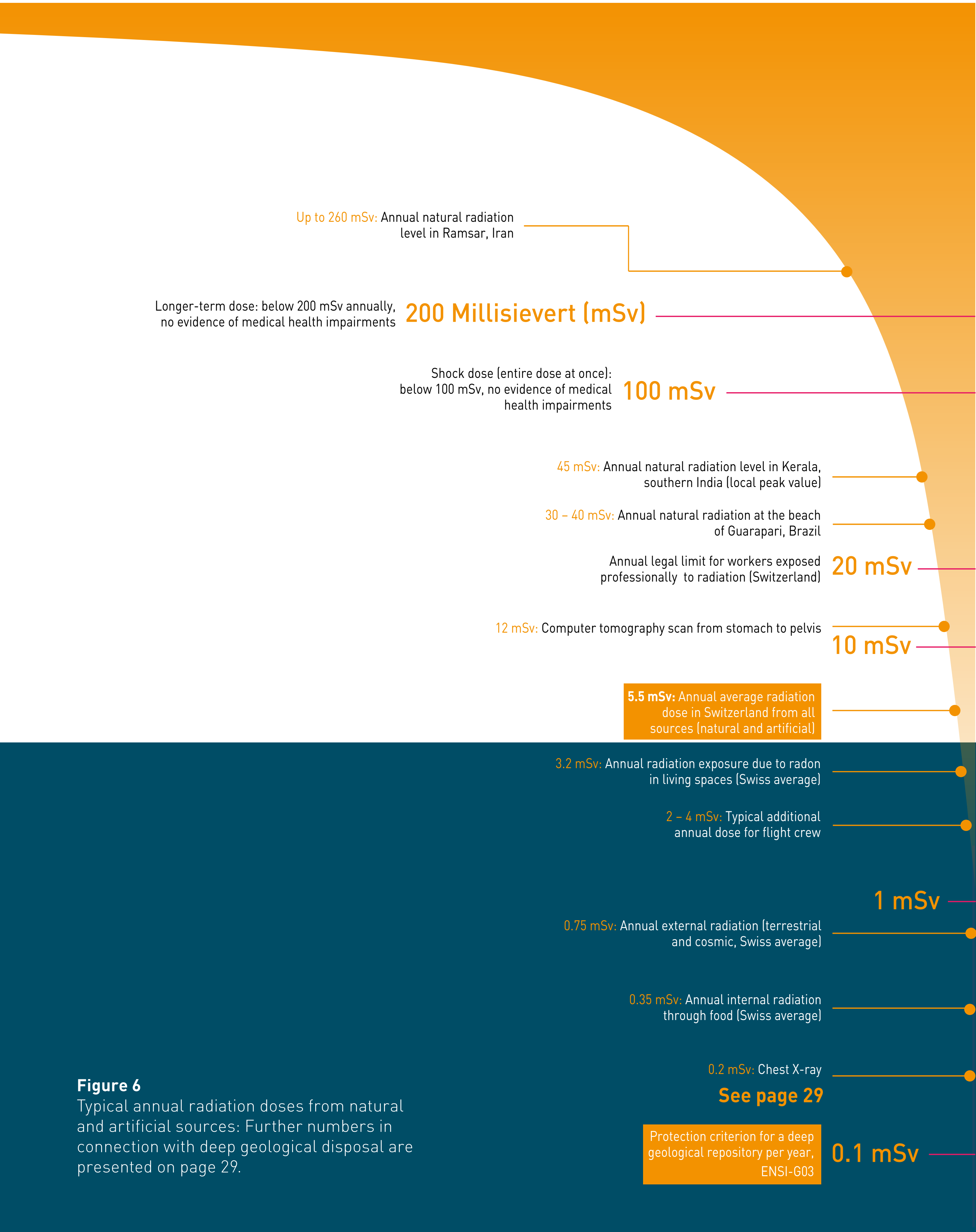


Figure 6
Typical annual radiation doses from natural and artificial sources: Further numbers in connection with deep geological disposal are presented on page 29.

Today, tomorrow and th

Deep geological repositories fo

Scientists around the world agree that deep geological disposal of radioactive waste is the safest solution. Underground, the waste can decay over millennia until it has reached a harmless level comparable to that of natural radiation.

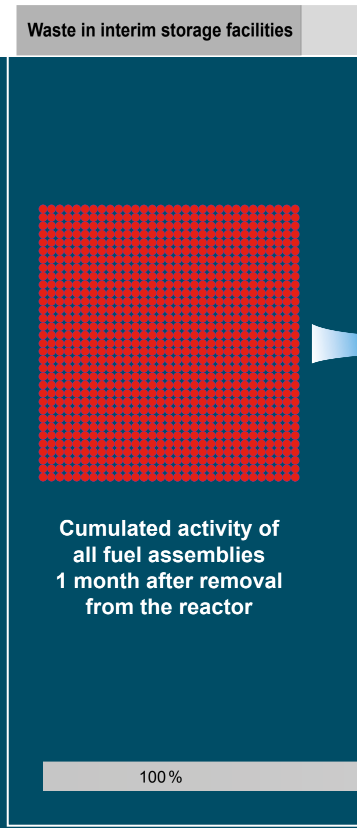
Radioactive waste must be disposed of in a way that ensures the permanent protection of humans and the environment. To achieve this goal, it must be kept separate from our habitat. Numerous geological investigations have shown that the underground in different areas of Switzerland has remained undisturbed over very long periods of time. It can be shown that rock formations remain stable and retain their properties over many millions of years, allowing for the safe containment of radioactive waste over long timescales. Deep underground and unaffected by occurrences at the earth's surface, time essentially comes to a standstill.

How long must the waste be contained?

Most of the radioactive waste decays quickly (see Figure 7). After around two hundred years, the radiation level of the waste in a deep geological repository amounts to only a few per cent compared to its level at the time of emplacement. The proportion of radioactive substances with long half-lives radiates less strongly but over a longer period of time.

After 200 000 years, the high-level waste (HLW) is about as radiotoxic as the corresponding amount of natural uranium ore that was mined to make fuel assemblies. For the safety analyses, a time period of one million years is considered.

Figure 7
Decay of high-level waste over a time period of one million years



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r long-term protection

Other concepts rejected

Aside from deep geological disposal, other waste solutions have been examined. These include:

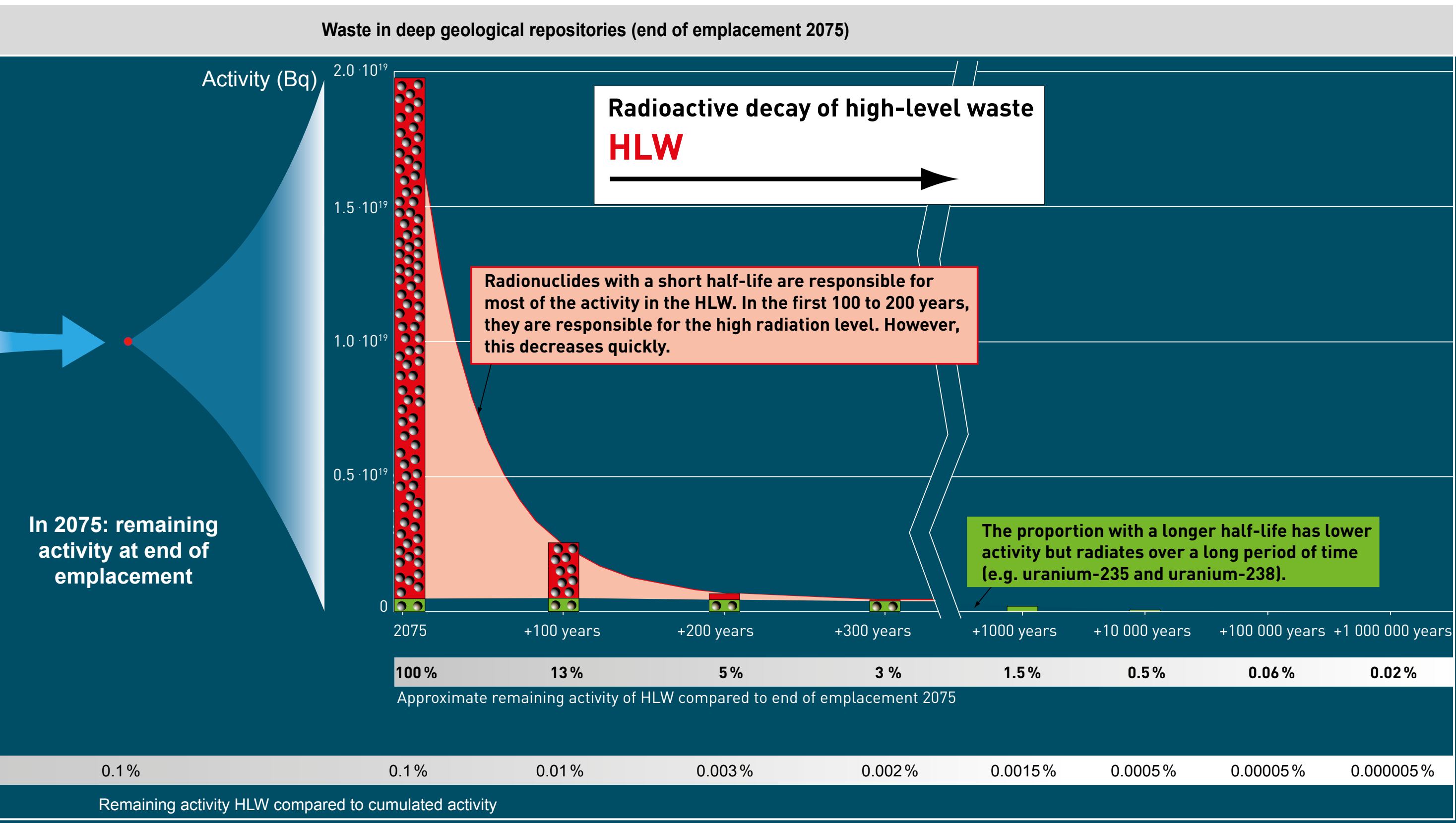
- Diluting the radioactive waste in the environment
- Disposal in undisturbed marine sediments
- Disposal in Antarctic ice-sheets
- Disposal in outer space

These concepts are no longer pursued. Disposing of waste in the sea, for example, is highly disputed and legally prohibited today. Using rockets to aid in disposal is too risky in case of explosions on take-off.

In Switzerland, the Nuclear Energy Act stipulates the disposal of radioactive waste in deep geological repositories. This is considered the safest method not just in Switzerland but is recognised by experts worldwide.

Long-term safety from the very beginning

Measures for the long-term safety of a deep geological repository already begin during site selection, layout and the construction of underground installations. During the site selection process, zones with deformed rock layers (fault zones) are avoided. The repository must, on the one hand, be constructed at sufficient depth to be protected from glaciers and erosion. On the other hand, excessive depth can compromise the engineered barriers and the host rock. The layout of the emplacement drifts in the host rock is important for the optimised emplacement of the radioactive waste. This ensures the best conditions for the permanently safe containment of the wastes.



Opting out of deep disposal means monitoring

Should a deep geological repository not be constructed, the waste would have to be permanently stored at the earth's surface. This would present society with an unsolvable task. Monitoring and maintaining such surface facilities would have to be ensured over many millennia. Societal developments are not foreseeable over such long time periods. Wars, revolutions, but also epidemics, could disrupt the continued monitoring of the waste, and there would be a risk of letting it fall into the wrong hands.

Sealed, but monitored

The Nuclear Energy Act stipulates the monitoring of radioactive waste. In the pilot repository (see page 16), the behaviour of the different safety barriers can be monitored after closure of the emplacement drifts. During this period, it must be possible to retrieve the waste without significant effort.

The monitoring results must be applicable to the processes occurring in the main repository as they form the basis for the decision to close the deep geological repository (Nuclear Energy Act, Article 66).

The duration of the monitoring phase is not stipulated. Future generations must decide themselves if and when they want to implement the final closure of the repository.

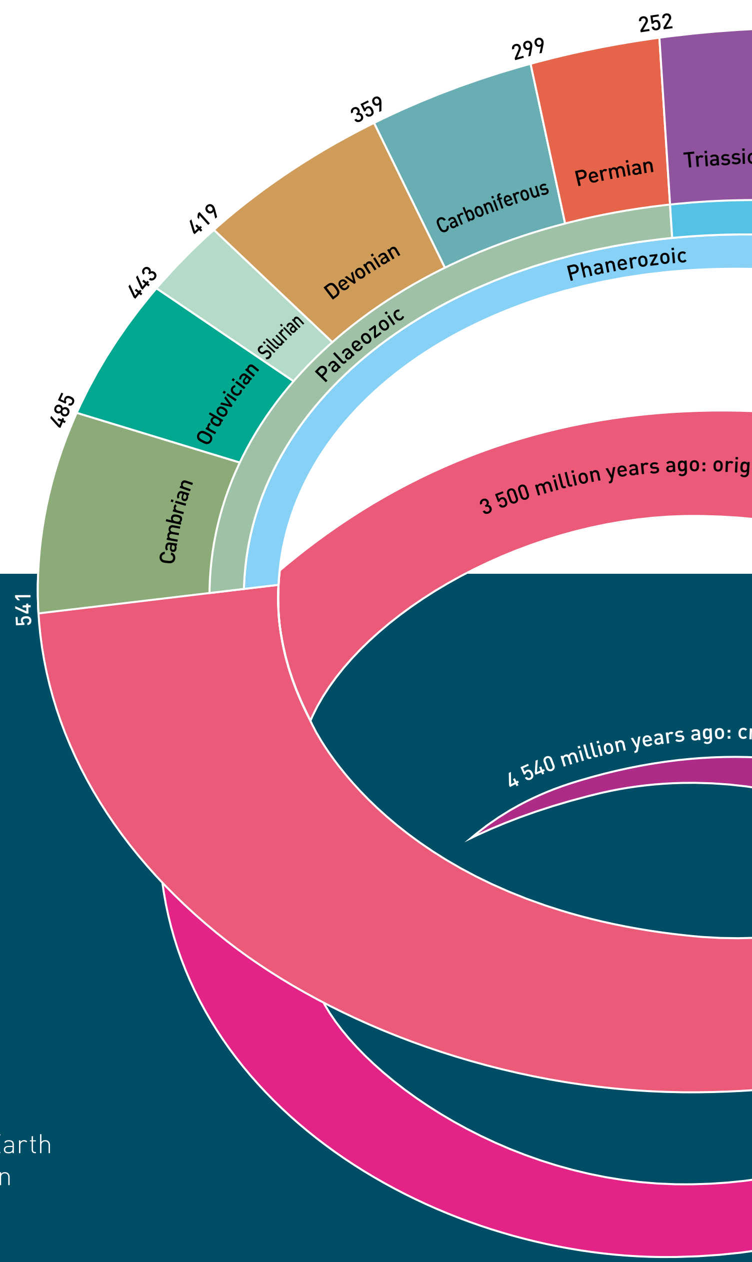
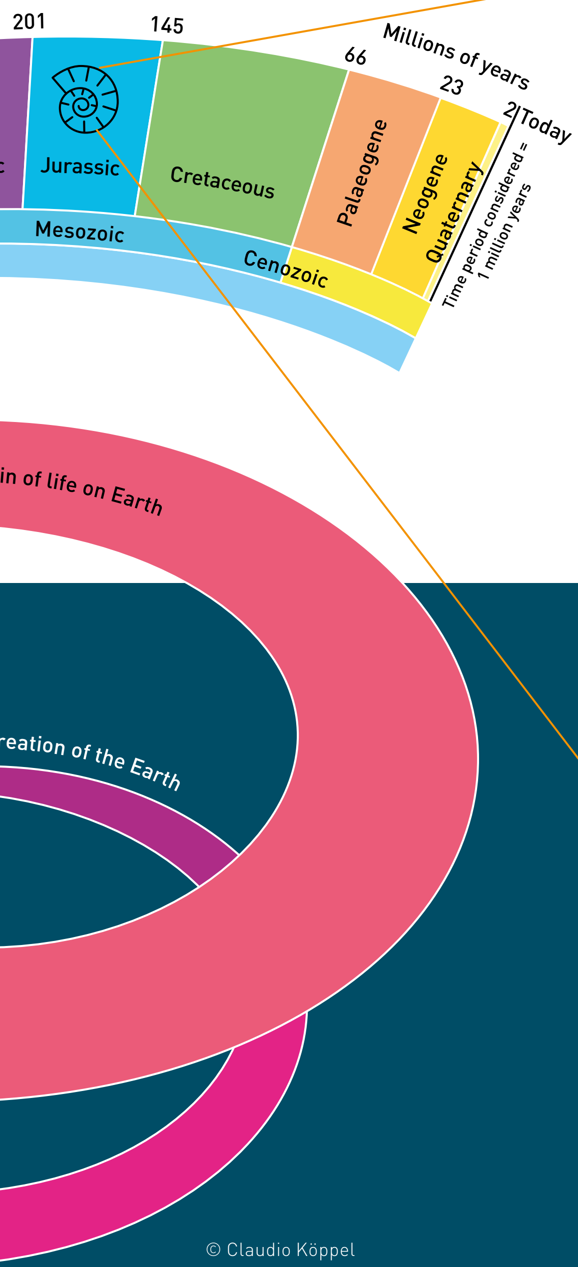


Figure 8
By the standards of human history, one million years is an inconceivably long time period. Compared to the age of the Earth (4.54 billion years) or the age of the Opalinus Clay (175 million years) proposed as the host rock for radioactive waste in Switzerland, it is only a short amount of time.

Barriers provide safety

In accordance with the Swiss disposal concept, a deep geological repository can be left unsupervised once it has been permanently closed. This means that it is passively safe during the entire containment period and does not require monitoring in the long term. The repository is robust against future developments at the earth's surface or underground – with no need for human intervention. This is made possible through different engineered and natural barriers that reliably contain the radioactive waste.



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Opalinus Clay as the host rock

The argillaceous rock Opalinus Clay was formed in a shallow sea approximately 175 million years ago during the Jurassic period. Properties such as self-sealing and good radionuclide retention make the Opalinus Clay an ideal host rock for deep geological repositories. The Opalinus Clay was named after the fossil shells of the ammonite "Leioceras opalinum". Its name is derived from the iridescent (opalescent) sheen of its shell.

Deep geological disposal – safe

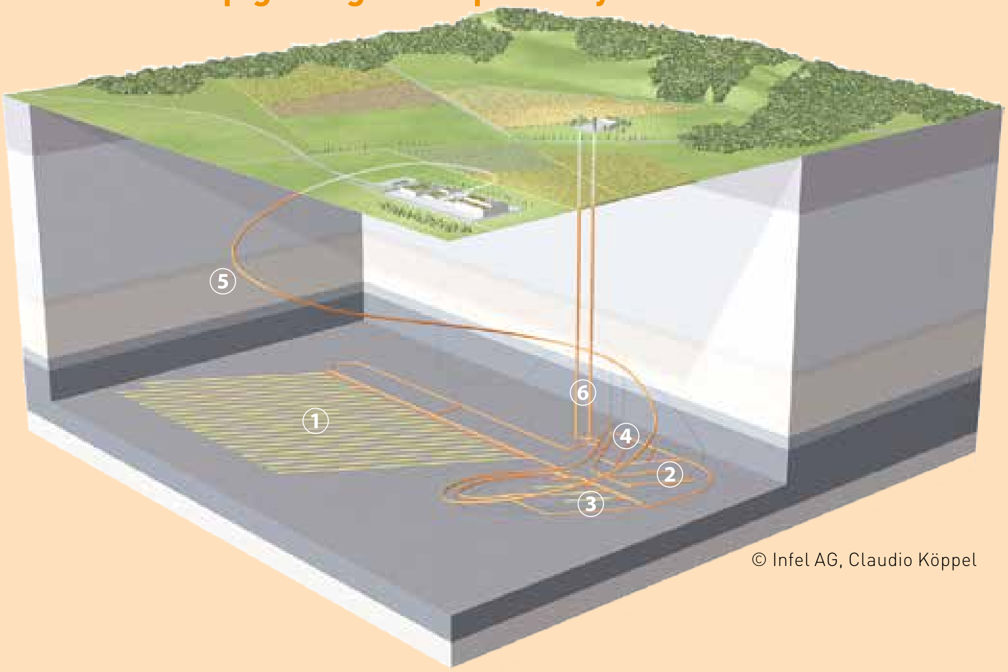
High-level waste must be isolated from the human habitat and thus also from the earth's surface for a very long period of time. This can be ensured by multiple safety barriers.

The safe containment of radioactive waste in a deep geological repository over long timescales (see text-box) can be ensured through a combination of engineered and natural barriers (see page 17).

Every individual barrier has the task of protecting the waste from disturbances and retaining the radioactive substances until they have decayed to natural levels.

The next pages provide a brief insight into how these safety barriers work.

Components of a deep geological repository for HLW



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1 Main repository for SF/HLW
Emplacement drifts for spent fuel assemblies and high-level waste

2 Repository for long-lived ILW
Emplacement rooms for long-lived intermediate-level waste

3 Pilot repository
Short emplacement drift in the deep geological repository where a representative volume of radioactive waste is disposed of. The pilot repository will be observed during the entire operating and monitoring period

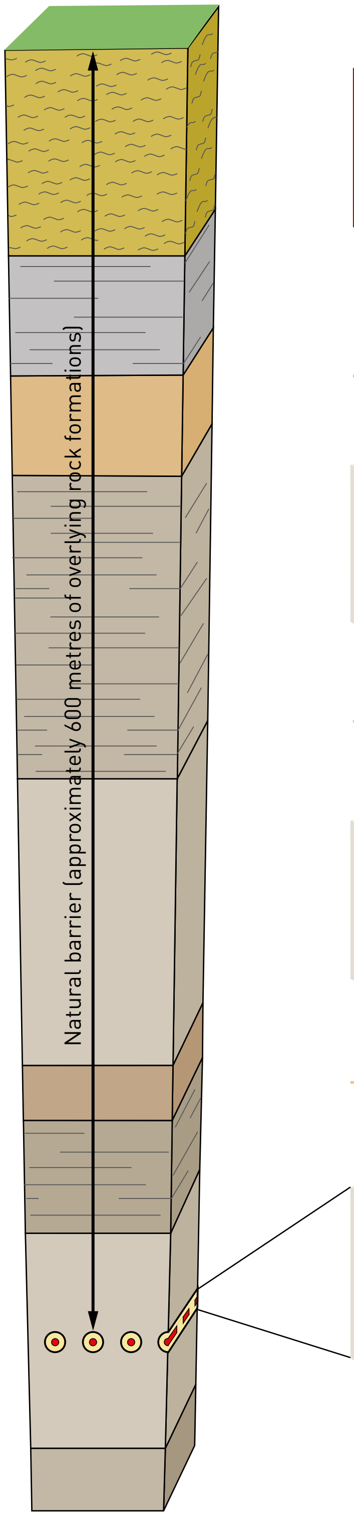
4 Test area
This area is used for collecting data required for the operation of the facility

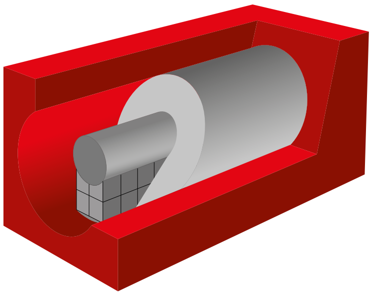
5 Access tunnel
Access from the surface facility to the deep geological repository; access through shafts is also possible

6 Ventilation shaft and construction shaft
Shafts for the construction and ventilation of the deep geological repository

ty over long time periods

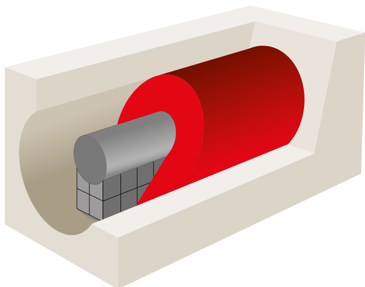
Safety barriers in a deep geological repository for high-level waste (HLW) and spent fuel assemblies (SF)





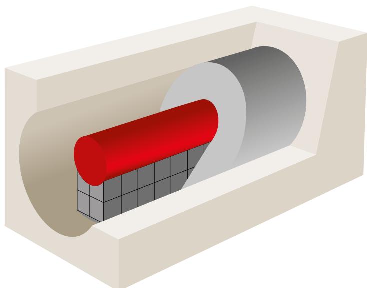
Natural barrier

- The emplacement drifts are constructed in the **host rock** (Opalinus Clay). The permeability of the rock is very low. Like bentonite, Opalinus Clay can bind radionuclides and thus retain them. The host rock and the rock layers above it protect the waste and the engineered barriers (e.g. against glaciers and erosion).



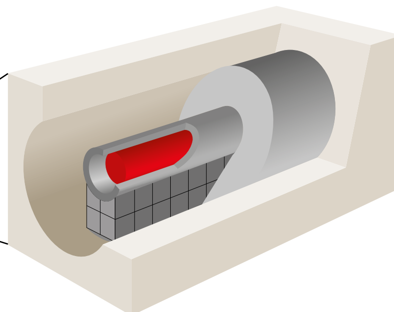
Engineered barrier

- The **bentonite** (clay) tunnel backfill has a very low permeability and swells on contact with moisture, thus sealing fissures and fractures. The clay minerals bind radionuclides.



Engineered barrier

- The thick-walled **disposal canisters** prevent the release of radioactive substances for at least 10 000 years.



Engineered barrier

- The **glass matrix** or the **fuel assemblies** and the radionuclides they contain have a very low solubility. This means that even when water enters the disposal canisters, radionuclides are dissolved in the water at a very slow rate.

The future evolution of a deep g

By conducting experiments in underground rock laboratories in Switzerland and using models, scientists investigate the future behaviour of the safety barriers in a deep geological repository.

0 to 100 years

Bentonite slowly saturates

After the emplacement of the disposal canisters, the voids in the drifts of the main repository are backfilled with bentonite (see Figure 9). The bentonite slowly saturates with porewater that gradually diffuses from the surrounding Opalinus Clay host rock into the bentonite around the canisters. No free water flows through Opalinus Clay but it is still contained in its pore spaces. The water volume bound in the rock is approximately 120 litres per cubic metre of Opalinus Clay. By absorbing water, the bentonite begins to swell and thus forms a practically impermeable homogeneous mass. The swelling bentonite also closes fissures generated during the construction process. The bentonite thus supports the self-sealing capacity of the Opalinus Clay.

Waste remains under control

Approximately 20 years after the start of emplacement, all the drifts are backfilled and sealed. Accesses to the deep geological repository remain open during the entire monitoring phase. The waste is monitored in a pilot repository (see page 16). It is important that the sensors used for monitoring have a long operational lifetime as they have to work properly for decades. At present, for example, scientists at the Mont Terri Rock Laboratory are examining fibre-optic cables for measuring temperature. These sensors may be suitable for future use in a pilot repository.

Figure 9
At the Mont Terri Rock Laboratory, an experiment is already being conducted to test the backfilling of the emplacement drifts on a 1:1 scale.

eological repository

100 to 1000 years

Once the monitoring phase has ended, the deep geological repository is closed and all underground installations and access structures that are still open are backfilled and sealed. Monitoring can then be continued from the earth's surface.

Canister as a strong barrier

The current reference concept foresees the use of steel disposal canisters with a wall thickness of at least 15 centimetres. They must effectively contain the radioactive waste during the first thousands of years (see Figure 10). Alternative materials include copper or ceramics; Nagra is currently investigating these in cooperation with international research partners. The disposal canisters are expected to have a minimum lifetime of 10 000 years.

Radiation shielded

Direct radiation is shielded by the canisters, the tunnel backfill, the repository installations and the host rock. At a distance of just one to two metres from the tunnel wall, the radiation level of high-level waste is already below that of the rock's natural radiation level.

Conflicts of use can be ruled out

Potential conflicts of use are taken into consideration when selecting the siting regions. Of particular importance is whether economically exploitable raw materials exist in or close to the host rock. These include petroleum, natural gas or a potential geothermal energy source. Avoiding these regions reduces the risk of future generations looking there for these types of raw materials.

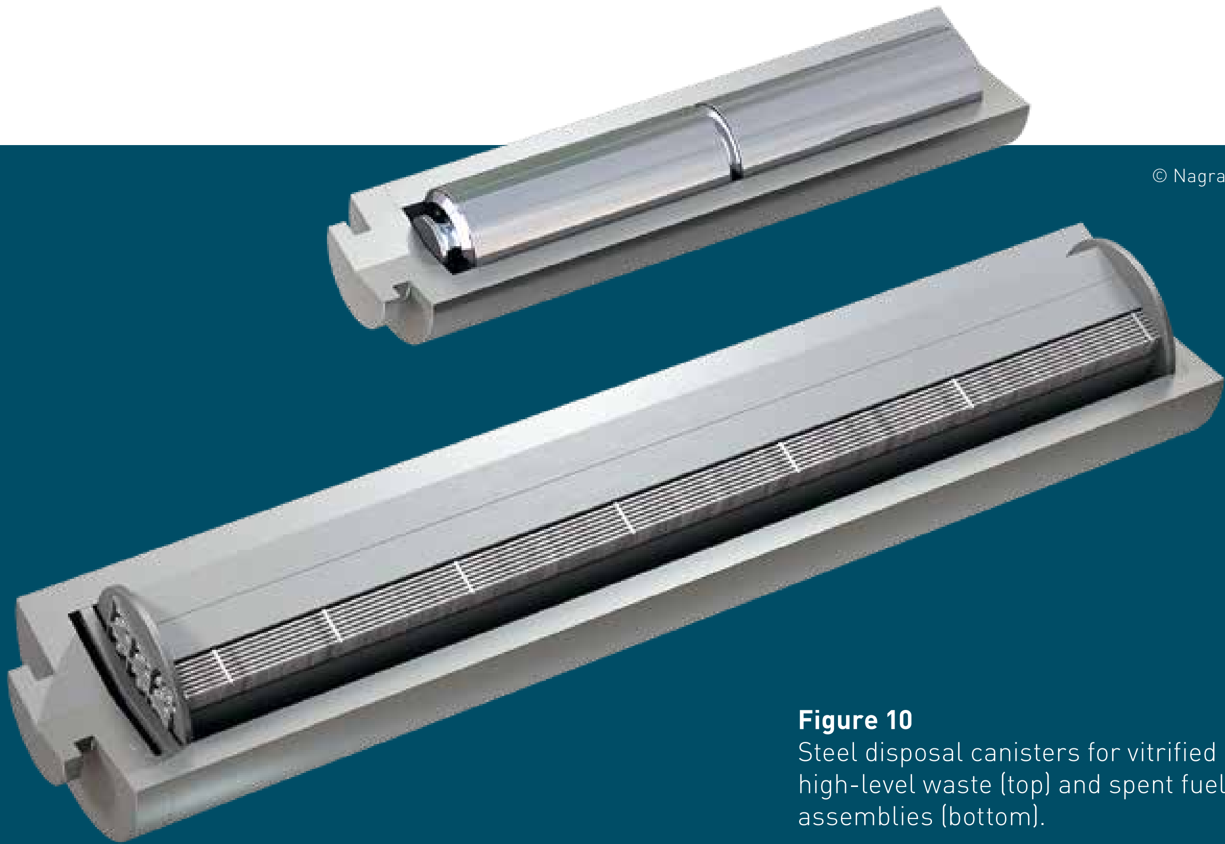


Figure 10
Steel disposal canisters for vitrified high-level waste (top) and spent fuel assemblies (bottom).

1000 to 10 000 years

Bentonite is saturated with water

By now, the bentonite is completely saturated with water and its properties resemble those of the surrounding host rock. It is practically impermeable and has the ability to bind radionuclides. This means that most of the substances remain attached to the clay minerals and are prevented from migrating further.

Waste cools down

The heat generated by the decay of the radionuclides in the high-level waste decreases continually over time. After approximately 1000 years, the thermal output of the fuel assemblies amounts to only roughly eight per cent of the value at the time of emplacement. The temperatures of the waste and the surrounding host rock have equalised.

Effects of gas formation can be controlled

The disposal canisters begin to corrode on contact with porewater. As part of the reaction between water and iron, hydrogen gas is produced. This non-radioactive gas must be allowed to escape or its volume reduced to avoid any unacceptable increase in the pressure in the emplacement drifts. Gas production could otherwise lead to the formation of fissures in the host rock and create pathways that could accelerate the migration of radionuclides. Experiments in the Mont Terri and Grimsel rock laboratories (see Figure 11) as well as calculations show that, even when steel disposal canisters are used, the gas pressures in the emplacement rooms remain below the point where the formation of fissures in the host rock is expected. The gas can be released at the interfaces between the host rock and bentonite.

Figure 11
Numerous experiments are being conducted in the Mont Terri Rock Laboratory, including some on gas transport.

10 000 to 100 000 years

The disposal canisters are designed to remain absolutely tight for at least 10 000 years. Later, when they may have corroded through, the waste can come into contact with the surrounding porewater from the bentonite.

Radioactive substances can now dissolve very slowly from the spent fuel and the vitrified waste from reprocessing. Both are only poorly water-soluble. As there is no flowing water surrounding the waste canisters, the dissolved radionuclides can only move through the bentonite very slowly by diffusion.

What is diffusion?

Diffusion is a passive equilibrium of the concentration of dissolved substances between areas with higher and lower concentrations. A simple example is when a sugar cube is dropped into a cup of coffee. After a while, the coffee becomes sweet even if it has not been stirred. The sugar molecules diffuse until the level of sweetness in the coffee is the same everywhere, in other words until the concentration of sugar molecules has equalised in the coffee.

The host rock becomes the most important barrier

Radionuclides that have not yet decayed in the canister or during diffusion through the bentonite are retained by the Opalinus Clay as an additional natural barrier (see Figure 12).

Figure 12
Nagra has evaluated the Opalinus Clay as a host rock for the deep geological repository for high-level waste and spent fuel assemblies.

Like bentonite, the Opalinus Clay has the ability to retain radionuclides. In addition, it is practically impermeable. Material transport is mainly by diffusion, as in bentonite.

Keeping radionuclides away from the human habitat

To keep radionuclides away from the human habitat, the deep geological repository must limit the transport of radionuclides with groundwater by means of a system of safety barriers. Even if faults are present in the rock formations, groundwater cannot penetrate into the repository via these disturbances and enable the transport of radioactive substances. This is due to a further characteristic of the host rock: its self-sealing capacity. When Opalinus Clay comes into contact with water, its clay minerals begin to swell. Any fissures that formed are closed again and potential water flowpaths are sealed (so-called self-sealing). This has been demonstrated in numerous experiments and can be directly observed in outcrops (see Figure 13).

Legend

Fault zone

Shear direction

Figure 13
A fault zone runs through the Opalinus Clay in the photo, but the rock remains dry (Mont Terri Rock Laboratory).

Up to 1 000 000 years

No climate model can offer a reliable forecast over such a long time period. Within one million years, climate conditions will probably change several times and extensive glaciation cannot be ruled out. For this reason, different climate scenarios are considered for site selection.

Deep beneath the glacier

Geological processes such as erosion occur very slowly. However, to reliably prevent the exposure of the repository through glacial impacts or through uplift of the earth's surface (with erosion occurring simultaneously), it must be constructed at a suitable depth. A HLW repository should be constructed at a depth of approximately 600 metres below the earth's surface depending on the site (see Figure 14, pages 24-25). Past geological developments provide clues about future erosion rates. It is thus possible to predict the future based on past events.

Nature also shows us how natural disposal systems, barriers or the host rock behave over very long periods of time. Examples of this are presented in the following section on natural analogues. They provide parameters and important indications for the model calculations.

Earthquakes – a danger for deep geological repositories?

Strong earthquakes cannot be ruled out during the long time period under consideration. Deep geological repositories are thus constructed away from known underground fault zones, avoiding faults where stress can build up and suddenly be released. Within the disposal zone, a safe distance is maintained from faults. This prevents the disturbance of disposal containers and engineered and geological barriers due to movements at such zones. Fractures newly formed by earthquakes are quickly closed due to the swelling of the clays. This prevents radioactive substances from migrating with the water in the fracture.

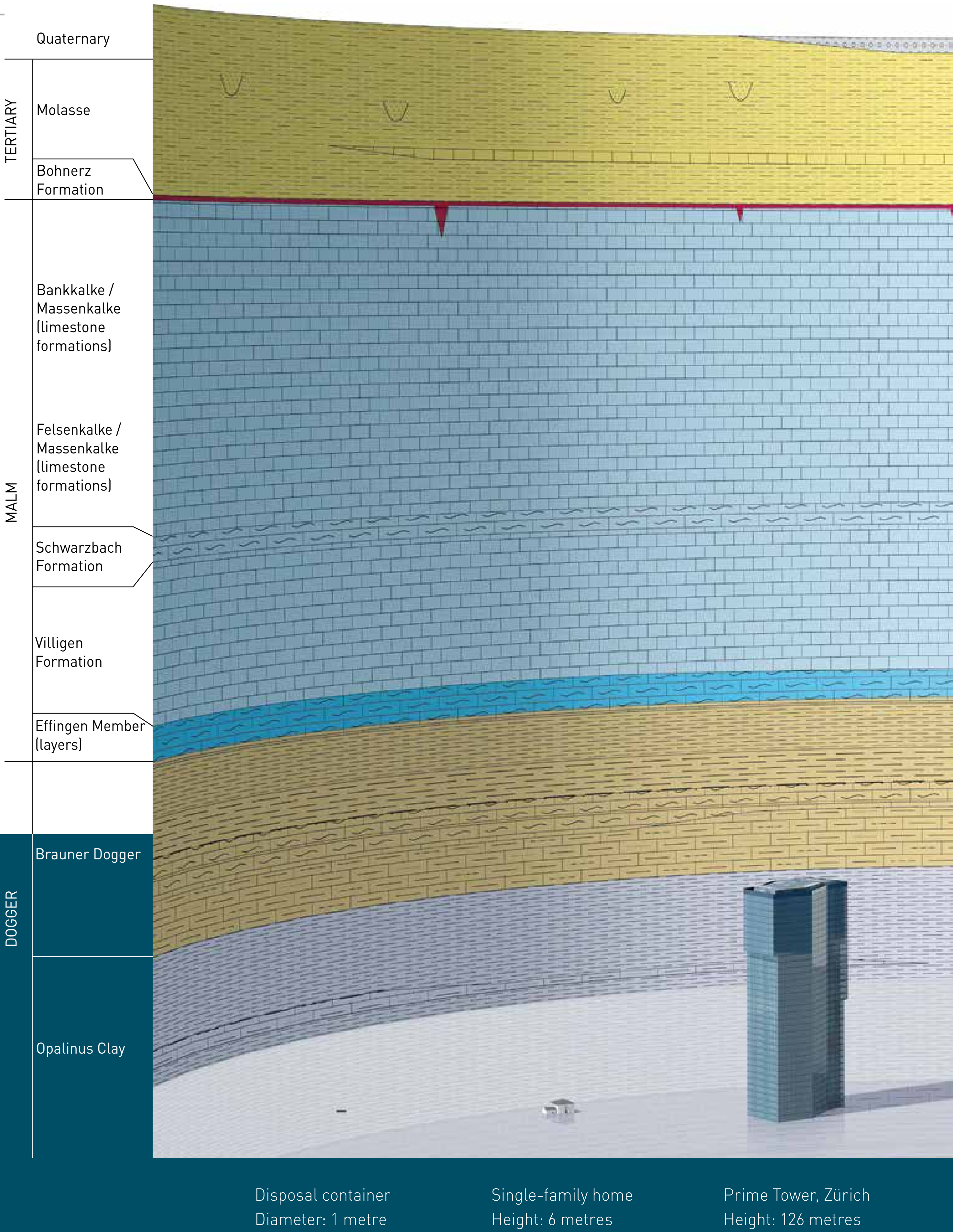
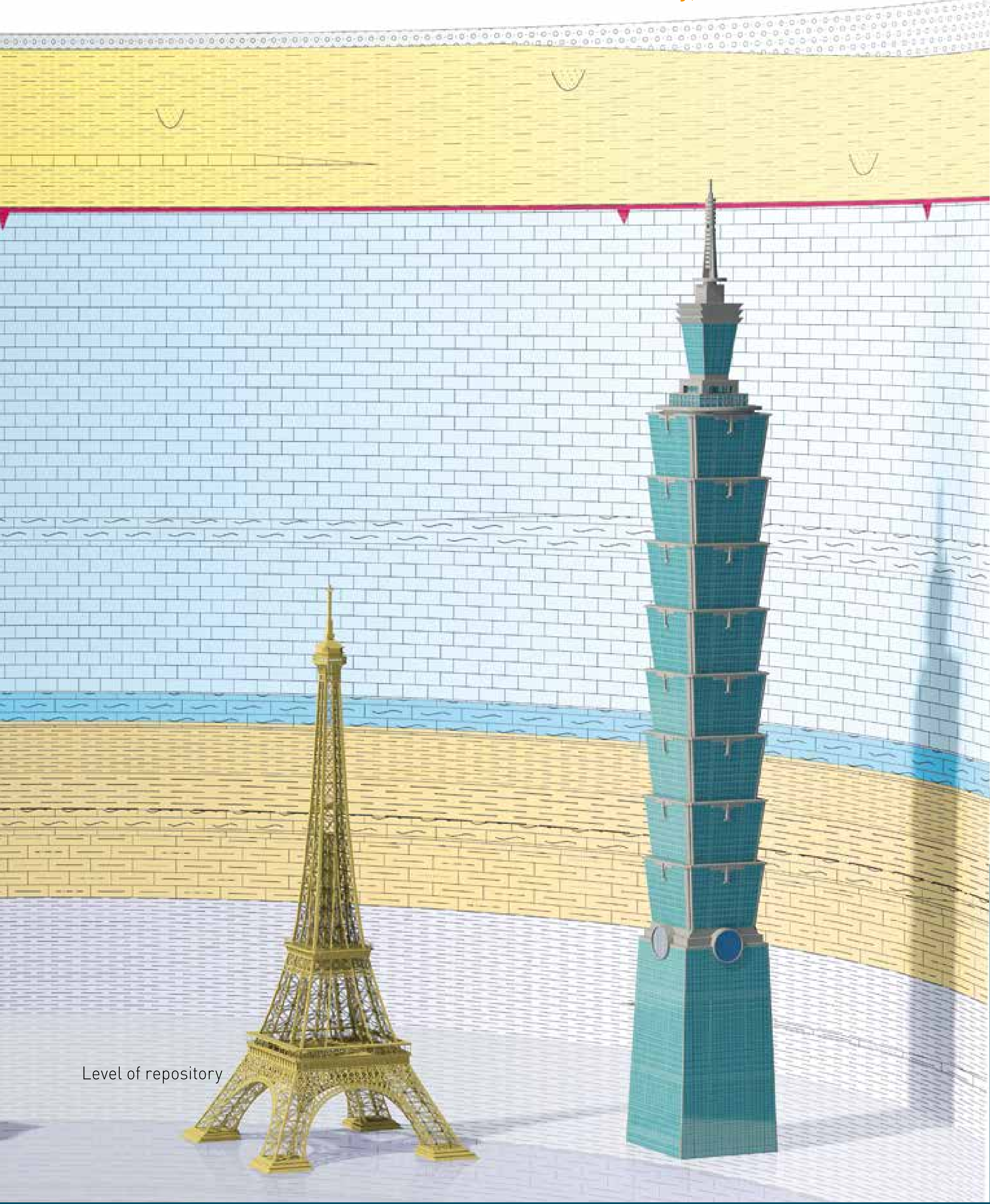


Figure 14
This graphic illustrates the depth of a deep geological repository compared to the height of various structures.



© Nagra

Eiffel Tower, Paris
Height: 324 metres

Taipei 101, Taipei
Height: 508 metres

What can nature teach us about

Studies of natural processes that occur over very long time periods help us to understand the long-term behaviour of deep geological repositories.

It is not possible to conduct experiments over thousands of years. How can one then be sure that a deep geological repository will retain radionuclides over very long time periods?

Processes and phenomena can be found in nature that are similar to those occurring in the environment of a deep geological repository. These so-called natural analogues deepen our understanding of how repositories will evolve over long timescales. As opposed to short-term laboratory experiments, it is possible to observe processes and phenomena that have been ongoing for many millions to billions of years.

Natural reactor as an example

The natural reactors in Oklo (Gabon, Africa) are an important natural analogue. Approximately two billion years ago, natural nuclear chain reactions took place, resulting in the formation of several tonnes of highly active fission products under very high pressure and high temperatures (up to 600 °C) that continuously decayed over time. These figures are not the most important lesson for deep geological disposal of high-level waste. The key fact is that, over a time period of two billion years, the fission products were transported only a few metres. Nature has thus already created a deep geological repository at Oklo (see Figure 15).

Glass serves as a barrier

Lava erupting from a submarine volcano alters to volcanic glass because it cools off very quickly (see Figure 16). The best-known example of volcanic glass is obsidian. Stone Age cultures favoured it due to its properties for making tools and weapons.

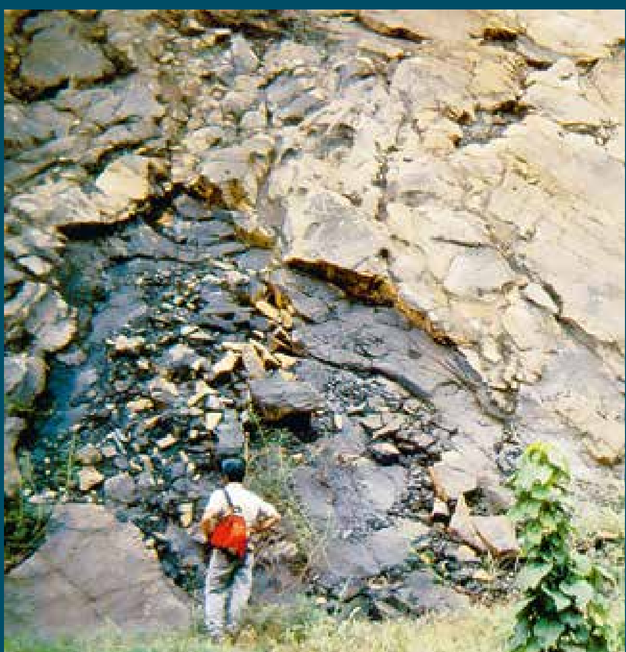


Figure 15
The natural reactor in Oklo is a good example of a natural repository and the retention of radionuclides in rock.

disposal?

These tools are very well preserved to this day. Investigations of volcanic glass that formed in the sea show a corrosion rate of only a few micrometres over 1000 years. The very slow rate at which this process occurs means that glass is an excellent barrier for the containment of radionuclides.

Waste products are generated during the reprocessing of spent fuel assemblies. These are solidified in a vitrification process and transported to the repository in welded steel containers.

Steel corrodes slowly underground

Steel is used for disposal canisters in deep geological repositories. The corrosion rate of steel can be estimated using archaeological artefacts. Humans have been able to make steel for approximately 3 500 years. How well these steel artefacts have been preserved provides information on their corrosion rates. In environments low in oxygen – as in a planned repository – metals corrode very slowly. The corrosion layer itself functions as an additional protective layer against further corrosion.

Opalinus Clay contains seawater

The Opalinus Clay host rock is also a type of natural analogue. The approximately 175 million-year-old rock still contains 10 to 20 grams of dissolved salt per litre of porewater. This salt comes from the ancient sea in which the Opalinus Clay was originally deposited. The seawater contained in the rock over many millions of years demonstrates how well Opalinus Clay can retain substances over millions of years.

Further reading
Nagra special issue number 1: "Spuren der Zukunft" (in German)

Figure 16
Volcanic glass is formed when lava cools off very quickly.

How can safety be demonstrat

The site selection and conceptual design of a deep geological repository ensure its long-term safety. Nagra conducts extensive safety analyses that illustrate the performance of the engineered and natural barriers after the repository has been properly closed.

Deep geological repositories have to meet the highest safety requirements. From the start, the primary goal of the selection process for potential geological siting regions has focused on long-term safety. The law and regulatory requirements call for the long-term safety of deep geological repositories to be demonstrated in safety analyses. These are conducted in several steps and become increasingly detailed. The knowledge gained is used to modify the conceptual design of the repository if necessary.

The legally permitted additional maximum radiation dose for the population is 0.1 mSv annually. This is roughly equivalent to one fiftieth of the average radiation exposure (see Figure 1, page 4). The analyses must demonstrate that the protection objective is met.

Various scenarios examined

Nagra conducts extensive safety analyses to investigate whether the deep geological repositories will exceed the specified maximum dose. These analyses form the base for evaluating whether a repository is acceptable from a safety perspective.

In the safety analyses, the potential release of radionuclides present in a deep geological repository and their potential migration pathways from the repository to the human habitat are assessed quantitatively. The calculations are based on the waste inventory as well as on scientifically underpinned data on the properties of the planned engineered and natural barriers. These properties include: location, geometry and properties of the rock, structural design, retention capacity of the barriers and the regional hydrological situation. All these factors are input into the model calculations. They also take uncertainties into account, which means that unfavourable conditions are also analysed when evaluating safety. The results are compared to the protection criterion (see Figure 17).

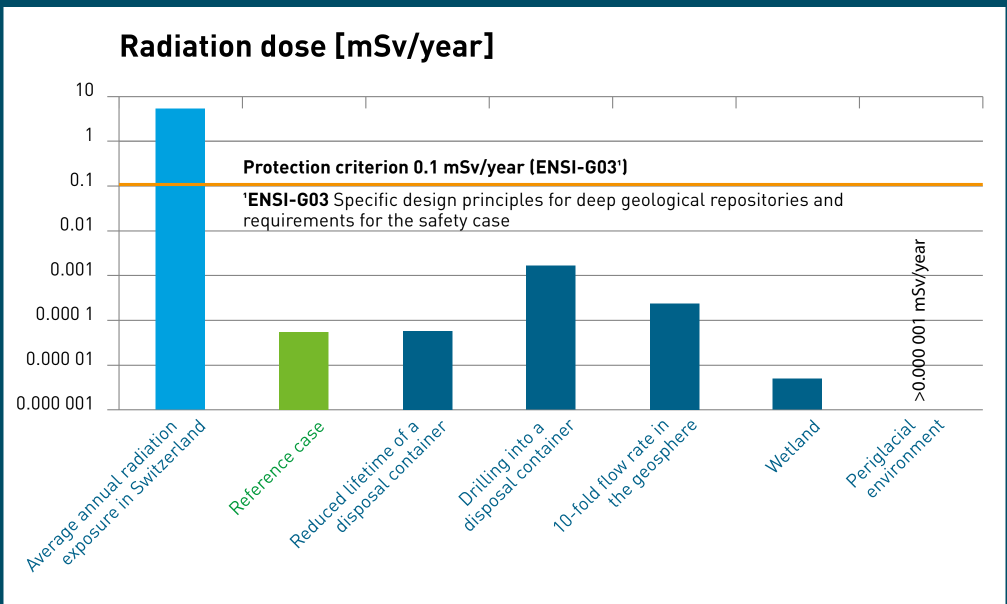


Figure 17
The safety analyses have to demonstrate that the dose values remain below the protection criterion (simplified, source: NTB 02-05, Table 8.2-2).

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Scenarios covering all eventualities

Nagra looks at many different scenarios when conducting safety analyses. These include:

- Increased movement of water through the disposal zone
- Unfavourable diffusion values
- Increased solubility of radionuclides
- Elevated dissolution rate of emplaced fuel assemblies
- Reduced lifetime of disposal containers
- Decreased retention capacity (sorption) of the engineered barriers and the host rock
- Alternative climate variants

Protection criterion is met

Safety analyses to date have shown that, even under pessimistic, partly hypothetical assumptions about the behaviour of the engineered barriers and the host rock, the protection criterion of 0.1 mSv annually is met (see Figure 17). Human intrusion is considered in the safety analyses so that the possibility of directly drilling into a disposal container is also taken into account. Even in this case, the maximum radiation dose to the population remains below the officially stipulated protection criterion.

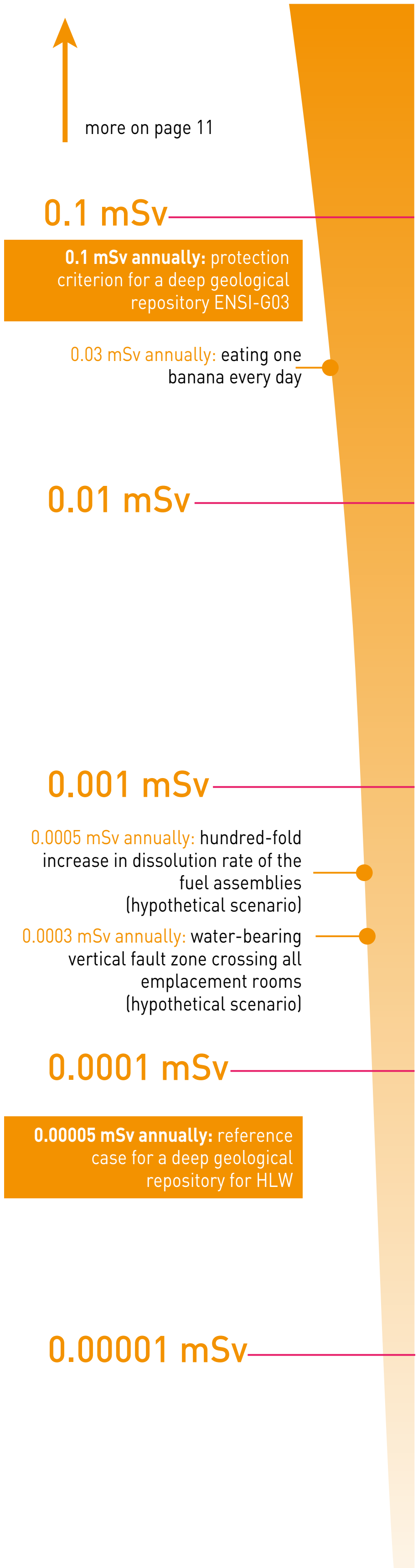

Figure 18
The safety analyses calculate the annual individual dose for a human. The diagram shows the maximum values for a time period of one million years. A diagram comparing these figures to natural levels can be found on page 11.

Passing on messages ov

Many countries around the world are considering the question of how to preserve knowledge about deep geological repositories for future generations. One possibility is to keep the information in different archives.

Knowledge about the site and the waste inventory of a deep geological repository must be preserved for as long as possible. Erecting warning signs to prevent inadvertent human intrusion is under discussion. The Swiss Nuclear Energy Act stipulates the permanent marking of a deep geological repository. The Nuclear Energy Ordinance calls for documentation that preserves all knowledge of the repository. After closure, the Federal Government must ensure that the information is preserved. How can this knowledge be maintained and passed on over very long time periods?

Preserving knowledge

An international expert group of the Nuclear Energy Agency (NEA) of the OECD is looking at possibilities and strategies for solving this problem in its project "Preservation of Records, Knowledge and Memory across Generations". The group is developing strategies for preserving information and knowledge about deep geological disposal of radioactive waste over long time periods. The core issue is the idea of not just collecting knowledge in one place, but preserving information on the waste inventory, construction and location of the deep geological repositories in archives belonging to national and international government authorities. This measure should prevent all knowledge being lost at once.

If future societies go through major upheavals, the responsible authorities must still be able to make well-informed decisions based on all available knowledge. The primary goal of passing on information is to avoid an inadvertent intrusion into the repositories.

Messages for 100 generations?

None of the scientific studies and none of the countries dealing with the issue of marking deep geological repositories expect the marking to last

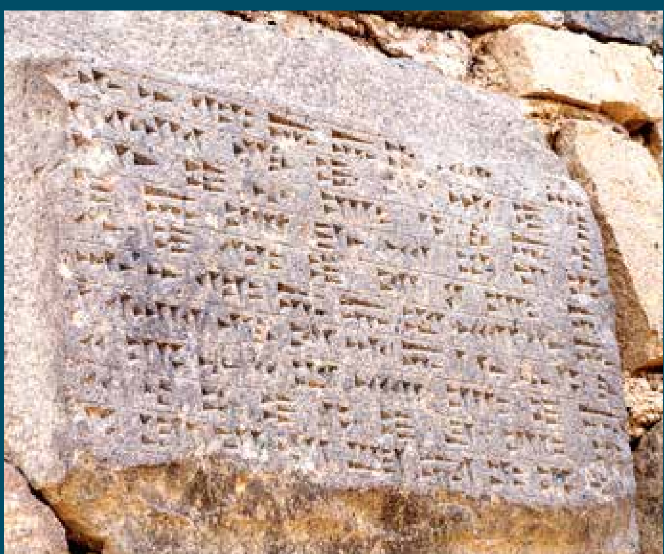

Figure 19
Cuneiform inscription on a wall of the ancient fortress Erebuni located in present-day Armenia (approximately 800 B.C.)

er millennia

for a million years, but rather for several thousand years. The radiotoxicity of the waste will have decreased significantly after this time.

Marking deep geological repositories

Research on passing on knowledge over generations and marking deep geological repositories is still in its infancy. Languages and symbols change constantly. What should unambiguous symbols look like that will still warn people if scripts and symbols change in the future (see Figures 19 and 20)?

The durability of the information medium is also important. Various ideas are under discussion for marking the site of a repository: on-site structures or clay fragments buried in the ground bearing information about the repository.

Long-term information

The safety of a deep geological repository depends on its location and design. The radioactive waste must be safely enclosed until it has decayed to a harmless level, and without the need for human intervention. Preserving knowledge about a repository is beneficial even when it is not a prerequisite for long-term safety. Passing on the information to several national and international authorities and archives is a good approach to preserving knowledge.

Passing on and preserving knowledge for future generations is not just a challenge in radioactive waste disposal. Preserving knowledge is a recurrent, major challenge for society.

Figure 20
These international hazard symbols warn of ionising radiation. The symbol to the right is supplementary and illustrates the correct behaviour when exposed to strong sources of radiation.

Glossary

Atom
(Ancient Greek: atomos "indivisible") Atoms are made up of a positively charged nucleus (consisting of protons and neutrons) and a shell consisting of negatively charge electrons. In their normal state, these atoms are electrically neutral. They are charged by removing or adding an electron. This process is called ionisation and the resulting particle is an ion.

Bentonite
Bentonite is a rock consisting of several clay minerals with a strong ability to absorb water. It is formed by the weathering of volcanic ash and is used to seal structures. It is considered as a potential barrier in the deep geological disposal of radioactive waste. Bentonite is also found in other products such as cat litter.

Caesium (Cs)
Silvery in its pure state, this extremely reactive alkali metal melts at body temperature. The natural isotope Cs-133 is stable. All other caesium isotopes are radioactive and occur only as synthetic fission products of nuclear reactions.

Conceptual design
The arrangement of building components to ensure that they meet their defined purpose. This can relate to all aspects of designing, constructing, manufacturing, operating and terminating a project.

Corrosion
The gradual transformation of a substance through the impact of other substances. One example is the corrosion of iron when it comes into contact with air and is exposed to moisture. This process is more commonly known as rusting.

Fault (geology)
A tectonically generated discontinuity where blocks of rock are moving or have moved against each other. Faults can vary in length between millimetres and kilometres (fault zone).

Fuel assembly
A fuel assembly consists of a bundle of fuel rods. These contain fissile material in the form of fuel (usually uranium). Fuel assemblies are used in the reactor of a nuclear power plant for the production of energy through nuclear fission. The primary sources of the radioactivity of a spent fuel assembly are uranium, neptunium, technetium, iodine and caesium.

Half-life
The amount of time it takes a specific radionuclide to decrease its amount and thus also its radioactivity to half of its original value. For example, the half-life of caesium-137 is approximately 30 years (see Figure 21).

High-level waste (HLW)
Waste that emits strong radiation and consists of fission and activation products separated from spent fuel during reprocessing and then immobilised with glass. In Switzerland, spent fuel assemblies that are not reprocessed are also considered high-level waste.

Natural analogues
Natural analogues are geosystems, materials and processes occurring in nature whose behaviour over long periods in the past is relevant for deep geological repositories. They include materials manufactured by humans.

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Pilot repository
In a pilot repository, the behaviour of the waste, the backfill and the host rock is observed until the end of the monitoring phase. The resulting knowledge forms the basis for the decision to close the deep geological repository. The processes and systems monitored (e.g. safety barriers) must be transferable to the main repository.

Porewater
The water present in voids in soils and rocks.

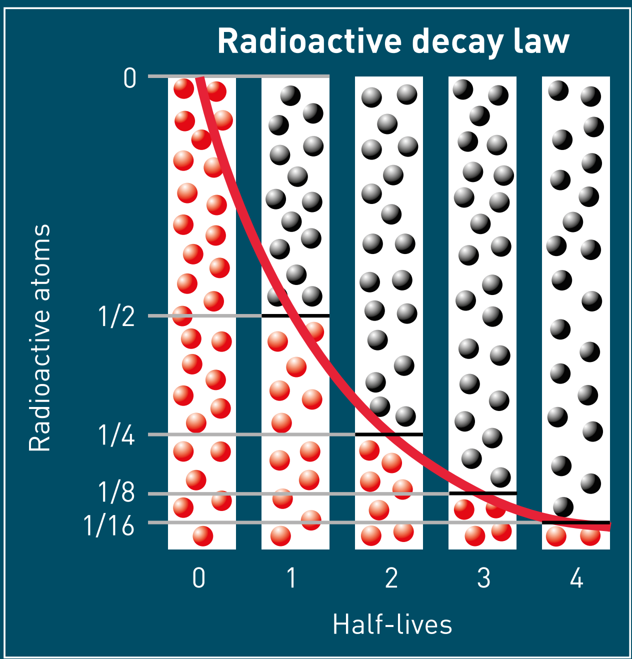

Figure 21
The half-life is the amount of time it takes half the nuclei of a radioactive isotope to decay. The half-life varies from isotope to isotope and can range from fractions of a second to billions of years.

Protection criterion
For every future evolution considered likely, the release of radionuclides may not at any point exceed an annual individual dose of 0.1 mSv at the earth's surface (Guideline ENSI-G03).

Radionuclide
Unstable atomic nucleus that spontaneously decays while emitting ionising radiation. There are naturally occurring and artificially produced radionuclides.

Radiotoxicity
Term describing the damage radioactive substances can cause when they enter the human body.

Radon (Rn)
A radioactive noble gas that is a component of the air. It is responsible for the largest proportion of natural radiation occurring at the earth's surface. It is produced by the decay of uranium underground and then rises to the surface by migrating through rock fissures. In Switzerland, the average effective dose per person caused by radon is approximately 3.2 Millisieverts annually. This amounts to roughly 60 per cent of the average annual radiation exposure.

Reference case
The reference case represents the most plausible situation and its evolution in a simplified manner. Safety analysis shows the effects of alternative scenarios compared to the reference case.

Reference concept (canister)
The thick-walled steel canister assumed in safety analyses.

Reprocessing
A chemical process whereby fissionable substances are separated from spent fuel. Residual uranium and plutonium are recovered from the spent fuel and used for the production of new fuel assemblies.

Underground rock laboratory
An underground laboratory constructed directly in rock where experiments can be conducted under realistic conditions on a 1:1 scale (e.g. to examine the properties of rocks or the construction of a repository).

Waste inventory
All of Switzerland's radioactive wastes are recorded in an inventory containing data on the origin and activity of the materials.

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