Rock Solid?

A GeneWatch UK consultancy report

Rock solid?

A scientific review of geological disposal of high-level radioactive waste

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Cover

 The world's first nuclear reactor was rebuilt at this site in Red Gate Woods near Chicago in 1943 after initial operation at the University of Chicago.

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Executive summary

No country has yet completed an operational geological disposal repository for high-level radioactive wastes or spent nuclear fuel resulting from nuclear electricity generation, despite commitments adopted in the 1970s.

The nuclear wastes intended to be sent to a deep geological repository are those generated in the core of the nuclear reactor, either spent nuclear fuel itself, or high-level wastes which are part of the spent nuclear fuel (separated from it using the chemical process called nuclear reprocessing). Each reactor is re-fuelled multiple times during its lifetime, therefore the quantities of radioactivity from any national nuclear power programme are many times greater than have ever been released during a nuclear accident.

These wastes generate significant quantities of heat and are highly radioactive. Studies suggest that the heat is sufficient to create an uplift of the rock at the ground surface of around 10 cm or more, around 1 000 to 2 000 years after such wastes are buried around 500 m beneath the surface. The heat and radiation, plus the damage and disturbance caused to the rock and groundwater when the repository is excavated, create a major disturbance to the conditions underground at the repository depth. Repository conditions will evolve over time over the order of 100 000 years before returning to the steady state of the undisturbed geology (assuming no major disturbances, such as earthquakes, glaciation or human intrusion in that time). Even then, excavation damage will remain and could provide fast routes for radioactive water or gas to leak from the repository. The wastes will remain radioactive for even longer: thus, the design life of a deep geological repository is intended to be up to a million years.

Construction of a repository requires a significant financial commitment and excavation of very large quantities of rock. This is many times the volume of the wastes, due to the need to space canisters widely to prevent the repository temperature rising above 100^{O}C. During the operational phase (emplacement of wastes), there is a risk of accidents. However, the focus of this report is on post-closure risks, i.e., the period of time after the repository has been filled in and is no longer intended to be actively managed. Over time, radioactive substances (radionuclides) will leak from the repository into the surrounding groundwater and/or be released as radioactive gas. The safety case for a deep geological repository relies on containment of some of these radionuclides and dilution and dispersion of others, through the surrounding rock and biosphere. These processes are intended to take place sufficiently slowly that much of the radioactivity decays before it reaches the surface and thus doses of radioactivity to future generations are intended to be very low.

The deep disposal concept rests on three premises:

- The packaging (canisters, backfill – usually containing clay – surrounding them, and further backfill in the excavated tunnels and deposition holes) will be able to withstand the intense heat and radiation from the wastes and the high stresses this creates in the surrounding rock.

- The complex chemical and radiological changes that will occur over an extremely long period are well enough understood to ensure that the integrity of the waste containers and backfill is maintained for tens of thousands of years.
- A site can be identified that meets the necessary geological requirements over a period of hundreds of thousands of years.

Based on a literature review of papers in scientific journals, the present report provides an overview of the status of research and scientific evidence regarding the long-term underground disposal of highly radioactive wastes. The focus is on spent nuclear fuel and high level waste, which is heat-generating. However, some issues associated with the disposal of lower-level wastes are also noted, where these are intended to be sent to the same repository (usually in a separate section). In particular, these lower-level wastes contain organic material and are expected to generate significant quantities of radioactive gas which could leak into the environment and/or disturb the combined repository.

Many countries have failed repeatedly to identify suitable sites for deep geological disposal, despite numerous attempts, and may never be able to do so. Several countries are now actively investigating alternatives, such as deep borehole disposal (several kilometres underground), combined with longer-term dry storage. However, a number of countries have selected sites for deep geological disposal, or are close to doing so. Finland has constructed a repository but has yet to bury any nuclear waste in it. Sites have also been selected in Sweden, France, Canada and Russia, with only Sweden so far being close to authorisation to begin underground construction. Site selection involves a major commitment to a particular geology and deep disposal concept. There are two main such concepts:

- In hard fractured rock (such as granite), copper canisters contain spent nuclear fuel and are surrounded by bentonite clay (intended to swell and hold the containers in place, protect the canisters from chemical degradation, and to delay the release of some radionuclides) (e.g., Sweden, Finland);
- In clay rocks, steel containers are used for vitrified high-level waste (i.e. high-level waste sealed in glass), and clay, or a mix of crushed clay rock, sand and/or clay is used as backfill (e.g., France).

There are some variations. For example, whilst Sweden and Finland propose using 5 cm thick copper canisters, Canada plans to use only a 3 mm copper layer on a steel canister (in a hard rock repository). Other countries planning to use clay rock may or may not also add a copper layer to steel canisters. Some countries have a mix of spent nuclear fuel and vitrified high level waste.

All repository designs also include substantial quantities of cement and/or concrete (and sometimes other materials), to support structures, shield radioactivity emitted by the wastes and/or fill fractures or plug tunnels.

There are concerns regarding both repository concepts, casting significant doubt on the wisdom of making a commitment to a costly major infrastructure project at a particular site at the current time. For example:

- In clay rocks, the design-life of steel canisters is too short to outlast the long period of time during which intense heat from the radioactive wastes would affect the physical and chemical processes occurring in the repository. Clay repositories

require significant quantities of steel and/or concrete to prevent galleries from collapsing. However, cement water (together with heat, radioactivity and microbes) will damage the ability of clay to swell, and thus its abilities to protect nuclear waste containers from rock stresses and to delay the release of radionuclides. In addition, it remains unclear if large quantities of gas produced due to corrosion of the steel would be released without damaging the backfill and surrounding rock.
- In hard (crystalline) rocks, disputes regarding the corrosion rate of copper have not been resolved, bentonite can also be damaged, and groundwater and gas flow through complex networks of fractures is still not fully understood. Claims that repositories in Sweden and Finland would withstand expected future earthquakes and glaciations are also highly speculative.

For both concepts, recent evidence has increased concerns that, even in areas with long-dormant faults, these could be re-activated by the heat in the repository, leading to earthquakes and/or creating fast routes for radionuclide escape. Future glaciations are also now believed to potentially affect faults in the repository area, even if an ice sheet is some distance from the proposed repository site. In addition, it is increasingly being recognised that the role played by underground microorganisms (microbes), including bacteria and fungi, in critical chemical reactions is not fully understood.

This review identifies a number of processes that could compromise the containment barriers, potentially leading to significant releases of radioactivity:
- Copper or steel canisters and overpacks containing spent nuclear fuel or high-level radioactive wastes could corrode more quickly than expected.
- The effects of intense heat generated by radioactive decay, and of chemical and physical disturbance due to corrosion, gas generation, cement water, and resulting changes in mineral content, could impair the ability of backfill materials to protect the canisters from stresses in the rock and to trap some radionuclides.
- Build-up of gas pressure in the repository, as a result of the corrosion of metals and/or the degradation of organic material, could damage the barriers and force fast routes for radionuclide escape through crystalline rock fractures or clay rock pores.
- Poorly understood chemical effects, such as the formation of colloids, could speed up the transport of some of the more radiotoxic elements such as plutonium.
- Unidentified fractures and faults, or poor understanding of how water and gas will open up and flow through excavated tunnels, fractures and faults, could lead to the release of radionuclides in groundwater much faster than expected.
- Excavation of the repository will damage adjacent zones of rock and could thereby create fast routes for radionuclide escape.
- Future generations, seeking underground resources or storage facilities, might accidentally dig a shaft into the rock around the repository or a well into contaminated groundwater above it; or deliberately seek to extract canister metals or nuclear materials for military use.
- Future glaciation could cause faulting of the rock, rupture of containers and penetration of surface waters or permafrost to the repository depth, leading to failure of the barriers and faster dissolution of the waste.
- Faults could be re-activated, creating fast routes for radionuclides to escape or leading to earthquakes which could damage containers, backfill and the rock.

Although computer models of some of these processes have undoubtedly become more sophisticated, fundamental difficulties remain in predicting the relevant chemical and geochemical reactions and complex coupled processes (including the effects of heat, mechanical deformation, microbes, changing chemistry, and coupled gas and water flow through fractured crystalline rocks or clay) over the long timescales necessary.
The existence of multiple interacting processes at different scales also undermines the 'multi-barrier concept' in which each barrier (waste containers, backfill and rock) is presumed to act independently to contain the wastes. For example: corrosion of canisters and wastes generates gas which can damage both the bentonite barrier and surrounding rock, as well as carrying radionuclides up to the surface; mineral changes to bentonite (due to heat, microbes or cement water) may mean it cannot prevent nuclear waste containers being corroded or being breached due to high stresses in the surrounding rock.

In contrast to the simple picture often presented publicly, of stable, unchanging rock formations containing wastes over geological timescales, the scientific literature highlights the significant disturbance to the rock caused by excavation of the tunnels and the extreme heat and radioactivity emitted by the wastes.

The following over-arching issues continue to remain unresolved:

- the high likelihood of interpretative bias in the safety assessment process because of the lack of validation of computer models, the role of commercial interests and the pressure to implement existing road maps despite important gaps in knowledge. Lack of (funding for) independent scrutiny of data and assumptions can strongly influence the safety case.
- lack of a clearly defined inventory of radioactive wastes in many countries, as a result of uncertainty about the quantities of additional waste that will be produced in new reactors, increasing radioactivity of waste due to the use of higher burn-up fuels, and ambiguous definitions of what is considered as waste.
- the question of whether site selection and characterisation processes can actually identify a large enough volume of rock with sufficiently favourable characteristics to contain the expected volume of wastes likely to be generated in a given country.
- tension between the economic benefits offered to host communities in some countries and long-term repository safety, leading to a danger that concerns about safety and impacts on future generations may be sidelined by the prospect of economic incentives, new infrastructure or jobs. There is additional tension between endorsement of deep disposal as a potentially 'least bad' option for existing wastes, and nuclear industry claims that deep repositories provide a safe solution to waste disposal and so help to justify the construction of new reactors.
- potential for significant radiological releases through a variety of mechanisms, involving the release of radioactive gas and/or water due to the failure of the near-field (engineered) or far-field (rock) barriers, or both.
- significant challenges in demonstrating the validity and predictive value of complex computer models over long timescales.
- risk of significant escalation in repository costs.

1. Introduction

This report examines the current state of scientific evidence regarding the geological disposal of spent nuclear fuel and other high-level and long-lived radioactive wastes in a deep geological repository (DGR) around 500m underground.

No country has yet completed an operational deep geological repository for high-level radioactive wastes resulting from nuclear electricity generation, despite policy commitments adopted in the 1970s.

In 2008, the Radioactive Waste Management Committee (RWMC) of the Organisation for Economic Co-operation and Development (OECD)'s Nuclear Energy Agency (NEA)[1] concluded that "*geological disposal is technically feasible*" and that a "*geological disposal system provides a unique level and duration of protection for high activity, long-lived radioactive waste*". In 2011, the European Union (EU) adopted a nuclear waste directive which endorses deep geological disposal.[2]

However, analysis of the existing scientific evidence shows there are many difficulties with the claim that there is a consensus in favour of deep geological disposal. This report is based on a literature review of research on deep disposal published in peer-reviewed scientific journals. It provides an overview of the status of research and scientific evidence regarding the long-term underground storage of highly radioactive wastes, and asks whether this evidence supports the view that such wastes can be disposed of safely underground. This report is an update of an earlier report, published in 2010.[3] It finds that significant scientific uncertainties remain and it accordingly questions whether strong conclusions in favour of deep geological disposal can be drawn until all the relevant issues have been addressed.

2. Nuclear power and radioactive waste

The International Atomic Energy Authority (IAEA), which promotes the use of nuclear power, states that, at the end of 2023, 413 nuclear power reactors were operational worldwide.[4] According to the IAEA, about two thirds of this nuclear power capacity has been in operation for more than 30 years and almost 30% for more than 40 years.[5] The USA, France, China, Russia and the Republic of Korea are the countries with the most nuclear generating capacity.[6] Nuclear power's relative share of the global electricity mix fell below the 10 per cent mark in 2022 for the first time in around 40 years (the peak value was 17.5% in 1996).[7] According to the IAEA, the majority of new reactor units are being built in Asia, whereas most of the reactors being dismantled are located in North America and Western Europe, where several countries are phasing out nuclear power. In Europe, 168 reactors are in operation (average age of 35.6 years), 13 reactors are under construction and 128 are being dismantled. In Finland and Slovakia, new reactors began operating in 2023. The World Nuclear Industry Status report provides an independent review of these industry figures.[8] It reports that, as of mid-2023, 407 reactors were operating in the world, four less than a year earlier, 31 below the 2002-peak of 438 and at least 24 of the 58 ongoing construction projects were delayed.

Nuclear electricity generation creates large quantities of radioactive wastes, not only in nuclear power plants themselves, but at every stage, from uranium mining to decommissioning of nuclear facilities at the end of their lifetimes. The most highly radioactive wastes are those which are produced in the core of the reactor. The focus of this report is on spent nuclear fuel (SNF) and high-level nuclear waste (HLW), known as 'heat-generating' wastes. SNF is nuclear fuel that has been involved in the nuclear chain reaction at the heart of the reactor (see Box 1). Some countries intend to dispose of spent nuclear fuel directly, but in other countries it is first reprocessed (Box 2). Reprocessing changes the characteristics of the wastes that will ultimately be sent to a deep geological repository by separating out the heat-generating part of the SNF, which is then known as high-level waste (HLW). Countries that have reprocessed some or all of their spent nuclear fuel (SNF) will send high-level waste (HLW) and some intermediate level waste (ILW) to a repository, instead of SNF. However, they will usually also have to accommodate some un-reprocessed SNF and/or spent MOX fuel (see Box 1). In general, the intermediate-level waste (ILW) that is to be included in the inventory of wastes for a deep underground repository is that containing long-lived radionuclides (i.e. those expected to take a long time to decay).

Tonnes of heavy metal, abbreviated as tHM, is a unit of mass used to quantify uranium, plutonium, thorium and mixtures of these elements. The global total of spent nuclear fuel was estimated by the IAEA to be 390 000 tHM at end 2016[9], but this had increased to 430 000 tHM by end 2020 figures, with an estimated annual discharge from nuclear reactors of about 10 000 tHM per year.[10] About 70% of this spent fuel is stored (with 35% of this in dry storage and 65% in wet storage) and the remaining 30% reprocessed. Spent nuclear fuel is regularly removed from operating nuclear reactors (usually at regular intervals of one or two years).[11]

The amount of radioactive waste produced in a reactor depends on the reactor type. On the basis of data from 1992, the IAEA estimates that one year's operation of a light water reactor (LWR) producing 1 GW of power typically results in spent fuel assemblies containing a total of 30 to 50 metric tHM, with an initial activity of around 5 to 8.3 million TBq of radioactivity[12]. One Becquerel (Bq), is one radioactive decay per second (see Box 3). One Terabecquerel (TBq) is 1000 000 000 000 Bq (also written 10^{12} Bq). According to the IAEA, current reprocessing procedures would separate about 15m^3 of vitrified high-level radioactive waste from this quantity of spent fuel. These figures are indicative only and have changed significantly with time. More modern reactors using higher burn-up fuel will produce smaller quantities of spent fuel but with higher levels of radioactivity per fuel rod. These changes can have significant implications for the safety case for a repository.[13,14]

Box 1: Categories of radioactive waste

Naturally Occurring Radioactive Material (NORM) includes radioactive wastes created by mining and milling of naturally occurring uranium ores in order to produce fuel for nuclear reactors.

Low-Level Waste (LLW) makes up the bulk of the volume of waste produced in the nuclear fuel chain. It consists of materials such as paper, rags, tools, clothing and filters, which may contain small amounts of mostly short-lived radioactivity.

Intermediate-Level Waste (ILW) contains higher levels of radioactivity and normally requires shielding. It includes resins, chemical sludges, metal fuel cladding, and contaminated materials from the decommissioning of reactors or from nuclear reprocessing. Short-lived ILW is typically disposed of in shallow land burial, but long-lived ILW is destined for geological disposal.

High-Level Waste (HLW) and **Spent Nuclear Fuel** both contain fission products (radioactive elements created when atoms are split in the nuclear chain reaction) and transuranic elements (see Box 5) generated in the reactor core. These are highly radioactive and generate heat due to radioactive decay. In countries where spent nuclear fuel is reprocessed, liquid high-level waste is separated from other radioactive waste streams (see Box 2) and is vitrified (turned into glass blocks) before disposal. Depending on the waste disposal concept the heat-generating spent fuel and high-level waste require a cooling period of several decades prior to ultimate disposal.

Box 2: Nuclear reprocessing

Nuclear reprocessing involves treating spent nuclear fuel by means of a chemical process (usually by dissolving it in nitric acid[15]) after it has been removed from the reactor and stored for several years. The spent fuel is separated into plutonium, uranium, and high-level and intermediate-level wastes, and radioactive waste streams are also discharged into the sea and air.

Liquid high-level wastes are stored in tanks, which require constant cooling, and are later vitrified (turned into glass blocks). The volume of high-level waste contained in these glass blocks is smaller than the volume of the original spent nuclear fuel[16]. However, reprocessing increases the total volume of radioactive material, and creates a large volume of long-lived intermediate-level wastes, which are usually also considered to require deep underground disposal[17].

Three countries (France, India and Russia) currently have reprocessing plants which take spent nuclear fuel from non-military reactors on a commercial scale (with France having by far the largest reprocessing capacity), whilst the UK has shut down reprocessing. [18,19,20,21] Japan and China have pilot plants and aim to reprocess commercially in the future. Japan's Rokkasho reprocessing plant, which began construction in 1993, is still not operational.[22] Reprocessing facilities were originally developed to extract plutonium from spent nuclear fuel in order to make nuclear weapons. The idea that separated plutonium could be re-used in a new generation of plutonium-fuelled reactors (known as 'fast breeder' reactors), which would also generate more plutonium for re-use in future fuel, has failed repeatedly, leaving countries with large stockpiles of unwanted plutonium.[23] Plutonium from civil reactors, separated from spent nuclear fuel in commercial reprocessing facilities, can also be used to make nuclear weapons and thus poses a nuclear proliferation threat.[24] The separated plutonium from commercial reprocessing is now mainly added to existing stockpiles, although some is used in the production of mixed-oxide (MOX) nuclear fuel, mainly in France. According to the World Nuclear Association, MOX fuel provides almost 5% of the new nuclear fuel used today and fuels about 10% of France's reactors.[25] Spent MOX fuel is not reprocessed and poses greater challenges in a repository than spent uranium fuel. Separated uranium was originally intended to be reused as nuclear fuel, but at present this rarely happens, probably as a result of its poor quality compared with fresh uranium (due to contamination with unwanted uranium isotopes).

At end 2016, civil stockpiles of plutonium have been estimated at 116.5 tonnes in the UK, plus an additional 24.1 tonnes of separated plutonium belonging to other nations; 84.9 tonnes in France, plus an additional 24.1 tonnes of separated plutonium belonging to other nations; 8.5 tonnes in India and 9.3 tonnes in Japan.[26] Russia and the USA have the largest quantities of military plutonium and some of this has been transferred to civilian stockpiles. In addition, around 57 tonnes (in Russia) and 8.1 tonnes in the USA result from civil nuclear programmes. Because of the health, environmental and proliferation risks plutonium presents, it must be kept in very secure conditions, at high cost. The UK has recently taken the decision to dispose of its civil plutonium stockpile in its proposed geological disposal repository.[27] Research is taking place into how to first immobilise the plutonium by converting it into a mechanically and chemically stable ceramic material.[28] This process will need to take into account the need to ensure proliferation resistance (i.e., to make it difficult to extract the plutonium for use in nuclear weapons).[29]

Many European countries, as well as Japan, sent some of all of their spent nuclear fuel for reprocessing in France or the UK in the past. However, this practice has largely ceased due to concerns about costs, the harm to human health and the environment caused by the radioactive discharges, and the nuclear proliferation risk associated with separated plutonium.[30] Vitrified high-level wastes from past reprocessing are intended to be returned from the UK and France to the countries of origin. However, intermediate-level wastes will remain in the UK and France.

The USA reprocessed spent nuclear fuel in the past, although not on a commercial scale. It ceased the practice in 1997 due to concerns about the nuclear proliferation risks associated with separated plutonium, along with a combination of severe technical, economic and safety problems.[31] The USA also has significant quantities of military nuclear wastes and France, the UK, Russia and China are also nuclear weapons states with a significant legacy of wastes from nuclear reprocessing for weapons production. However, the focus of this report is on the wastes from non-military nuclear power production.

In Europe, the Sellafield site in England and La Hague in France were the main reprocessing plants for decades, although reprocessing at Sellafield has now shut down. Significant radioactive discharges to sea and air have been made from both sites over many decades, including an estimated 276 kg of plutonium released into the Irish Sea from Sellafield.[32,33] The ultimate cost of cleaning up Sellafield, which contains some of the UK's waste from nuclear weapons programmes as well as nuclear power generation, has been estimated at £136bn and could take more than 100 years.[34] Radioactive waste is leaking into groundwater at the site.[35] The Strategy on Radioactive Substances adopted by the Oslo and Paris Convention (OSPAR) in 1998, which covers discharges to sea in the North-East Atlantic area, requires that by the year 2020 the discharges, emissions and losses of radioactive substances be reduced to levels where the additional concentrations in the marine environment above historic levels resulting from such discharges, emissions and losses are close to zero.[36] Although the UK has shut down nuclear reprocessing, in 2021, this commitment was postponed to 2050, to allow France to continue to reprocess.[37]

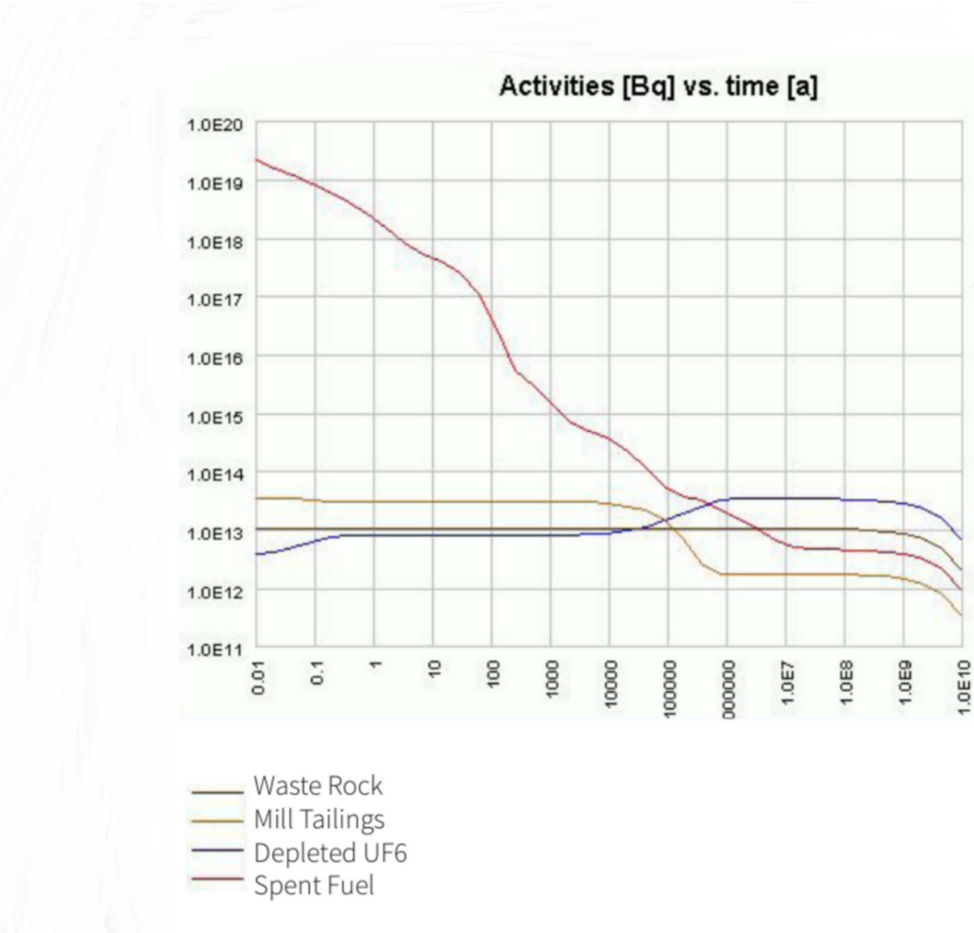
Figure 1 shows how the radioactivity of spent fuel decays with time, compared to the various products of uranium mining: waste rock, mill tailings and depleted uranium, UF6).[38] In this figure, 1.0E12 Becquerels means 10^{12} Becquerels, or 1 000 000 000 000 Becquerels. This figure is illustrative only, because different decay curves are associated with different types of nuclear fuel and different burn-ups. Burn-up is a measure of how much energy is extracted from a given amount of nuclear fuel and has been increasing as new nuclear fuels are developed. The radionuclide content, including the content of fissile material, and hence the decay curve, will differ for higher burn-up spent fuels, those containing plutonium (known as MOX) and those from different reactor types. [39,40] There are significant uncertainties in calculations of the radionuclide inventory and decay heat from each type of fuel.[41,42,43] For specific fission products, calculated uncertainties in the inventories in spent nuclear fuel before it is sent to a repository can reach up to a factor of ten, with greater uncertainties for MOX than for uranium fuels. [44] This also leads to uncertainties in decay heat, which is important because a temperature limit of 100˚C is an important design limit for a deep underground repository, which influences the spacing of the spent fuel canisters and hence also repository costs (see Section *5.3. Costs*).

For comparison, in the Chernobyl nuclear accident in 1989, it is estimated that around 5 300 PBq of radioactivity was released (i.e. 5.3 x 10^{18} Bq, or 5.3 million TBq).[45] This is a significant part of the radioactivity within a single reactor core at a given time. Each deep geological disposal facility is intended to take spent nuclear fuel from multiple nuclear reactors, each of which has been re-fuelled multiple times during its lifetime, so the total quantity of radioactivity is much higher. Some of the reactivity will decay whilst the spent fuel is in storage prior to being placed in a repository. However, although this will mean some short-lived radionuclides are no longer dangerous, the total radioactivity will remain high for hundreds of thousands of years (see Figure 1).

In France, spent nuclear fuel and reprocessed plutonium and uranium are not currently classified as nuclear waste, on the grounds that spent fuel is a recyclable material and that reprocessed uranium and plutonium might be used to make fresh fuel.[46] This situation results in large volumes of radioactive material that may ultimately be buried in a repository not being included in the official inventories of radioactive waste.

Spent nuclear fuel requires interim storage, to allow time for cooling after it is first removed from a reactor during refuelling. Wet storage involves keeping the spent fuel rods in racks under water in cooling ponds. Dry storage requires the use of casks designed to cool the waste by air convection and to protect it from fires and mechanical impacts. Storage is discussed in Section *6. Alternatives*.

Figure 1: Example of decay of spent nuclear fuel generated by a 1 000 MW nuclear power reactor each year[47]



2.1. Harmful effects of radioactive wastes

Nuclear waste generates concerns because the radiation it emits (known as ionising radiation) can cause cancer and other serious illnesses in humans, and harm other living organisms (see Boxes 3 and 4). High-level nuclear waste is so radioactive that exposure to it is deadly. High doses of radiation cause skin burns, radiation sickness and death. Lower doses of radiation damage human cells in a way that increases the risk of diseases such as cancer and cardiovascular disease (see Box 4). The higher the dose the greater the risk. If radioactive wastes leak from an underground repository, they will contaminate the environment and expose people to low levels of radiation which can harm health. The safety assessment for a repository is required to take account of this.

Box 3: Radioactivity

The basic constituents of radioactive wastes are called radionuclides. These are atoms which are unstable and change to other more stable forms in a process known as radioactive decay, until a stable form is reached. The unit of radioactivity is the Becquerel (Bq), defined as one decay per second. The half-life is a measure of how quickly a particular radionuclide decays: it is the time taken for the radioactivity to decay to half of its initial value. Different radionuclides have different half-lives, varying from fractions of a second to millions of years.[48]

After the decay of a radionuclide atom, the remaining nucleus can be either stable (i.e. non-radioactive) or unstable. If it is unstable, it will decay again: for some radionuclides long chains of decays result as one atom changes to another and then another, emitting radiation at each step.

When a radionuclide decays it can emit alpha, beta or gamma radiation.
Alpha radiation consists of two protons and two neutrons bonded together in a particle that is identical to the nucleus of a helium atom. It can be emitted when a heavy radionuclide decays. Alpha particles are easily blocked (for example by a sheet of paper), but can be very dangerous if they are emitted inside the human body (for example, from a radionuclide breathed into the lungs, or ingested by eating or drinking contaminated food or water).
Beta radiation consists of high-energy electrons (or positrons). It is more penetrating than alpha radiation and can penetrate living matter to some extent. However, it is less damaging, so the same amount of exposure does less damage than exposure to alpha radiation.
Gamma radiation consists of electromagnetic radiation of very high energy. It is often produced at the same time as alpha or beta particles, or at the end of a long chain of decays. Gamma rays act like powerful X-rays which can pass through the human body, necessitating protection by thick shielding (for example, lead or concrete).

The harmfulness of radiation varies with the kind of radiation and its energy.

Box 4: Health effects of ionising radiation

The health effects of ionising radiation are not fully understood. Until recently, the estimates of harm were based mainly on the ongoing study of survivors of the Hiroshima and Nagasaki bombings in 1945, supplemented by some more recent studies (e.g. of the effects of medical exposures to radiation and the Chernobyl accident). However, studies of nuclear industry workers have recently confirmed evidence that low doses of radiation increase the risk of cancers, which can occur decades after the exposure.[49,50,51] There is also evidence that exposure to radiation can increase the risk of cardiovascular disease.[52]

People can be exposed to radiation either externally, when radionuclides decaying outside the body expose it to ionising radiation, or internally if radionuclides are breathed in or swallowed (for example, by eating radioactively contaminated food). Some radionuclides bioaccumulate and/or biomagnify in living organisms. Bioaccumulation is the gradual buildup in an organism or an organ over time. Biomagnification is the increase in concentration of a substance higher up the food chain (see Section *4.9. Transport of radionuclides in the biosphere*).

Radiation can cause genetic damage to cells. Sometimes this damage can be repaired by mechanisms within the cell, but sometimes it can lead to the out-of-control growth of cancer cells. Damage to eggs or sperm can be passed on to future generations. As well as DNA damage, other biological mechanisms through which radiation could cause harm also exist.[53,54,55,56]

Radiotoxicity is a measure of how harmful a radionuclide is to human health when inhaled or ingested: it depends on the type and energy of the radiation emitted and the radionuclide's biochemical behaviour in the human body (for example, whether it is excreted quickly or builds up in bones or organs). The harm that is done depends on the dose of radiation received. But calculating this dose is not straightforward.

The International Commission on Radiological Protection (ICRP) is an advisory body which sets international standards on the calculation of doses and radiological protection.[57]

High-level radioactive wastes and spent nuclear fuel are so radioactive that the decay process generates significant amounts of heat. They contain a wide variety of radionuclides, each with different physical and chemical properties. [58] Each radionuclide decays differently and has a different half-life. The physics of radioactive decay is well understood, but the inventory of radionuclides in the wastes is not well known. In addition, the chemistry of how wastes will behave in a repository is very complicated, because each element can take different forms and form a variety of compounds. Some of the chemicals may dissolve easily and leak out of the repository in groundwater, while others may stick to the backfill or the surrounding rock and thus be contained more easily. Some can also biomagnify in the food chain once they reach the living environment (known as the biosphere), and each one may have different health effects on humans exposed to it. A few of these radionuclides and their relevant properties are described in Box 5.

Box 5: Radionuclides and deep geological disposal

A chemical element is a pure chemical substance containing one type of atom. Each element has a different number of protons in its nucleus – known as its atomic number. Isotopes are atoms of the same element but having different numbers of neutrons. Unstable isotopes are radioactive. Chemical species are a specific form of chemical substance. The chemical form of a radionuclide can influence have it reacts with other chemicals and behaves in living organisms.

Actinides. The actinides are a series of elements with atomic numbers from 90 to 103 (thorium to lawrencium, including uranium and plutonium). They are all radioactive and have a number of different radioactive isotopes. Only thorium and uranium occur in significant quantities in nature.

Elements that are heavier than uranium are known as transuranic. They are produced in a nuclear reactor when uranium is irradiated. Many actinide isotopes have long half-lives (tens of thousands of years) and are also highly radiotoxic. They exist in large quantities in spent nuclear fuel; successful containment of actinides is therefore very important in the safety case for a geological repository.

Mobile radionuclides. Some radionuclides are expected to escape more easily from deep repositories in significant quantities because they are highly mobile in groundwater and have long half-lives, meaning that they are likely to reach the biosphere before they have decayed and so pose a risk to living organisms. In a deep geological repository, negatively charged (anionic) species are not expected to be significantly retarded in the backfill or the rock.[59,60] The main radionuclides of concern are iodine-129 (half-life 15.7 million years), chlorine-36 (half-life 300 000 years), selenium-79 (half-life 295 000 years) and technetium-99 (half-life 212 000 years).[61] These radionuclides are less radiotoxic than the actinides, but occur in large quantities in high-level radioactive wastes. Radioactive iodine that is ingested by humans tends to concentrate in the thyroid gland, where it can cause thyroid cancer and other problems. Technetium-99 bioaccumulates in the food chain, particularly in shellfish such as lobster.[62] Selenium is an essential micronutrient for many organisms and selenium-79 can also bioaccumulate in the food chain.

Carbon-14 has a half-life of 5 715 years and undergoes beta-decay into nitrogen-14. It is relevant to radioactive waste disposal because it is the main radionuclide that might escape from a repository as gas, in the form of carbon dioxide (CO_2) or methane (CH_4). Carbon-14 exists mainly in irradiated metals (especially steels), and steel also releases hydrogen when it corrodes, which can react with carbon to form methane. Smaller quantities of carbon-14 in irradiated uranium can also impact on safety if the corrosion rate is high. In countries where long-lived intermediate level wastes (ILW) are also destined for the repository, decaying organic material in these wastes can also give off these gases.[63]

Fissile materials are those isotopes of plutonium and uranium, and some lesser alternatives (isotopes of neptunium and americium), that can cause a nuclear chain reaction if brought together in a sufficient quantity (known as the ‘critical mass’). It should be noted that the fissile content of a repository can increase over a period of millions of years and that some risks, such as the risk of criticality occurring spontaneously underground (see Section *4.4.5 Criticality*) continue over this time frame.[64] All fissile materials can be used to make nuclear weapons if a sufficient quantity can be obtained, and thus require international safeguards (e.g., site inspections) and physical measures to prevent their diversion for nuclear weapons’ use by governments or terrorists.[65]

Although radionuclides with short half-lives decrease significantly over time they can also be created in the repository by the decay of other long-lived radionuclides. Thus, some of these so-called ‘daughter’ radionuclides can be important for the safety case.[66]

3. The concept of deep geological disposal

Research on nuclear waste disposal began in the1950s but a concerted attempt to solve the problem did not begin until the late 1970s.

In the UK, in 1976, the influential Flowers Report, published by the UK Royal Commission on Environmental Pollution, concluded that “*There should be no commitment to a large programme of nuclear fission power until it has been demonstrated beyond reasonable doubt that a method exists to ensure the safe containment of long-lived radioactive waste for the indefinite future.*”[67] In April 1977, the Swedish Parliament passed the groundbreaking Nuclear Stipulation Act (*Villkorslagen*) that reinforced this standpoint by requiring the operators of nuclear power plants to have “*proven how and where a completely safe final storage facility*” could be constructed for spent nuclear fuel or reprocessed high-level waste before operating permission was granted. In the USA, the Interagency Review Group on Nuclear Waste Management called for the development of geological repositories for high-level nuclear waste disposal in 1979.[68]

Since the adoption of these policies in the late 1970s, the focus of high-level nuclear waste disposal has been on burying wastes underground. Other options – such as firing the waste into space in rockets, burying it under the Antarctic ice sheet, or dumping at sea – have been progressively ruled out as unfeasible and/or unsafe. As a result, deep geological disposal has dominated research priorities for some 50 years.[69,70]

The option of deep geological disposal would involve excavating a repository in bedrock hundreds of metres underground. The rock can be of different types, the most common ones that have been considered are granite, clay or salt. The radioactive waste would then be put in containers which would in turn be placed in deposition holes in tunnels in the rock. These would be backfilled to keep the containers in place and to slow the release of radionuclides from the waste once the containers had lost their integrity by corrosion or other chemical or physical processes. The site is supposed to be chosen so that the flow of water through the waste and back to the surface would be slow enough for the radioactivity to decrease significantly before the living environment above the repository could become contaminated. The release of gas from corroding canisters and other structures, and radioactive gas from the waste itself, also needs to be considered, as does the risk of future earthquakes or glaciation affecting the repository. The geology of the chosen site and the engineered barriers around the waste are intended to be passively safe (i.e., not to require human intervention) after the closure of drifts and shafts. Some designs would also allow retrieval of wastes should future generations decide to undertake this. However, this is usually restricted to the period before ‘closure’ of the repository, after which intervention is supposed to be unnecessary.

The idea behind geological disposal is that multiple barriers will ensure the long-term protection of the living environment from the radioactive wastes. This is sometimes known as the multi-barrier concept. The main barriers are the nuclear waste containers, the backfill surrounding them (usually based on clay and sometimes referred to as a buffer), the backfill filling the underground tunnels, and the rock itself. Central to the multi-barrier concept is the idea that if one barrier fails, the others will prevent too great a release of radionuclides into the living environment. However, as discussed in Section *5. Overarching unresolved issues*, it is questionable whether the barriers are really independent.

The key stages for implementation of geological disposal are:

- establishment of the waste inventory
- development of concepts and technologies
- site selection and characterisation
- design of the deep geological repository
- safety demonstration based on scientific knowledge and demonstration of technology
- licensing
- construction and manufacturing
- waste emplacement
- backfilling and sealing
- final closure.

Siting and licensing a repository may take several decades and construction is expected to take another decade. Final closure is expected to be at least another several decades after the start of the operational phase (see Box 6).

As well as the repository itself, encapsulation facilities would also be needed, which may or may not be at the repository site. Here spent fuel or the vitrified waste from reprocessing (i.e., high level waste in glass blocks) would be placed in canisters or overpacks. Long-lived intermediate-level waste is often encapsulated in concrete or bitumen and may be placed in steel barrels.[71] Larger reactor parts that are long-lived intermediate waste may be deposited whole or in pieces in containers. A transportation system would also be necessary to transport the highly radioactive wastes from interim storage facilities to the encapsulation plant and on to the geological disposal facility.

Box 6: Three stages of geological disposal

Construction

During the initial construction phase, no nuclear waste is present underground at the disposal site. However, large volumes of rock will need to be excavated in order to create a system of tunnels big enough to accommodate the designated quantities of radioactive waste (see Section *5.3. Costs*). The site will also require some above-ground facilities: in some cases, these will include facilities to temporarily store and/or package nuclear waste; in others, waste will be packaged elsewhere for transfer directly to the underground tunnels. For example, in Switzerland, encapsulation and interim storage will take place at the ZWILAG storage facility, close to the village of Würenlingen in the canton of Aargau.[72] Corrosion or accidental damage can occur before the waste is placed in the repository and it is important to consider this in the safety case.[73,74,75]

Operation (emplacement)

The operational phase of a repository is the period of decades during which radioactive waste is placed into the tunnels. For example, in France, the planned closure date is 2170.[76] Because nuclear waste is now being handled at the site, workers will be exposed to low levels of radiation and nuclear accidents might occur.[77,78] In some scenarios, large quantities of radioactivity could be released into the environment, for example, as the result of accidents, including fires or explosions.[79] Generally, operation will begin before construction is complete, with more tunnels being constructed on one part of a site whilst others are already being filled. This could lead to problems if an accident in part of the site under construction impacts radioactive waste that has already been placed in another part. An accident involving radioactive material might also affect workers in the construction area. Packaging or (or re-packaging) of wastes at above-ground facilities may continue during the operational phase, and this will carry its own risks. National deep disposal programmes differ in the extent to which monitoring, reversibility and retrievability of wastes are requirements during the operational phase.[80]

Closure and post-closure

Ultimately, the repository is closed by backfilling the access shafts and tunnels. In France, the decommissioning and closure phase is expected to last 20 years.[81] The post-closure phase lasts indefinitely, as no future intervention is anticipated. The aim is to limit the exposure of future generations to the radioactivity in the waste over very long timescales (hundreds of thousands of years), without passing on the responsibility of managing the wastes to people who are not yet born. However, problems can occur post-closure if radioactive water or gas leaks into water supplies or into the atmosphere.

The issues that give rise to potential concern are reviewed in Section *4. Literature review of post-closure issues*. The repository is a dynamic environment, the host rock will have been damaged by the excavation and backfilled (usually with a type of clay called bentonite), there will be significant heat and radiation from heat-generating radioactive wastes, and water will re-enter and wet the backfill and containers over a time period of tens of thousands of years. [82] There are also risks of unintentional or intentional intrusions into the repository. An underlying problem is the difficulty predicting the risks to future generations over the very long timescales for which long-lived radioactive wastes will remain dangerous, and of informing future generations of the threats (see Section *5. Overarching unresolved issues*). For comparison, some of the world's oldest complex building structures to date, such as the Egyptian pyramids, are only up to around 4 500 years old and the human species (*Homo sapiens*) is believed to have emerged around 300 000 years ago.

The deep disposal concept rests on three premises:[83]

- A site can be identified that meets the geological requirements over a period of hundreds of thousands of years.
- The complex chemical and radiological changes that will occur over this period are well enough understood.
- The packaging arrangements will be able to withstand the intense heat and radiation they will be subjected to.

Public trust in the proposals is also necessary.[84,85] The need for long-term (inter-generational) societal governance must also be considered throughout the construction and operational phases. Although the intention behind the deep geological disposal concept is that the repository will be abandoned post-closure, there is also a need to consider the role of future societies over this much longer period, including whether or not (and how) they might be warned about the dangers of excavating a repository site.

3.1. Safety assessment

Before a proposed repository can be licensed for use, a safety assessment must be produced and approved by the relevant government regulators.

The International Atomic Energy Agency (IAEA) manages the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management.[86] It publishes guidance documents on the siting of geological repositories and safety standards for their operation.[87] The Nuclear Energy Agency (NEA) also plays a role.[88] The NEA publishes a list of the 'Features, Events and Processes' (FEPs) relevant to the post-closure safety of a geological repository.[89] However, it is up to national governments and regulators to determine the regulatory approvals process and whether safety assessments are adequate. Updated safety cases may be submitted to regulators at various stages of decision-making, including site selection, approval for construction, and approval for the start of the operational phase (emplacement of wastes). At the time of writing, no safety case has yet been approved to begin the operation of a deep underground repository, although Finland has completed the construction phase (see Section *3.2. National programmes for geological disposal*).

In Germany, for example, a generic safety case has been produced for two potential clay rock sites in Northern and Southern Germany.[90] This safety case refers to the host rock as the 'containment providing rock zone' (CRZ) and requires that:

- The integrity (containment abilities) of the CRZ is maintained for one million years and is not disturbed by either internal or external processes;
- The integrity of the geotechnical barriers is maintained over their designated functional period. In Germany, this has been defined as the period during which the repository conditions are changing due to the intense heat emitted by the radioactive wastes;
- 'Criticality' (i.e. a nuclear fission reaction) does not occur;
- The potential future radiological exposure to the future population is insignificant.

The International Commission on Radiological Protection (ICRP) provides recommendations and guidance on all aspects of protection against ionising radiation (i.e., radiation from nuclear materials). It bases its recommendations on three fundamental principles – justification of exposures, dose optimisation, and the limitation of radiation exposure.[91] The principle of justification requires that any decision that changes the amount of radiation exposure should do more good than harm. Optimisation requires that radiation exposure should be kept as low as reasonably achievable, taking into account economic and societal factors.

Safety assessment requires the post-closure behaviour of the radioactive wastes in a repository to be predicted hundreds of thousands to millions of years into the future. The limitations of the computer models that are used to make these predictions and the difficulties of validating them – i.e., of confirming that they will give sufficiently reliable predictions over such long timescales – are discussed in Section *5. Overarching unresolved issues*.

In order to meet the safety requirements, predicted doses to a 'reference person' living near the proposed repository are supposed to be calculated many generations into the future. The habits used as a basis for this calculation (e.g., consumption of foodstuffs and use of local resources) should be typical of the small number of individuals expected to be most highly exposed.[92] The principle of optimisation also requires steps to be taken to minimise exposures by, for example, choosing a suitable geological site, and designing the repository in a way which minimises likely future radiation exposures (e.g., by spacing the wastes to limit heat damage and choosing appropriate materials for the containers and backfill), taking into account economic and social factors.

The inventory of wastes is also important because it determines the quantities of different radionuclides, the chemical reactions that will take place, the volume of rock likely to be needed and the amount of heat that will be generated by radioactive decay. Newer reactors tend to use higher burn-up fuel (burn-up is a measure of how much energy is extracted from a given amount of nuclear fuel). Because high burn-up spent fuel contains increased amounts of long-lived hazardous radionuclides, such as americium, curium and plutonium, for the same amount of energy produced, and generates significantly more heat, the proposed use of high burn-up fuel in new nuclear reactors could have significant implications for repository safety cases. Mixed-Oxide fuel (MOX), containing plutonium (from reprocessing, see Box 2) as well as uranium oxide also has higher radioactivity and heat generation than older uranium-based nuclear fuels.[93,94,95]

3.2. National programmes for geological disposal

Repository programmes are at different stages in various countries, and involve several different approaches to containing highly radioactive wastes.

To date, major problems with deep geological repository programmes have been encountered in several countries, for example the UK, Germany, South Korea and the USA (Box 7).

Box 7: Examples of difficulties with geological repository programmes

United Kingdom (UK)

The UK is now on its sixth attempt to find a deep geological disposal site. The first attempt, begun by the UK Atomic Energy Authority (UKAEA) in 1976, was abandoned in 1981, with a second and third attempt also unsuccessful.[96] At the fourth attempt, planning permission for a Rock Characterisation Facility (the first phase of the planned deep geological repository) near the Sellafield nuclear site was rejected in 1997.[97] The planning inspector concluded that the site near Sellafield was unsuitable for a repository for safety reasons.[98,99,100] The chosen site met none of the geological criteria or guidelines that had ever been developed to identify appropriate sites.[101] Geologists who gave evidence against the plans concluded that the planning inspector's comprehensive dismissal of the site would make it hard to return to it.[102,103] However, new geological criteria which do not exclude the Sellafield area were then developed and the planning system changed.[104,105] Three communities near Sellafield expressed an interest. However, the regional council (Cumbria County Council) rejected the plans in 2013.[106,107,108] The Government then removed the local authority's right to veto a repository and started the search for volunteers again.[109] Recently, a volunteer site in the East of England withdrew from the process, leaving only two local areas next to Sellafield as potential sites again.[110] The potential option of developing an offshore deep disposal site, accessed via Sellafield, has been introduced, however this has raised several concerns, including that plutonium contained in sediments in the Irish Sea (as a result of past discharges from Sellafield) could be remobilised.[111,112] The UK's repeated failures to implement deep disposal, or develop an alternative, have been described as '50 wasted years', and the assumptions underlying the policy of deep disposal have been questioned.[113] In August 2025, a UK Government unit which assesses the costs and risks of major infrastructure projects rated the geological disposal facility as 'red', meaning, "*Successful delivery of the project appears to be unachievable*".[114] The whole life costs were estimated at £20bn as a mid-range assessment, to £54bn as a high-end assessment.

Germany

In Germany, the deep disposal concept was originally based on the use of rock salt as the host geological formation. From 1967 until 1978 the Asse II salt mine was used for disposal of low- and intermediate-level radioactive wastes, including some long-lived wastes. In January 2010, the German authorities decided that all the waste from Asse II needed to be retrieved and repackaged due to safety problems, including the leaking of saline water into the chambers.[115] Repository shafts were constructed in 1985–90 in another salt dome site at Gorleben, selected for disposal of spent nuclear fuel as well as high-level waste from overseas reprocessing.[116] In 2000 a moratorium was placed on activities at Gorleben as a result of continuing concerns about the suitability of rock salt for geological disposal. This moratorium was lifted in March 2010 to examine further whether Gorleben would be a suitable site for the final storage of spent nuclear fuel.[117] However, these plans were abandoned and backfilling of the Gorleben site started in late 2024.[118] Germany is now engaged in a new search for a site for a geological repository.[119]

United States
Yucca Mountain, Nevada, was identified in 1987 as the sole US site to be investigated for a high-level waste repository.[120] Plans at Yucca Mountain differed from those in other countries in that the waste was supposed to be placed above the water table, where it would not be in contact with the groundwater that flows through most rocks. However, rainwater was still expected to enter the repository and to cause corrosion.[121,122] A major concern was its siting in a geologically active area where there has been significant volcanic activity and faulting. The programme was halted in 2010 after the Obama administration announced that a new plan would be developed.[123] Since then, plans for a deep geological repository have been in limbo while the U.S. Department of Energy (DOE) has investigated technical issues associated with alternative disposal options and efforts to develop a consent-based siting process for interim storage of spent nuclear fuel.[124,125] The failed nuclear waste disposal plan at Yucca Mountain took 25 years and cost $15 billion according to some estimates, or $96.2 billion according to others.[126,127] Potential alternatives are now being discussed, such as the increased use of dry storage and the potential use of deep boreholes in the future (see Section *6. Alternatives*).

South Korea
So far, nine attempts have been made to site a deep disposal facility for high-level radioactive wastes in South Korea and all have been unsuccessful due to opposition and the detection of active faults or larger than expected faults at proposed repository sites.[128] South Korea has still not designated a repository site. In South Korea, it is also assumed that spent nuclear fuel will be ‘pyro-processed’ (a form of reprocessing – see Box 2 - which involves dissolving the spent nuclear fuel in molten salts) to reduce the amount of high-level radioactive waste before it is placed in a deep underground repository.[129] However, the scientific plausibility of pyro-processing is highly questionable as the technology is still in the developmental stage.[130] All spent nuclear fuel from nuclear reactors in South Korea is currently stored in wet storage facilities within nuclear power plants for an undisclosed period of time.

Nevertheless, a few countries now have selected a site for a deep geological repository for spent nuclear fuel (see Table 1). In Finland a repository and encapsulation plant has been built but no license for operation has yet been granted. In Sweden, a court granted a permit for construction of a repository to begin with several conditions following legal challenges and underground construction can begin in a few years when the regulatory authority approves a new safety analysis report (see also Box 14).[131,132] France, Switzerland, Canada and Russia have also selected sites. France has submitted a license application for the construction of a repository.[133] In Switzerland and Canada, the process of regulatory approval is at an early stage and in Russia approval has only been granted for site-specific underground rock laboratory (URL, see Box 8), with a view to making a final decision on the repository at a later stage. China is constructing an ‘area-specific’ URL, which is based in the target geological area but not necessarily at the final deep disposal site.

National laws and regulations differ in relation to how licences to construct and operate a repository are granted, and how a final decision is approved. A licence to construct a repository is not necessarily the same as an operation licence to place radioactive waste there. Although the suitability of the site for geological disposal will generally be a factor in granting a licence for construction, a more complete safety case is likely to be needed by regulators before radioactive wastes can begin to be transported to and buried at the site (see Section *3.1. Safety assessment*). For example, in Finland, the Radiation and Nuclear Safety Authority (STUK) has been given a one-year extension, to end 2025, to review Posiva's application to operate a repository at its chosen site (submitted end 2021), and is seeking further information from the company.[134] In Switzerland, the official review and approval process is expected to last about 6 years and may include a national public referendum.[135,136] In Canada, site selection followed local votes and regulatory processes will follow.[137] Nevertheless, given high construction costs (see Section *5.3. Costs*), approval of construction at a particular site implies a very high level of commitment to that site.

Table 1: National programmes for deep geological disposal with sites selected

Country	Agency or Company responsible	Stage	Site and host rock types	Waste types	Details
Finland	Posiva Oy[138]	Licence for construction approved in 2015. A test operation (using dummy fuel) started in August 2024.[139]	Site of previous underground rock laboratory (URL), ONKALO (Olkiluoto, Eurajoki). Metamorphic rocks (migmatite-gneiss).[140]	SNF (5 500 tonnes in 3 000 canisters).[141]	Depth of 400–430 m. 10 km of tunnels constructed, with 40 km more planned.
Sweden	SKB[142]	Permit approved in October 2024. Above-ground construction began in January 2025.[143] Plan to be ready for disposal in the mid-2030s, and fully extended in the 2080s.	Forsmark, Östhammar. Crystalline rock (granite).	SNF (12 000 tonnes in 6 000 canisters).	Depth around 500 m. More than 60 km of tunnels planned.
Switzer-land	NAGRA[144]	Nördlich Lägern in the canton of Zurich (surface facilities at Haberstal, near	Clay rock.	Around 1400 m^3 of SNF assemblies and 100 m^3 of HLW.	Depth of 900 m.[146]

		Stadel village[145]). Licence application made in November 2024.			
France	ANDRA[147]	Cigéo Project located on the border of the Meuse/Haute-Marne departments (Eastern France). Site-specific URL. License application to be final disposal site made in 2023.[148]	Clay rock.	HLW and long-lived ILW, in two separate disposal zones.	Depth of 500 m. To cover a surface area of around 15 km² by its 100th year of operation.
Canada	NWMO[149]	Wabigoon Lake Ojibway Nation and the Township of Ignace were selected in November 2024. Full safety case to be prepared.	Igneous rocks (granodiorite, tonalite, granite)	SNF	Depth of 650-800 m. 175 years to implement. SNF to be sent there from the 2040s, over a period of 45 years or more.
Russia	National Operator for Radioactive Waste Management (NORWM)[150]	Nizhnekansky Rock Massif at Zheleznogorsk in Krasnoyarsk Territory (Siberia). Site-specific URL approved in 2016. Decision on use for repository to be made in 2030.[151]	Crystalline rock (granitic-gneiss).[152]	HLW and SNF.	Investigation to 700 m. Exploratory shafts at 450 to 520 m.[153]

Box 8: Differing roles for Underground Rock Laboratories (URLs)

In Finland, a site-specific underground rock laboratory (URL) was first constructed at what has now become the chosen repository site. In some countries (e.g. Russia and France) a site-specific underground rock laboratory (URL) has been approved, which is intended to become the repository at a later date, should further investigations not rule it out.

China is constructing an 'area-specific' underground research laboratory (URL), which is based in the target geological area but not necessarily at the specific site where nuclear waste (HLW and SNF) will be sent for geological disposal.[154] The Xinchang site in the Beishan area, located in Gansu Province of northwestern China, has been selected as the final site for this URL, in granite. The aim is to build a national geological repository by 2050, at a similar depth to the URL (560 m). Although the site of the URL is the preferred site for the repository, a site at Shazaoyuan is retained as a back-up site, hence this site is not listed in Table 1. In China, the Beijing Research Institute of Uranium Geology (BRIUG) is responsible for the design and construction of the URL and the China National Nuclear Corporation (CNNC) is the company with responsibility for deep geological disposal.[155]

Some other countries have URLs which are not intended to become the final repository site (Grimsel and Mont Terri in Switzerland, Tournemire in France, Äspö in Sweden, HADES in Belgium[156]), or where investigations have stalled (Gorleben in Germany, Yucca Mountain in the USA) or closed (Whiteshell in Canada).[157] There is also a URL at the Honorobe site in sedimentary rocks in Japan[158] and another in granite at the KAERI Underground Research Tunnel (KURT) in South Korea.[159]

National programmes that have selected sites (or are close to doing so) can be divided into two types based on the geology of the proposed site. The 'host rock' is the layer of rock in which the radioactive waste is intended to be placed, around 500m below ground level. Some countries (e.g. Finland, Sweden) plan to excavate the repository in hard rock types (see Box 9), usually described as 'granite', although these sites may contain more than one rock type. Metamorphic rocks are hard rocks which have been modified by heat and pressure in the past, such as gneiss. Igneous rocks are formed through the cooling and solidification of magma or lava. Some metamorphic and igneous rocks are crystalline, e.g., granite (which crystallises from hot liquid magma below the earth's surface). Thus, these repository programmes focus on such crystalline rocks. Other countries (e.g. Switzerland, France) plan to excavate the repository in clay rocks (also called 'argillaceous' rocks), a type of sedimentary rock (see Box 10). Clays are usually formed of very small particles formed by the erosion of igneous rocks. The geology of each site is in fact very complex (see Section *4.5. Bedrock properties and hydrogeology*), nevertheless it is useful to distinguish between these two different approaches.

Countries that have not yet selected sites are also mainly considering disposal in clays or in hard rocks. For example:

- Belgium (ONDRAF/NIRAS[160]) is considering two different clay formations (Boom clay and Ypresian clay) in north-eastern part of the country;
- China has constructed its 'area-specific' URL in granite (hard rock).

Other countries are at a much earlier stage of site selection (or have made several failed attempts to find a site, see Box 7). Some of these countries are nevertheless considering the option of geological disposal in one of the two host rock types described in this report (e.g. Japan[161], the UK[162]), or have already decided which of the two rock types is most relevant to them (e.g., South Korea and Czechia both focus research on hard rocks[163]). Other rock types, e.g., salt domes and volcanic tuff, have been considered in the past, but work on these is currently stalled (see Box 7), although the U.S. continues to send long-lived intermediate-level radioactive wastes from its nuclear weapons' programme to its Waste Isolation Pilot Plant (WIPP) in New Mexico, which is based in salt beds. Although these types of rock may be considered again in the future, they are not discussed further in this report. Some countries may struggle to find suitable geology (e.g., Japan, due to risk of earthquakes, see Box 15).

In the Netherlands, radioactive waste is stored above ground for a period of at least a hundred years, with a view to making a decision about long-term radioactive waste management later (in around the year 2100).[164]

A commitment to a particular geological site also implies a commitment to one or other of the repository concepts outlined in Box 9 and 10. This could prove problematic if the combination of materials to be used (metals, clays, cements) prove unsuitable for use in a repository. Similarly, an encapsulation plant is designed to package wastes in a particular way that is consistent with the repository concept. Re-packaging wastes using different materials is an expensive and potentially hazardous process, due to the presence of high levels of radioactivity.

Box 9: The hard rock (Swedish) concept[165]

In the Swedish concept for a deep geological repository, also adopted by Finland, spent nuclear fuel will be placed in cast iron frames surrounded by 5 cm thick copper canisters. The canisters will be deposited in hard bedrock (mainly granite or gneiss) at a depth of 500 m and surrounded by highly compacted bentonite clay. Canada, Russia and China also plan to use hard rock sites, although details of the repository design may differ (for example, Canada plans to use only a 3 mm layer of copper on its spent fuel canisters[166]).

Once the repository is closed, groundwater will come into contact with the canisters containing the wastes. The developers expect the copper canisters to corrode very slowly in the absence of oxygen. In Sweden and Finland, the target lifetime for containment of radioactive waste in the canisters is 100 000 years.

The bentonite and surrounding crystalline bedrock are water-conducting, so the only absolute barrier to radionuclide migration will be the copper canisters, for as long as they remain intact. Once the canisters have corroded, radionuclides are expected to leak into the surrounding water. The bentonite clay is intended to act as a physical buffer, giving the canisters mechanical support, as it swells in water. It is also meant to slow or prevent corrosive substances in the groundwater from reaching the cannister and to slow the movement of some radionuclides, particularly the highly radiotoxic actinides if a cannister is breached (see Box 5).

The bentonite clay and bedrock are expected to slow the movement of radionuclides to the biosphere. However, absolute containment until the waste has decayed is not expected and some of it will migrate to the surface in groundwater or as gas.

Box 10: The clay rock concept (France, Switzerland, Belgium)[167]

The French concept for deep disposal differs from the Swedish one in two main respects. Firstly, the rock type will be clay, not crystalline; secondly, vitrified high-level wastes will be placed in steel overpacks rather than copper canisters. Steel is expected to corrode more rapidly than copper, so the safety performance of the repository is expected to be more reliant on the surrounding backfill and clay rock. The developers expect the clay rock to swell, holding the canisters in place, closing any cracks, and trapping some radionuclides.

In France, Switzerland and Belgium, high-level waste (HLW) is being sent for disposal, due to the past use of reprocessing (Box 2). In some countries (e.g. Belgium) both HLW and un-reprocessed spent fuel is already planned be included.[168] It is likely that all countries that have used reprocessing will also have some un-reprocessed spent fuel to be disposed of towards the end of the operation of their nuclear reactors. For some countries (e.g., France) this will include spent MOX fuel.

In many countries, long-lived intermediate-level wastes (ILW) are also included in the inventory for the repository and perhaps some low-level wastes as well (e.g., in Switzerland). Such waste forms are generally expected to be placed in a different section from high-level waste or spent nuclear fuel, and can be spaced more closely together because they are not heat-generating. The quantity of ILW is larger in countries that have reprocessing plants (e.g., the UK and France). Although these wastes contain a lower-level of radioactivity and are not heat-generating, they pose additional challenges because the level of containment provided by their packaging is often lower, and in some cases they may pose a fire risk or a higher risk of release of radioactive gases (see Section *4.2.2. Corrosion of intermediate-level waste packaging*).

The construction of a repository in clay rock is challenging, due to the need to support shafts and tunnels with steel/iron and/or concrete.[169] In hard rock, which is highly fractured, developers need to avoid potential deposition holes with high groundwater inflow. [170]

In Sweden, SKB submitted its application documents for a deep geological repository in 2011.[171] In Finland, Posiva's application for a deep geological repository was made in 2012 and is also publicly available.[172] In France, ANDRA submitted its licence application in 2023.[173] In Switzerland, NAGRA made the documentation for the general licence application of its deep geological repository publicly available in June 2025.[174,175]

3.3. Potential for significant radiological releases?

A number of low- and intermediate-level radioactive waste disposal sites have operated over the last 50 years. However, many of these supposedly final disposal sites have already caused unexpected environmental contamination, highlighting how difficult it is to predict what will happen to buried wastes, even over short timescales. Examples are the Dounreay nuclear waste shaft in Scotland, which exploded in 1977,[176] the Centre de Stockage de la Manche storage site in France, where water supplies in the aquifer became contaminated,[177] the Asse II salt mine in Germany (see Box 7) and the U.S. Waste Isolation Pilot Plant (WIPP), for wastes from its nuclear weapons programme, where safety issues included an explosion and a leak causing radioactive contamination in 2014.[178] Moreover, the disposal of high-level wastes raises unprecedented challenges because of the very long half-lives and radiotoxicity of these wastes.

Enthusiasts for deep geological disposal argue that there are examples (known as natural analogues) which demonstrate that geological formations are capable of isolating highly volatile and flammable substances such as oil and gas underground for hundreds of millions of years.[179] Concentrated natural uranium deposits have been largely confined for millions of years at sites such as Cigar Lake in Canada, and there is even an example of a natural underground nuclear reactor containing uranium and fission products in Oklo, Gabon.[180]

However, the emplacement of high-level waste in an underground repository would entail a major perturbation of the geological system, involving:[181]

- (i) a large number of tunnels covering an area of several square kilometres
- (ii) the release of significant amounts of heat, initially of the order of tens of thousands of kilowatts per square kilometre
- (iii) intense radiation and significant quantities of highly toxic radionuclides, each with its own complex chemistry.

Manufacturing and quality assurance concerns generally lie outside the scope of scientific reviews and are not considered further below. However, failure to meet high specifications for engineered barriers (i.e., the containers, backfill and other engineered structures) could also lead to problems such as: faster corrosion of metals; failure of clay backfills to hold nuclear waste containers in place and seal tunnels; failure of cement plugs in tunnels; or failure of grouting to plug damaged rock.

Significant releases of radioactivity from an underground repository could occur if the near-field (i.e., engineered) or far-field (i.e., geological) barriers were breached in ways that allowed radioactive groundwater or gas to escape faster than expected. In 2010, Nuclear Waste Advisory Associates, a UK-based consultancy, listed over a hundred scientific and technical issues that remain to be resolved in relation to producing a robust safety case for the deep disposal of radioactive wastes: similar issues were discussed in the earlier version of this report (published in 2010), and in a subsequent compilation of these issues available on the Nuclear Waste Advisory Associates website.[182]

The current state of knowledge about these issues is considered in the literature review that follows.

4. Literature review of post-closure issues

The deep disposal concept rests on three premises[183]:

- The packaging (canisters and backfill) will be able to withstand the intense heat and radiation from the wastes and the high stresses this creates in the surrounding rock.
- The complex chemical and radiological changes that will occur over this period are well enough understood to ensure that the integrity of the waste containers and backfill is maintained for tens of thousands of years.
- A site can be identified that meets the necessary geological requirements over a period of hundreds of thousands of years.

Construction of a deep repository creates an Excavation Damaged Zone (EDZ), creating fractures in the rock, which may create fast routes for radionuclides to escape in future water or gas flows (see Section *4.5.2. Excavation damage*).[184,185] Tunnels must be supported, e.g., with steel supports, especially in bedrock with high rock tension. Wastes are packaged and sealed in deposition holes using a variety of different materials (e.g. copper or steel canisters), and the deposition holes are then backfilled, usually with clay or mixtures of clay and sand. Closure requires a large number of clay or clay and sand-based seals to be put in place to seek to limit water flow and radionuclide transfer from the disposal cells to the biosphere. Cement and cement-based products (concrete) are also widely used in repository designs: for example, to line or plug tunnels, or to package wastes.[186] The issues associated with corrosion of the canisters and damage to the clay (e.g. due to the intense heat in the repository, or chemical disturbance by cement water) are reviewed in Sections *4.2. Corrosion of canisters, wastes, and repository structures* and *4.3. Damage to bentonite and clay rocks*).

Once constructed and filled with radioactive wastes, the life cycle of a deep geological repository involves several phases, during which intense heat and radioactivity from the wastes change the repository conditions significantly over time, such as how wet it is and the changing chemical conditions.[187] There is considerable uncertainty about the timing of these phases, which also depend on the repository design, geology and waste types. The process of filling a repository with radioactive waste may take several decades (see Box 6). Oxygen, which enhances corrosion rates, will be present until the waste container is sealed in the deposition hole. The removal of oxygen may take only days after closure to be removed by chemical reactions or the activity of bacteria, or it might be trapped for longer. Water will then gradually flow back into the repository. Due to the intense heat and radioactivity emitted by the radioactive wastes, it could take around 100 000 years before conditions in the repository return to those similar to before it was disturbed. These changing conditions, including intense heat and radiation are reviewed in Section *4.1 Changing repository conditions*.

The focus of this report is on designs in which the waste is below the water table and the backfill is expected to become saturated with water after the repository is closed. In the USA, the Yucca Mountain site is above the water table, but this has now been abandoned (Box 7) and is not discussed further in this chapter.

The changing conditions below ground result in complex interactions between different processes, including the release of substantial quantities of gas, some of which may be radioactive. Microbes, which can survive below ground in the intense heat of the repository, play an important role in some of these processes. Because of the extremely long time-scales involved, researchers rely on computer models to try to predict the complex interactions between the effects of heat, water flow, stresses in the rock and engineered barriers, changing chemistry and the effects of microbes, each of which can affect each other. These are known as coupled thermo-hydro-mechanical-chemical-biological (THMCB) models.[188] The term "coupled processes" implies that each process potentially affects and is affected by the initiation and progress of all other processes.[189] The response of a rock mass to radioactive waste storage cannot be predicted with confidence by considering each process individually or in direct succession. In practice, most computer models do not include all of these processes or their interactions because of the complexities involved, so major challenges remain. As the chemical and biological conditions are difficult to model, most modelling is only of temperature, hydrology and mechanics (THM), and, even when limited to these physical processes, there are difficulties in reproducing existing experiments and extrapolating the results to the long timescales involved. The state of development of these computer models is reviewed in the relevant sections below, and the broader issues associated with the impossibility of validating such models over extremely long timescales are discussed separately in Section *5. Overarching unresolved issues*.

Repository conditions can change further due to events such as human intrusion, glaciation and earthquakes, discussed in Sections *4.6. Human intrusion and human error*, Section *4.7. Glaciation* and Section *4.8. Faults, seismicity and earthquakes*. When radionuclides reach the biosphere (in which living organisms, other than microbes, are present), they can build up in the food chain, as described in Section *4.9. Transport of radionuclides in the biosphere*).

It should be noted that the use of higher burn-up nuclear fuels and fuels containing plutonium (MOX) may have implications for repository safety cases because of higher radioactivity and heat generation from these fuels than from older low burn-up uranium-based fuels.[190,191] In particular, higher burn-up and MOX fuels contain more minor actinides (actinides other than uranium and plutonium), which increase the release of neutron and gamma radiation and heat when they decay. These issues are largely neglected in the literature review below, as they have not yet been studied extensively.

4.1 Changing repository conditions

As the repository is filled with waste containers, heat generating radioactive wastes (high-level waste, HLW, and/or spent nuclear fuel, SNF) will heat up the repository. Most repository designs attempt to limit the temperature to below 100^{o}C, by allowing the wastes to cool sufficiently before emplacement and by spacing them far enough apart, however some countries are investigating whether money could be saved by increasing the temperature limit to 150^{o}C.[192] In some cases, the temperature may be higher than any previously experienced in the host rock: for example, the maximum temperature undergone by the Opalinus clay in Switzerland during geological history is estimated at around 70^{O}C.[193]

In a repository in hard (crystalline) rock, the maximum temperature may be reached 10 to 100 years after waste emplacement, remaining close to this temperature for up to 1 000 years, before gradually reducing and reaching the original background temperature after 100 000 years (these timescales are approximate and will depend on the repository design and geology).[194,195] During construction, the underground water in the repository must be pumped out, and/or prevented from entering tunnels by sealing fractures with cement or grout, but after closure it will re-enter the repository galleries. The pressure will also increase back from atmospheric pressure to the pre-construction pressure at depth in the rock (heating from the wastes may increase the pressure further). In hard rock, a process of re-wetting of the clay (bentonite) container and tunnel backfill is expected to begin after around 1 000 years, once the temperature has cooled down sufficiently, and may take tens or thousands of years depending on the rock type.[196] In Sweden, re-saturation times of thousands of years have been predicted, albeit with significant uncertainties.[197] This timescale is highly uncertain and some computer modelling suggests that desaturation (i.e. drying out) of clay rocks is limited.[198] Some calculations imply much faster re-wetting: based on an assumption that the bentonite is still 67% saturated at the start of the re-wetting process, modelling suggests it could take only between tens and hundreds of years (10 to 80 years in crystalline rock and 35 to 720 years in clay rock).[199] In the presence of water, corrosion processes may begin again, this time in the absence of oxygen (i.e., 'anoxic' processes). Whilst the repository is still in its operational phase, oxygen will be present until the emplacement room or repository is sealed. Thereafter oxygen concentrations will drop, as chemical reactions and microbes in the repository will use it up. This process has been estimated to take from about a month to several years.[200] Experiments in rock laboratories suggest that microbes can use up oxygen in the deposition holes in a matter of days.[201] After around 100 000 years, the repository is expected to be both fully saturated and back to its original temperature and to remain in this state indefinitely, unless geological processes (such as earthquakes or glaciation), or human intrusion, disturb it.[202,203] Estimates of the duration of the transient phases (i.e., when temperature and water flows are changing due to the presence of the wastes) are highly uncertain and may vary for different repository designs. For example, a generic safety assessment for clay rocks in Germany estimates that the transient phase in the repository will be complete after around 50 000 years.[204]

It is important to remember that conditions in the repository may not be uniform. For example, temperatures may be higher in the centre of the repository than on the outer edges. Areas of a disposal tunnel that are closer to the plug (exit of the tunnel) could possibly have a higher oxygen content if they are not fully sealed and this will continue while access tunnels remain ventilated during the operational phase (i.e., during emplacement of the wastes, which may take decades).[205]

The changing chemical conditions inside the repository are very important because they will influence which chemical reactions can occur and at what rate. This in turn will affect the corrosion rates of the waste containers, the properties of the bentonite clay expected to be used as backfill, and how quickly the wastes dissolve and migrate through the backfill and rock. Relevant chemical properties in a repository will include how acidic or alkaline the groundwater is (its pH) and its redox (reduction-oxidation) potential, both of which can change with time. Solutions with a pH less than 7 are said to be acidic and solutions with a pH greater than 7 are said to be basic or alkaline. Reduction potential (Eh) is a measure of the tendency of a chemical species to acquire electrons and thereby be reduced. Both Eh and pH influence the type of chemical reactions that can occur. Understanding and predicting the rate of the complex chemical reactions which will occur underground is central to a robust repository safety case. However, many gaps in knowledge and uncertainties remain.

The life-cycle of the repository is more complicated in repository designs which also include long-lived intermediate level wastes (ILW), often in a separate area, because these are not heat generating. Whilst this simplifies some aspects, it also means that these waste types will not dry the area around them and may become wet more quickly, speeding up corrosion processes. ILW uses different packaging and may also contain different types of waste (e.g., organic material which may give off gases[206]). The risk of fires in ILW during the operational phase may be significant, because some long-lived ILW is packaged using bitumen (including in Belgium, Czechia, Denmark, Finland, France, Japan, Sweden, Switzerland, Ukraine and USA), which is highly flammable.[207,208,209,210] In Germany, asphalt (which contains bitumen) is proposed to be used as a sealant in some parts of the drifts in a proposed clay rock repository, as the proposed bentonite seals in the drifts take decades to swell to reach their full sealing capacity and the drift support can act as a preferential pathway for potentially contaminated water.[211] It is unclear to what extent other repository designs may also make use of asphalt. Fire risk is not discussed further in this section, which focuses on post-closure risks. However, it should be noted that a fire could jeopardise the whole future of the repository, as well as posing major risks to workers and the public.

The main post-closure processes that take place in this context are discussed below.

4.2. Corrosion of canisters, wastes, and repository structures

Copper or steel canisters or overpacks will be used to contain the spent nuclear fuel or high-level waste when it is placed in the repository. As groundwater from the surrounding rock flows into the repository, these canisters or overpacks will begin to corrode and eventually their radioactive contents will be released into the groundwater. The instant release fraction (IRF) is the fraction of the radioactive inventory that will be released from the waste "immediately" after the spent fuel rod cladding fails, and the waste containment is compromised.[212] These are the radionuclides that have migrated into the inner-rod void space. Some of the preferentially released radionuclides are characterized by both relatively long half-lives and high degrees of mobility, e.g., iodine-129 and chlorine-36 (see Box 5). Some radionuclides will dissolve in groundwater, whilst others are released as gases. In the longer term, other radionuclides will be released as the spent fuel matrix slowly dissolves. In most repository designs, clay backfill around the containers is intended to delay the movement of some of these radionuclides, however the backfill can also be compromised by some of the processes occurring underground (see Section *4.3. Damage to bentonite and clay rocks*).

It is not possible to conduct corrosion experiments over sufficiently long periods to be meaningful and therefore the conclusions drawn depend on computer modelling approaches, the assumptions made (in both experiments and models), and the highly uncertain predictions of repository conditions discussed in Section *4.1 Changing repository conditions*, above.[213]

The Swedish safety case assumes that copper canisters 5 cm thick will contain spent nuclear fuel for 100 000 years. However, there has been much debate about the corrosion rate of copper (discussed further below). In Canada, a copper coating is also expected to be used, but in a much thinner (3 mm) layer.[214] Some other countries considering deep disposal in crystalline rock have not yet committed to the use of copper, perhaps due to its high costs and possible limited availability in future (see Section *5.3. Costs*). In France, steel overpacks are expected to be used instead, and other countries planning deep disposal in clay rocks may or may not add a copper coating to steel canisters. In France heat-generating wastes are in the form of HLW rather than spent fuel, and in some other countries this is also the case (or both HLW and spent nuclear fuel are expected to be sent to the repository). Steel is expected to corrode much more rapidly than copper: with a typical design life of 1 000 years. Actual life may be significantly longer than design life and the predicted lifetime of the steel overpacks in Switzerland is of the order of 10 000 years.[215] However, this is also dependent on many assumptions about the corrosion of steel in the changing repository environment, discussed further below. Compared to the Swedish approach (assuming copper corrosion is as slow as the developers expect), the safety case for burial in clay rock is much more dependent than on the performance of the clay backfill and bedrock, due to the expected faster corrosion of steel than copper canisters.

An inner material is also needed between the insides of the canisters and the spent fuel assemblies they contain, to prevent the gap filling with water and leading to criticality (a nuclear chain reaction) occurring (see Section *4.4.5 Criticality*). A cast iron insert will be used in the Swedish copper canisters; other materials (for example, glass or depleted uranium), each of which has different advantages and disadvantages, are being considered as possible alternative inserts in steel canisters in other countries.[216,217]

High level waste (HLW) that has been separated from spent nuclear fuel by reprocessing (see Box 2) is initially in liquid form and is solidified and vitrified (i.e. turned into glass blocks) before disposal. Most countries with vitrification plants (Belgium, France, Germany, UK, US, Japan and India) use a type of glass known as borosilicate glass, however a different type of glass (sodium-aluminium-phosphate glass) is used in Russia.[218] Glass has some disadvantages for deep disposal. It can be damaged by heat and humidity and radionuclides will leach if it is crushed.[219] Radiation from the nuclear waste contained in it can also damage the glass, and leaching from the glass can increase significantly if it is in contact with water whilst still emitting gamma radiation (due to radiolysis of water).[220,221] Some of the radionuclides are held uniformly in the glass, whilst others crystallise at the bottom of the glass during vitrification.[222] The various materials in a repository, including borosilicate glass, ceramics (if used), and metals lead to complex interactions between corrosion mechanisms, as the chemical products of one type of corrosion can affect another.[223] In particular, the corrosion of nuclear waste glass is enhanced by the presence of steel. However, none of the experiments carried out to date can stimulate the actual repository conditions and there remain many unanswered questions, which have been described by researchers as being of critical importance.[224]

After oxygen in the repository has been used up, corrosion of steel will release hydrogen gas into the repository. Corrosion of copper may also release hydrogen much earlier than expected if corrosion occurs in pure water, as some scientists suggest. Corrosion of some wastes can also release carbon dioxide or methane, which may be radioactive (containing carbon-14). The build-up of gas pressure could be harmful, since a sudden release of pressure (or explosion) could damage the repository. Alternatively, slow release of gas could open up fractures in the backfill or rock, and speed up the release of some radionuclides from the repository (see Section *4.3.3. Effects of gas on the clay barrier and surrounding rock*, Section *4.4.4. Release of radioactive gas* and Section *4.5.3. Gas flow*).

Corrosion during the unsaturated and partially saturated phases of the repository (i.e., during emplacement and while the temperature remains high, drying out the wastes) has not been as well-studied as corrosion under saturated conditions.[225] Although the repository is expected to dry out due to the heat from the radioactive wastes, it is important to remember that water can be retained in sealed spent fuel canisters if they are not adequately dried before emplacement.[226]

These issues are discussed in more detail below.

4.2.1. Corrosion of copper

The Swedish concept for deep disposal uses copper canisters because the corrosion rates are expected to be extremely slow. In Sweden and Finland a 5 cm thick copper canister is intended to be used, whereas in Canada, a much thinner 3 mm copper coating is proposed.[227] The corrosion behaviour of copper canisters is expected to change with time as the conditions within the repository evolve from warm and oxidising initially to cool and anoxic (oxygen-free), with water initially present, then lost due to heating from the heat-generating radioactive wastes, then re-entering as the repository cools.[228, 229]

Copper corrodes in air due to the presence of oxygen, forming copper oxides. There will be air in the repository during the decades when it is operational (i.e., while the waste is being emplaced). However, after the repository is closed, safety cases assume that all the oxygen will be rapidly used up by the metabolism of oxygen-using microbes (aerobes) and other chemical reactions, so that the copper canisters can no longer corrode in this way. After all the oxygen has been consumed, it is assumed that sulphides (e.g., hydrogen sulphide produced by microbes) will be the primary corrosive agent for copper canisters in a repository, and corrosion will proceed with the formation of copper sulphide and hydrogen gas, although corrosion rates are predicted to be very slow.[230,231,232,233] Corrosion due to microbes is discussed in Section *4.2.3. Role of microbes in corrosion*.

Nevertheless, there remains concern about the rate of corrosion of copper during the emplacement (operational) phase, when oxygen and heat are both likely to be present, and about whether the corrosion of copper is as slow as the nuclear waste disposal companies expect once the oxygen has been used up. In Canada, coating copper canisters with a polymer has been considered in the past as an option to provide protection during the early emplacement phase.[234] However, Canada seems to have settled now on a copper coating, with a steel insert.[235]

It has long been assumed that water alone does not corrode copper in an oxygen-free environment. If this assumption is wrong, the copper canisters used in the Swedish deep repository concept could corrode much more quickly than the current estimates suggest. The Swedish scientist Gunnar Hultquist first questioned this assumption in 1986, when he measured an increase in hydrogen concentration in the gas volume above copper in water: a finding replicated in subsequent experiments.[236,237,238,239,240] These findings were disputed by supporters of the Swedish safety case, but have been defended by the authors, with some support from others. [241,242,243,244,245] In 2009, the Swedish National Council for Nuclear Waste (Kärnavfallsrådet) held a seminar to discuss this dispute.[246] Subsequently, some papers have been published arguing against the corrosion of copper in pure water.[247,248] However, a recent (2024) review concluded that a definitive, reproducible experiment has yet to be conducted and this mechanism for copper corrosion, although disputed by some, can still not be completely ruled out.[249] Although the corrosion of copper in pure water is expected to be relatively slow, it could be speeded up considerably when taking place in the environment of repository ground water, which contains corrosive substances at high temperatures.[250] Recently, researchers working with the Canadian nuclear disposal company, NWMO, have recognised that it may not be possible to persuade regulators that the corrosion of copper in pure water is not possible. Instead, they are seeking to use new experiments place a limit on the rate at which such corrosion might occur.[251] This depends on measuring very small quantities of hydrogen released over a short-timeframe at laboratory scale and extrapolating the results to very long repository timescales. To date these experiments have been limited and the issue is still unresolved. Issues regarding this dispute are discussed further in Box 14.

There are several other uncertainties regarding copper corrosion that also need to be considered. How copper will corrode in a deep geological repository will change as the conditions in the repository change with time.[252,253] Numerous assumptions are made in experiments and computer modelling which may not be correct, as it is not possible to reproduce repository conditions as they change over long timescales into the far future (see Section *4.1 Changing repository conditions*).

Corrosion during the early phase of active operations (when oxygen is present) should not be neglected, as the copper will be exposed to humid air and perhaps high salt content in groundwater (speeding up corrosion).[254] The presence of contaminants such as sulphur dioxide or nitrogen dioxide may also increase corrosion rates during the operational phase. Different parts of the repository will be sealed at different times. Following sealing (usually in bentonite, see Section *4.3. Damage to bentonite and clay rocks*), sufficient moisture is likely to remain for corrosion to continue but the amount of oxygen will be limited to what is trapped in the pores of the backfill. As the oxygen is used up, corrosion processes change significantly. These processes can include radiation-induced corrosion (RIC), discussed further below. Trace gases that increase corrosion rates, such as hydrogen sulphide, may also be present in the repository. As the repository heats up, the bentonite closest to the canisters will dry out (at least to some degree), salt crystals will be deposited on container surfaces, and corrosion rates (which require water) will generally slow or perhaps halt. However, there are high levels of uncertainty about when (or whether) the container will become too dry for corrosion to occur. It is likely there will be water vapour in the deposition hole (even if there is no liquid water), which could deposit salt on the surface of the canisters, and water may also collect at the bottom of the deposition holes. In the longer term, groundwater will re-enter as the waste cools down and will re-wet the surface of the waste containers. It is not clear how the presence of salt crystals will then affect corrosion, but a process of localised corrosion may occur if oxidants are present. Experiments are still needed to evaluate this type of corrosion in the presence of salts and bentonite. When the bentonite is fully saturated any trapped oxygen will have been fully consumed. However, the effect of radiation at the surface of the spent fuel is expected to produce oxidising chemicals (mainly hydrogen peroxide, H_2O_2). These oxidising chemicals can increase corrosion of the containers and the spent fuel inside. Corrosion can also continue due to the presence of micro-organisms such as sulphide-reducing bacteria (SRB) (see Section *4.2.3. Role of microbes in corrosion*), as well as sulphide levels in the groundwater (these may be relatively high in Sweden and Finland). As the temperature in the repository reduces further, corrosion due to sulphide-reducing bacteria is likely to continue.

Other potential corrosion mechanisms that are generally neglected include stress corrosion cracking; and pitting.[255] If it occurs, stress corrosion cracking could lead to localised damage features that extend far into the copper (which is a thin surface later in the Canadian design). However, it is generally assumed that the specific environmental conditions needed will not occur in the repository. Pitting develops when the corrosion is confined to a small area on the metal surface, potentially leading to areas of greater corrosion damage. Pitting is also generally ignored in repository safety cases, however it may occur if wetting is not uniform. Penetration and distribution of corrosive chemical species into the copper microstructure can also occur. An elevated temperature greatly accelerates the penetration of corrosive species into the copper and the corrosion on the surface.[256]

Radiation induced corrosion of copper, due to the radioactivity of the spent nuclear fuel or high-level wastes, is another mechanism which has been shown to occur under repository conditions.[257] Radiation-induced corrosion (RIC), should be considered during any period when water and radiation exist simultaneously. In the Swedish and Finnish repositories (with 5 cm thick copper canisters), this type of corrosion on its own is not expected to occur fast enough to pose a direct threat to canister integrity. However, radiation-induced corrosion could change the chemical properties of the canister surface, possibly making it more vulnerable to other chemicals in the groundwater. The canisters are expected to be exposed to humid air for a significant time before being placed in the repository, during which time radiation-induced corrosion can also take place. Experiments suggest that irradiation in air followed by irradiation in anoxic water (the water after oxygen has been removed for the repository) can significantly increase the amount of copper that is oxidised.[258]

Creep is the tendency of a solid material slowly to move or deform permanently under the influence of stresses. Creep in copper occurs readily at the high temperatures expected in a nuclear waste repository. [259] As a result, phosphorus doped copper (Cu-OFP) is now intended to be used in the Swedish repository concept. The addition of phosphorus (P) appears to substantially increase the creep strength and the creep ductility.[260] However, according to the Swedish regulator, an adequate explanation of the behaviour of phosphorus-doped copper has yet to be provided and there is a need for further research.[261,262] The regulator highlights that creep brittleness of copper can potentially induce concentrated damage in certain directions meaning that the corrosion barrier of the copper shell can be reduced.

4.2.2. Corrosion of intermediate-level waste packaging

Some national disposal plans (especially in countries where spent nuclear fuel has been reprocessed) envisage the co-disposal of long-lived intermediate level wastes (ILW) with high level wastes (see Table 1), although this is usually in a separate area of the repository. In some countries, low level (LLW) wastes may also be included. Long-lived ILW is usually packaged using cement or asphalt (aggregates mixed with bitumen), inside steel containers, although polymers can also be used. [263] ILW packaged in cement is likely to leach, whereas asphalt is prone to ageing and the bitumen in it is flammable.[264] Where waste is packaged with bitumen, it can swell and crack as irradiation from the wastes inside causes gases (mainly hydrogen) to be produced, or through uptake of water.[265] Bitumen can also be degraded by microbes and is highly flammable if oxygen is present.

The evolution of a cementitious waste package for ILW is governed by several tightly coupled transport and chemical processes.[266] Calculated gas generation and water consumption are much higher under more realistic assumptions that take account of feedbacks between different physical and chemical processes as the cement degrades. Cement is alkaline, which is intended to delay steel corrosion, but which may also have negative effects on the properties of bentonite (see Section *4.3.2. Effects on clay of chemical disturbance due to corrosion*).

Generation of gases from intermediate-level wastes is considered further in Section *4.4.4. Release of radioactive gas*.

4.2.3. Role of microbes in corrosion

It has been known since the 1980s that micro-organisms (microbes), such as bacteria, might survive in a deep geological repository and that the effects of microbial activity could have profound impacts on waste containment.[267] In 1987, microbiology became a part of the Swedish scientific programme for deep disposal.[268] As well as surviving the intense heat and lack of oxygen after closure of the repository, microbes organised as a thin layer known as a biofilm can survive highly irradiated environments. [269] Microbes could have a number of adverse effects on the safety of a nuclear waste repository, including causing corrosion of metal waste containers.[270,271] The effect on clays is discussed in Section *4.3.4. Effects of microbes on bentonite and concrete*.

There is now no doubt that life could survive in a repository in the form of microbes, despite the heat and radioactivity generated by the wastes. Sulphide reducing bacteria (SRB) use sulphate instead of oxygen to respire and produce hydrogen sulphide as a result – this is a toxic, flammable chemical which can also corrode metals, including copper. Several studies have reported the existence of SRB in relevant host rocks and in bentonite.[272] For example, microbes including SRB have been found in groundwaters at the Forsmark repository site in Sweden.[273] Microbes including SRB also exist in clays, including bentonite: however, measuring microbes in clay rocks is extremely challenging.[274,275] Experiments conducted in Sweden have found that the sulphate-reducing bacterium *Desulfovibrio africanus* is present in commercially available bentonite, and survives and is viable after exposure to high salt concentrations (which may occur in groundwater at depth) and temperatures of 100°C for 20 hours.[276] SRB are also a characteristic component of the Opalinus Clay formation, investigated as a potential repository host rock in Switzerland.[277] Some microbes can switch from surviving on oxygen (aerobic) to using other chemicals to respire (anaerobic), and thus could contribute to using up the oxygen in the repository whilst also surviving afterwards.[278]

In experiments conducted in Canada's Underground Research Laboratory, culturable populations of microbes were found at all locations studied in the bentonite-based sealing materials.[279] Increased heat increases nutrient availability in bentonite-based materials and has a stimulating effect on microbial activity.[280] Migration of microbes through the bentonite appears to be slow, but migration along the metallic holder–backfill interface may be rapid, suggesting that cracks or interfaces may form preferred pathways for migration.[281]

Thus, microbes are likely to contribute to corrosion in a repository.[282] SRB can cause corrosion of metals, including both steel and copper, through both direct and indirect processes, known as microbially influenced corrosion (MIC).[283] MIC can occur through two mechanisms: corrosion through the production of corrosive chemicals (metabolites) such as hydrogen sulphide, or corrosion through the uptake of electrons from the metal (known as electrical MIC). As well as SRB, nitrate-reducing bacteria (NRB), can also cause MIC. Although such corrosion rates are likely to be slow there is concern that canisters could suffer pits or fissures.[284] This type of corrosion can generate gas which can have adverse impacts on the repository (see Section *4.3.3. Effects of gas on the clay barrier and surrounding rock*). However, some researchers argue that microbes far from the corrosion area might help to use up hydrogen gas and prevent it becoming such a major problem.[285] As well as hydrogen sulphide, acetate, which is also highly corrosive, can also be formed by microbiological processes deep underground.[286] In addition, microbial activity can indirectly influence solubility and hence the movement of radionuclides by the alteration of the geochemical conditions in the repository: this can either increase or reduce radionuclide transport (see Section *4.4.3. The role of microbes*).

According to a 2021 review, "*Current studies suggest that knowledge of MIC in repository-relevant conditions is insufficient to determine the degree of possible material damage or to model probable corrosion rates after repository closure*".[287] The authors also note that, "*There are significant uncertainties in predicting the extent of corrosion due to microbes, due to the many variables involved, including complex processes of different microorganisms causing different electrochemical reactions at different temperatures, availability of nutrients, and the release of metabolites that may have secondary effects on corrosion*".

In addition to microbes that are already present underground, microbes will be introduced in the process of excavating a repository.[288] If the repository is to be kept open for a long period of time there may be added difficulties with microbes due to the presence in the ventilated caverns of a humid, oxygen-filled environment. This could provide many potential niches for microbial growth, which could then affect the integrity of the storage canisters before closure.[289]

4.2.4. Steel corrosion and hydrogen gas generation

Steel is an alloy of iron and carbon that demonstrates improved mechanical properties compared to the pure form of iron. Corrosion of steel can occur through uniform corrosion, pitting corrosion or stress corrosion cracking.[290]

Iron and steel corrode rapidly in the presence of oxygen, but they also continue to corrode in anaerobic conditions (i.e., when the oxygen has been used up). Unlike in the case of copper (Section *4.2.1. Corrosion of copper*), the existence of this reaction is not disputed. In a deep repository, hydrogen will be produced by anaerobic corrosion of iron as well as steel. The pressure rise in a repository due to the formation of dissolved hydrogen, and the subsequent production of gas bubbles, might be sufficient to break or fracture the barriers and/or lead to the release of radioactive gases (this is discussed further in Section *4.3.3. Effects of gas on the clay barrier and surrounding rock*, Section *4.4.4. Release of radioactive gas* and Section *4.5.3. Gas flow*). Hydrogen embrittlement of the corroding metal might also occur, with detrimental effects on the mechanical characteristics of the overpacks or canisters.[291,292]

In the French concept, steel overpacks (without a copper coating) will be used for the vitrified high-level waste. In the Swedish concept, the canisters will contain iron, which will be exposed only once the copper has been corroded or damaged. Hydrogen can also be produced by radiolysis (the dissociation of molecules by radiation) of the organic waste contained in some waste packages. For example, in the long-lived intermediate-level wastes generated by reprocessing in the UK and France. If copper corrodes in pure water, as some evidence has suggested (see Section *4.2.1. Corrosion of copper*), hydrogen may also be produced by this reaction.[293] Both copper and steel/iron can also be corroded by microbes (see Section *4.2.3. Role of microbes in corrosion*).

Steel corrosion mechanisms and rates depend highly on the chemistry in the repository. For example, if the environment becomes acidic, corrosion rates will be much higher than intended and could compromise the integrity of steel containers. Research by the nuclear waste disposal company in France, ANDRA, found that oxidation of minerals (pyrite), present in so-called COx claystone, caused a significant pH drop in the environment in contact with the casing, making it acidic. This study explores the impact of acidic conditions and concludes that "*recent results have revealed that possible chemistry transients of clay porewater may trigger significant corrosion rates of carbon steel leading to potential risks of premature failure of metal components*".[294] As a result of these findings, this paper proposes injecting an alkaline grout material between the casing and the host rock. However, in repository designs containing bentonite, the effects of alkaline grout on bentonite may be harmful to the repository safety case, by damaging the bentonite backfill (see Section *4.3.2. Effects on clay of chemical disturbance due to corrosion*). Similar concerns may apply to the clay rock in the French repository design.

In 2020, researchers in the USA warned that corrosion could be significantly accelerated at the interfaces of different barrier materials, and that this has not been considered in the current safety and performance assessment models.[295] In particular they highlight the risk of pitting or crevicing of steel (localised corrosion) at the interface between steel and glass high-level waste containers (or ceramic containers, if these are used). This type of corrosion could allow corrosive chemicals to reach the glass and drastically increase the acidity within a confined space. This can cause accelerated failure of the stainless-steel canister and thus expose more of the glass. These experiments (conducted at 90^{o}C) find that the interfaces of metal-glass (or metal-ceramics) are prone to enhanced corrosion which could cause enhanced radionuclide releases from a nuclear waste repository.[296] This is due to the feedback effects between the corrosion of two different materials. These results have been dismissed by some advocates of deep geological disposal as being irrelevant to most repositories, as they were conducted in the presence of oxygen (intended to be relevant to the repository conditions expected at the now abandoned Yucca Mountain site in the USA, which is above the water table, rather than to repositories below the water table, where oxygen is expected to be absent after closure).[297] However, the authors say that these corrosion mechanisms should be considered for all repositories, as oxidants other than oxygen might be present, e.g., those produced by gamma radiation from the wastes (which can break the chemical bonds in water molecules, a process known as radiolysis).[298]

Chinese researchers argue that low carbon steel (proposed for use in nuclear waste containers in France, Switzerland, Belgium, Japan and China) may not be suitable for manufacturing geological disposal containers, although it might be possible to reduce corrosion by adding alloy elements (e.g. nickel and copper).[299] This conclusion is based on electrochemical corrosion experimental results from a simulated groundwater environment in the Beishan underground rock laboratory (URL). These researchers argue that there may be some residual oxygen in the repository, which has a profound effect and can create a significant effect of localised corrosion.

Some experiments suggest that the corrosion rate of iron and steel may be significantly increased by the presence of gamma radiation.[300] The effect of radiation at the surface of the spent fuel is expected to produce oxidising species (mainly hydrogen peroxide, H_2O_2) through the radiolysis of water (radiolysis is the dissolution of molecules by ionizing radiation). These oxidising chemicals can increase corrosion of the containers and the spent fuel inside. Spent nuclear fuel contains extensive fracturing, which could act as pathways for corrosion processes to attack and dissolve the waste.[301] However, the hydrogen produced, as well as the presence of iron inserts, is expected to inhibit oxidation of the spent fuel inside the canisters, stabilising the less-soluble reduced forms of the chemicals inside. Computer modelling suggests that the presence of hydrogen suppresses corrosion of spent fuel, even in the presence of fractures. However, numerous simplifications and assumptions are made, and the model cannot be fully validated even over the short timescales observed in small-scale experiments. This process has also been observed in experiments using spent MOX fuels. [302] However, because MOX fuel has an uneven (heterogenous) structure at small scales, local corrosion pits can occur in the zones with the lowest plutonium contents.

4.2.5. Summary of corrosion issues

The mechanisms for corrosion are still not fully understood. There are particular concerns about how complex chemical interactions between repository components (e.g., cement and clay) under the extreme repository conditions (intense heat and radiation) might enhance corrosion, and how corrosion may occur more rapidly at interfaces between repository materials. This could result in both copper canisters and steel overpacks corroding more quickly than expected, allowing faster than predicted release of radionuclides into groundwater. A key issue is whether copper canisters corrode in water in the absence of oxygen. If so, their design life has been significantly overestimated. The intense radiation in the repository is also likely significantly to increase the corrosion rate of steel. Corrosion of metals will generate large quantities of gas which may be radioactive and can have other adverse effects in the repository (discussed below in Section *4.3.3. Effects of gas on the clay barrier and surrounding rock*, Section *4.4.4. Release of radioactive gas*, and Section *4.5.3. Gas flow*).

4.3. Damage to bentonite and clay rocks

The sealing system in a repository is intended to delay the release of radionuclides after they have escaped from the copper or steel containers and also to protect the containers from physical disturbance and corrosion. It may consist of clay backfill around containers, borehole seals, backfill in access and main drifts and other (e.g. tunnel) structures, drift seals, and the lower part of the shaft sealing system.[303] The main sealing material of interest is clay, or clay and sand mixtures, and/or the clay rock itself (if the repository is located in clay rock). In addition, cement or cement-based materials (concrete) are also used extensively in repository designs, e.g., for tunnel supports and/or plugs.

In a hard rock repository, and most clay rock repository designs, bentonite (a very soft, plastic clay) surrounding the canisters or overpacks is expected to provide physical support. Thus, it is sometimes referred to as a bentonite ‘buffer’. The bentonite also influences the chemistry of the repository, potentially slowing the movement of some radionuclides – particularly the highly radiotoxic actinides (see Box 5 and Section *4.4. Solubility, sorption and transport of radionuclides*). Some clay rock repository designs (e.g., Switzerland) assume the waste packages will be surrounded by bentonite, whereas others (e.g., France) do not.[304,305] In France, a mix of crushed excavated clay rock itself, mixed with bentonite, may be used as backfill, and steel packages are expected to be placed inside a concrete pipe.[306,307] The mixture of crushed clay rock is expected to perform less well as a barrier than pure bentonite.[308] Similarly, mixing sand with bentonite results in a higher permeability than using bentonite alone.[309] Thus, some repository designs (e.g., in Sweden) intend to use pure bentonite (in the form of blocks and/or pellets) as the backfill.[310] In clay rock repositories, the surrounding rock could be affected by heat and other processes in a similar way to the effects on bentonite, e.g. cracking due to heat.[311]

The bentonite backfill around waste canisters must be designed very carefully with sufficient dry density to ensure a high enough swelling pressure to keep the canisters in position, and to limit microbial activity and transport of radionuclides in contaminated groundwater, but sufficiently low dry density to mitigate the impact of rock shear on the canister.[312] In modelling exercises, in which experimental data was used as test examples, there have been difficulties in predicting the swelling of the clay, with a strong divergence in results from computer models and some doubts about repository performance.[313] The microstructure of the bentonite is important with different pore sizes (micro-pores and macro-pores) playing different roles.[314] In addition, recent experiments have found that the swelling pressure may be significantly reduced in the presence of salty (high salinity) waters.[315] This is important because many groundwaters at repository sites are saline.

A number of physical and chemical processes could affect bentonite or clay rocks in ways which could compromise safety. These include the effects of the significant amounts of heat which will be emitted from spent nuclear fuel or high-level waste. The addition of sand to the bentonite can improve some properties (such as its strength), but it will still be affected by temperature.[316] Alkaline cement water in the repository, due to the presence of concrete or cement structures or packaging, can also damage clay.[317] The effects of heating and saturation with groundwater on the bentonite are complicated by corrosion at the interface between the compacted bentonite and steel canisters.[318] Freezing can also damage bentonite, but this is only relevant for repositories in areas where severe permafrost is expected in the future.[319]

Once the repository is sealed, moisture will be trapped and the excavated cavity will become re-saturated with groundwater, causing the bentonite backfill to swell.[320] The temperature will build up to a peak, which will be reached after some decades near the canister but may take hundreds of years in the surrounding rock. Heat-induced flow or convection and coupled thermal-mechanical processes will last much longer than the temperature pulse and could peak at about 10 000 years. To predict the consequences for the potential release of radioactive materials from the repository, complex interactions need to be included in computer models, such as the effects of the wetting and swelling of the bentonite and/or clay rocks on water, gas and thermal flows and the effect of the changing thermal gradient on the transport of water vapour in the bentonite and surrounding rock.[321] However, even in the absence of heat, such models cannot yet reproduce all the behaviours of clays observed in short-term experiments, such as shrinkage and shear strength at lower water contents.[322] Further, the stress history of the clay may play a role in its response to heating.[323] Developing understanding of coupled thermal, hydraulic, mechanical, chemical and biological (THMCB) processes (which can all affect each other) – and modelling and predicting these changing conditions - is recognised as the most important yet challenging topic for future studies in the area of deep disposal of radioactive wastes.[324,325] Yet, to date, most modelling is only of temperature, hydrology and mechanics (THM), and, even when limited to these physical processes, there are difficulties in reproducing existing experiments and extrapolating the results to the long timescales involved.

Most of the physical and chemical reactivity in a deep geological repository is concentrated at the interfaces of different materials (vitrified waste, steel/iron, bentonite, cement/concrete, and the granite or clay host rock). [326] To date, few studies have considered all the interactions between all the different materials in the repository, such as the impact of dissolution of the glass containing high-level waste (HLW) on steel and bentonite.[327] As a result, there remain many limitations and uncertainties in computer models.

4.3.1. Effects of heat and mineral changes on bentonite and surrounding rock

The intense heat from the high-level waste or spent nuclear fuel in the repository will heat up the backfill and the surrounding rock of the repository tunnels over a period of several decades as they are successively filled with the waste.[328] Temperatures will continue to be high for thousands of years and elevated for a timeframe of up to 100 000 years before returning to the background temperature of the host rock (see Section *4.1 Changing repository conditions*). The repository temperature depends primarily on the type of spent nuclear fuel (or high-level waste) and the spacing between containers (see Section *5.3. Costs*). A mixture of bentonite and graphite has also been investigated in South Korea as a possible way to improve heat conduction away from the canisters.[329]

The temperature rise produces water evaporation in the inner part of the barrier that results in a drying of the bentonite.[330] Vapour migrates towards the outer regions of the barrier where it condenses due to the lower temperature prevailing there. Because the bentonite is unsaturated and, therefore, under suction, water flows from the host rock to the barrier. Consequently, the barrier hydrates, starting in the outer zones close to the host rock and progressively moving inwards. Because of the low permeability of bentonite and host rock, hydration proceeds quite slowly but it is expected that the bentonite backfill material (which is placed in the repository in blocks) will become fully saturated in the long term. The bentonite deforms due to changes in temperature, suction and stresses and the development of the bentonite swelling stress as hydration progresses. However, here is considerable uncertainty in the timing of these processes (see Section *4.1 Changing repository conditions*). Some computer modelling of a rock laboratory experiment in Japan, involving heating bentonite, has been undertaken, but, to date, there is not enough measurement data to verify the numerical analysis and the simulation results performed by research teams vary and do not always reproduce the laboratory test results.[331] The full-scale heater emplacement experiment in Switzerland has also been modelled, taking into account the thermo-hydro-mechanical (THM) coupled behaviour of the bentonite and host rock (Opalinus clay).[332] Since thermal conductivity depends on saturation, the temperature in the bentonite also changes according to the degree of saturation. The thermal conductivity greatly affected the temperature change in the host rock, and the pressure change varied depending on the distance from the tunnel. At locations close to the tunnel, pressure drop occurred due to groundwater inflow caused by suction from the capillarity of the unsaturated bentonite. The authors conclude that the capillarity of unsaturated bentonite could inherently affect the THM behaviour within the disposal system. Capillarity (also known as 'capillary action') is the process of a liquid flowing in a narrow space without the assistance of external forces (e.g., water sucked up by a paint brush or blotting paper).

The different components in a repository all have different expansion coefficients and the way they move and compress may lead to a significant change in the hydraulic properties of the interfaces between them. There is a risk of mechanical damage because the pore water in the clay expands faster than the clay rock or bentonite when heated. Heating could cause significant pore pressure changes, particularly in clay, affecting the stress distribution, which could in turn damage the structure of the clay rock or bentonite backfill so that water flows through it more easily. Heating places high stresses on rock, which can damage it. Shear along a fracture in clay rock can increase water flow significantly (potentially speeding up the escape of water contaminated with radioactive substances) and pre-existing shear bands can be re-activated (see also Section *4.8. Faults, seismicity and earthquakes*).[333] Creep (slow movement which deforms the clay) can also increase with heating, with the clay becoming more ductile and viscous.[334] Furthermore, the heat could induce convective flow of groundwater in the surrounding rock, along with significant vaporisation of groundwater, which may be ventilated in the pre-closure stage. [335] This phenomenon complicates the prediction of how conditions in the repository will change with time, since the effects of water vapour as well as liquid water need to be considered.[336]

The variation in temperature hampers the function of bentonite over a long time-span.[337] For example, plasticity, swelling and moisture content all reduce with temperature, whilst hydraulic conductivity increases. In addition, the clay mineral content is affected by heat, with the formation of less-swelling or non-swelling minerals at higher temperatures, possibly degrading the important swelling and protective function of the bentonite backfill surrounding the canisters. The thermal history of the bentonite includes the heating due to the presence of the radioactive wastes and also a thermal gradient due to the lower temperature of the surrounding rock (which also varies with depth).

Heat can also have significant effects on the surrounding rock. In the Opalinus clay in Switzerland, a 2008 study found that the possibility of temperature-induced deformation of clay rocks due to the emplacement of high-level wastes cannot be neglected.[338] At the surface, an uplift of 10 cm to 1 m was predicted in this study. This is expected to occur smoothly and over a wide area, so is not considered likely to cause major damage to surface structures. However, below the surface significant damage could occur to tunnels and to tunnel linings, unless they are sufficiently strong or flexible. In a generic assessment of clay rock in Germany, uplift at the surface due to heat is expected to be in the range of 20 cm.[339] In granite, one study has estimated a maximum uplift of 17 cm after 2 000 years.[340] In this study, stresses are expected to be high enough to fracture the wall of the vault. A 2024 study analyses ground uplift around high-level radioactive waste (HLW) repositories using coupled thermo-hydro-mechanical (THM) numerical models, finding ground uplifts of 10 to 20 cm (depending on repository design and temperature) after 1 600 years.[341] In this study, a ground uplift of several centimetres is retained even after 10 000 years. Heat can also reactivate faults in clay or hard rocks, this is discussed separately in Section *4.8. Faults, seismicity and earthquakes*.

Impacts of heat on granite are discussed further in Section *4.5.1. Groundwater flow in the bedrock and fractures*, but, due to the similarities with bentonite clay, impacts of heat on clay rocks are discussed in this section. Several experiments have been conducted in rock laboratories to seek to understand the impacts of heating on repositories in clay rock.[342] These experiments have typically been conducted on the scale of a single cell of high-level waste (HLW) and in some cases have lasted several years. Although experimental knowledge can contribute to understanding, in some clay rock samples stress failures have occurred during heating and it is unclear how such failures could be ruled out in a future repository. In addition, following heating, the low permeability of clays may be only partially restored. Computer modelling is used to seek to reproduce the experimental results and subsequently to scale them up to the size of a full repository operating over time frames of hundreds of thousands of years. This requires so-called 'coupled' computer models which take account of the complex interactions between the heating, water flow, and mechanical and chemical properties of the clay rocks.[343] In attempts to model the liquid pressure in Opalinus clay during the heating phase (an experiment in the Swiss Underground Rock Laboratory), it was found that combining a shotcrete layer (sprayed concrete) with a simplified excavation damaged zone (EDZ), a ventilation phase, and a non-homogeneous (i.e., spatially varying) initial liquid pressure field (to account for excavation-induced effects) led to a substantial liquid pressure reduction in the clay during heating compared to models without these features.[344] However, differences between the models and the measurements remained, due to the substantial simplifications made. The authors conclude that better modelling of the EDZ is needed (see Section *4.5.2. Excavation damage*), as well as of the swelling of the bentonite. Comparisons with other computer models were also undertaken, which conclude that the EDZ and the shotcrete potentially influence the behaviour of the rock, causing higher differences between the models closer to the heater used in the experiment.[345] A close fit between models and data could only be obtained by using parameters outside the expected range for intact Opalinus clay. In clay rock, fracturing is a combination of shear and tensile failure. This localized fracturing highlights the complex interactions between mechanical and hydraulic processes during the heating phases, which has yet to be fully reproduced by computer models.[346]

There are significant uncertainties due to the relatively small scale and time duration of experiments on heated clays, the simplifications and assumptions needed to set up the experiments and the models, and the large variability in experimental findings.[347,348] For example, experiments on creep lasted up to 3 years, which is very short compared to the time-scales relevant to a nuclear waste repository. Also, many experimental results using clay depend strongly on the saturation of the samples, which is highly uncertain whilst the clay is being heated in the real-world situation of a full-scale repository. In addition, decisions made in relation to experimental galleries include how much water to inject before heating begins, and the timescale of heating (up to 10 years) is extremely short compared to that in a repository. Finally, computer models typically fail to include the area of excavation damage[349] or the viscous behaviour of clays, and some are still 'isotropic' (i.e. assume the response is the same in all directions, which is not correct for marine-deposited clay rocks). The conclusion of this work is that more advanced models are needed to take into account the processes occurring around the tunnels, including the modelling of hydraulic properties within the excavation damaged zone (EDZ) and creep.[350]

Multiple computer modelling teams have compared their capability to analyse and reproduce fracture initiation due to heating of clay rock (the COx clay formation in

France) based on a thermal hydrofracturing experiment in France's underground rock laboratory.[351] These models attempt to reproduce the nonlinear behaviour of the clay rock in response to stress due to heat, including: plastic strains prior to the peak strength; significant softening after peak; residual behaviour (due to previous stresses); non-associated flow rule (due to plastic strain); anisotropy (directional variation) in stiffness and strength; time-dependent creep deformations; damage and creep coupling and permeability increase due to damage. The models were reasonably successful in terms of time of occurrence and location but attempts to reproduce fracture aperture or fracture propagation were less accurate and remain areas for future research. Some problems arose due to limitations in the experiment (including difficulties isolating the measuring chamber).

Self-healing of clay rocks or bentonite backfill is important to seal fractures and gaps around the waste containers (although it should be noted that, even at room temperature, the fractured claystone is not restored to its permeability before fracturing, but permeability remains significantly higher, by two orders of magnitude[352]). Three different clay rock formations are being considered for repositories in Europe (Boom clay in Belgium, Callovo-Oxfordian clay, known as COx, in France and Opalinus clay in Switzerland) and each behaves somewhat differently.[353] The high calcium carbonate content of COx clay reduces the effectiveness of the self-healing processes in the clay rock, with limited self-healing when the clay content is low.[354] In this study, only one experiment was conducted above room temperature (at 80^{O}C), which delayed closure of cracks, and only one test examined the effect of gas flow (which also delayed the healing process). No experiments studied the combined effects of high heat and gas that might be expected in a repository. In Opalinus clay, the effectiveness of self-sealing processes also reduced at elevated temperatures, in some experiments becoming almost negligible at 90^{o}C.[355] Even at room temperature, it is important to realise that the rock does not fully recover its original properties. The memory of the fracture is still present and can be re-activated by hydromechanical processes.[356]

Recent work has highlighted the importance of including 'anisotropic' responses, i.e., different behaviours in different directions, due to the structure of clay rocks, which were deposited in layers in ancient marine environments (tens of millions of years ago).[357,358] For example, modelling of heat effects predicted movement of the tunnel wall – which did not remain in the position after excavation - and higher pressures in the pore water inside the clay rock when directional (anisotropic) effects were included, compared to when they were not.[359] In contrast, heating was predicted to cause less movement further away from the disposal tunnel than in the isotropic case. This research also found significant differences between the effects of heating under drained and undrained conditions. The authors suggest that draining of water from the tunnel might occur if the supporting structure had a perforated casing, for example. The computer model predicted that heating would cause much higher pore pressures under undrained conditions, with greater potential for damage to the rock. Clays are also composed of many different particle sizes and together with the effects of anisotropy, this further complicates calculations of how they will be affected by the heat and may increase stresses in heated clay rocks.[360] In a benchmarking exercise involving seven computer modelling teams from across Europe, results from different computer models showed greater discrepancies in the anisotropic case, likely reflecting the greater complexity involved.[361] In contrast to short-term behaviour, few conclusive results are available on the effect of temperature on the long-term behaviour of clay rocks. Further experimental studies are planned but these will last months, which remains very short compared to repository timescales.[362] Mechanisms are complex and non-linear and can include creep and thermal hardening.[363] In addition, the combined effects of gas and heat in the repository need further investigation.[364]

The repository is a complex geochemical system, which is also affected by the heat.[365] Once containers have corroded, the movement of radionuclides out of the waste packages depends on their own chemistry and also the background chemistry of the repository. Radionuclides may stick to granite or clays (sorption), or be transported through the rock as gas or carried in the groundwater, in ways which are influenced by temperature. There are major difficulties in studying the sorption of relevant radionuclides in repository conditions. [366] Assessing the chemical evolution of the repository is challenging because interactions at very small scales may influence the system at much larger scales.[367] These issues are discussed further in Section *4.4. Solubility, sorption and transport of radionuclides*.

The heat in a repository could have a significant impact on the mineral content of clays, changing its properties. The bentonite clay intended to be used as backfill in repositories consists mainly of montmorillonite, which is a member of the smectite group of minerals. However, depending on its source, it can also contain varying amounts of other minerals. For example, bentonite sourced from Wyoming (USA) is dominated by mainly sodium montmorillonite clay (80% by weight), but also contains quartz (3%), tridymite (4%), feldspars (4%), muscovite (3%) and small amounts of several other minerals and organic carbon.[368] Montmorillonite is a member of the smectite group of minerals. Smectite is considered to be a good backfill material because it swells in contact with water – slowing groundwater flow and also holding the waste canisters firmly in place – and because it can retain radionuclides by sorption (a process in which they become incorporated in, or stick to, the clay particles). Bentonite is familiar to some for its use in cat litter, which absorbs urine and odours.

The swelling bentonite is expected to exert a swelling pressure on the canisters, generating considerable stresses, which are intended to hold the nuclear waste containers in place in the repository and to limit the flow of groundwater to and from the canister surface.[369,370] However, when smectite clay is exposed to high temperatures and the geochemical conditions of a repository for a long time, it could be transformed into other minerals with different physical and chemical properties.

Smectite is converted to illite – a mineral with clay-sized particles, but which does not expand – in a reaction which becomes faster as the temperature increases. The smectite transforms into randomly interstratified illite–smectite layers, and eventually into illite, in a process known as illitization.[371,372, 373] This process results in bentonite losing its swelling properties. A geological site where bentonites occur naturally at Kinnekulle in Sweden suggests that a reduction of 50–75% in the proportion of montmorillonite (the smectite found in bentonite) may have taken place over about 1 000 years, at temperatures estimated to have reached a maximum of 150°C.[374] The repository temperature limit of 100˚C is intended to limit this process.[375] However, although the reaction is faster with heat, illitization has occurred in some experiments even at room temperature, contradicting earlier experiments suggesting it does not occur below 100˚C.[376,377] Studies have shown that within 1 000 years, the illitization of bentonite can lead to 1% to 8% loss in smectite volume fraction at 100˚C. However, the rate of conversion of montmorillonite to illite under repository conditions is in fact not yet known, including the effects of temperature, time, and potassium ion (K^+) content (which speeds up the reaction) on the rate of illitization. Laboratory experiments may not be reliable because the conditions deviate significantly from repository conditions. Most researchers have assumed that the source of potassium (K+) ions is feldspar within the bentonite, but it may also come from groundwater or cement water. The presence of alkaline cement (which may also include K+ ions) can speed up illitization and may have a catastrophic effect on the swelling capacity of bentonite (see Section *4.3.2. Effects on clay of chemical disturbance due to corrosion*).

The rate of illitization can also increase significantly with salinity, which is important because many deep groundwaters are saline. [378,379]

In addition, microbes can also de-stabilise smectite and convert it to illite (see Section *4.3.4. Effects of microbes on bentonite and concrete*).

Other mineral changes may also have effects that are not fully understood.[380] For example, the presence of other minerals (such as calcite and feldspar) in clay rocks can also trigger heat damage at the interface between these minerals and the clay.[381]

4.3.2. Effects on clay of chemical disturbance due to corrosion

Bentonite is expected to create stable pH conditions in the repository backfill.[382] However, chemical disturbance due to corrosion could change the backfill properties. This could affect both the swelling properties (by speeding up illitization) and its capacity to retain some radionuclides through sorption. Although capture (sorption) of strontium-90 by bentonite does not appear to be adversely affected by increased temperatures (up to 150°C), it is strongly influenced by pH, decreasing from about 90% at pH 13 (i.e., highly alkaline) to about 40% at pH 8.[383] However, highly alkaline cement water could also damage bentonite, as discussed further below, likely due to the presence of potassium (K^+) ions.

In the French repository concept, steel overpacks rather than copper canisters are expected to be used. Chemical interactions may occur between the bentonite and the steel containers.[384] The interactions between the corrosion products of steel, the surrounding groundwater and the bentonite are expected to create a chemical disturbance inside the engineered barrier system. Early modelling of the system over 100 years predicts that the porosity of the bentonite will increase, due to changes in its mineralogy, and that both the Eh (oxidation-reduction potential) and the pH (acidity or alkalinity) will change significantly. However, the model suggests that there will be a feedback effect, involving the clogging of pores in the clay near each steel overpack, which will slow the initial high corrosion rate and its influence on the mineralogy.[385] Many more recent studies have investigated how carbon steel corrosion may impair bentonite properties, with many different corrosion products expected to be formed, which will perhaps create protective layers which may slow further corrosion.[386] Thermo-hydro-chemical-mechanical (THCM) models have been used to seek to model corrosion processes occurring in small-scale laboratory tests, however there are many uncertainties and some corrosion products have not yet been accounted for. [387] Failing to account for mechanical processes, such as the swelling of bentonite, may lead to large errors in water content and concentrations and dissolved and precipitated species.

Chinese researchers note that the buffer performance of bentonite on the steel container surface will continuously deteriorate due to the effect of groundwater and iron corrosion products, which can further influence the corrosion behaviour of low carbon steel.[388] Based on experiments in the Beishan underground rock laboratory, they conclude that low carbon steel is unsuitable for use in a repository and state that, with the continuous migration of iron corrosion products and radiolysis products, the buffer performance of bentonite will further deteriorate until the entire multi-barrier system fails.

Iron frames for spent fuel (which are to be contained inside the copper canisters in the Swedish design) will also create a chemical disturbance in the same way.[389] Experiments suggest that high concentrations of iron ions can be reached in bentonite without any mineralogical transformations but that cation exchange capacity (CEC) and swelling pressure may be reduced and hydraulic conductivity increased, meaning faster escape of radionuclides.[390]

Large quantities of cement are also expected to be used in all repository designs, for construction and sealing, and may also be used inside barrels of intermediate level waste (ILW) where this is included in the repository.[391] Cement is alkaline, which is intended to delay steel corrosion, but which may also have negative effects on the properties of bentonite, for example reducing its swelling pressure and cation exchange capacity (CEC).[392, 393] A number of minerals are expected to form as a result of cement-bentonite interactions and computer models of this process have been developed.[394,395, 396] The creation of highly alkaline fluids is expected to degrade the clay rock at the interface with the barriers in the French repository concept, and concrete engineered barriers may also be susceptible to attack by groundwater containing dissolved sulphates.[397] Prolonged interaction between bentonite and alkaline fluids from neighbouring concrete structures can impair the swelling capacity due to significant changes in the chemical composition of the clay.[398] Experiments show that cementitious water (which is alkaline) causes a decrease in the swelling capacity of the bentonite. Computer modelling suggests that this is driven mainly by an increase in potassium fraction in the inter-layer water and by the dissolution of montmorillonite (the fraction of the bentonite responsible for its swelling properties). Thus, the presence of materials containing cement near the bentonite presents a threat to its long-term stability. The presence of highly alkaline cement results in the destabilization of primary minerals in clay rocks, leading to alteration at the interface between cement/concrete and repository host rock.[399] The cement will increase in porosity in some zones and both the physical (swelling) and chemical (sorption) properties of the clay could change. Changes in porosity may have a profound effect on the entire concrete-clay/rock evolution as it helps define the potential future transport pathways for radionuclides to leak from the repository and in some cases, the interaction of cement pore fluids with clay rock may enhance radionuclide mobility. There is particular uncertainty about what happens at temperatures above 25°C.

In China, the potential effects of cement water on bentonite have been studied.[400] These researchers argue that so-called ‘young cement water’ (YCW) will be present in a repository for the first 10 000 years. This water is highly alkaline (pH 13) and contains potassium (K^+) ions (in the form of Na-K-OH). This will be followed by a period of 10 000 to 200 000 years in which the repository contains so-called ‘evolved cement water’ (ECW), with a pH of 12 to 12.5, containing calcium cations (Ca^2+), before the pH gradually reduces to that of the original groundwater. Conducting experiments with these 3 different types of water, they found that dissolution of montmorillonite (the main constituent of bentonite) occurs in the samples that have been infiltrated with YCW, affecting the swelling property of bentonite significantly, mainly due to the potassium (K^+) ions in it. They conclude that "*buffering material under such chemical conditions is not conducive to the safety of HLW disposal*". Nevertheless, large quantities of cement are still expected to be used in most repository designs.

Since conventional concrete, which is highly alkaline (i.e., has high pH value of 12.5-13), can decrease bentonite swelling properties, resulting in a malfunction of the whole backfill system, low pH concrete (LPC) has been developed as a possible alternative.[401] However, LPC may increase microbial activity and diversity, potentially compromising the long-term safety of the repository system by increasing the risk of corrosion, degradation, and gas production. In the absence of oxygen after repository closure, some anaerobic microorganisms promote calcium carbonate ($CaCO_3$) precipitation, thereby enhancing self-healing. The potential for acid production remains a concern as it could destabilize the concrete matrix over time.

Other research programmes in crystalline rocks (e.g. in Sweden and Finland) have concluded that cement grout can affect the local geochemical conditions, that will affect the function of bentonite and then potentially cause adverse effects on long-term safety.[402] As a consequence, silica sol is now proposed as an alternative grout in Finland, and other options (such as low-pH cement grouts or other non-cement-based grouts) are being developed and tested.

Other research projects have studied the potential harm caused to cement by the presence of the clay. The project "Assessment of Chemical Evolution of ILW and HLW Disposal Cells" (ACED), part of the EU research programme EURAD, involves attempts to model the chemical evolution at the disposal cell scale. A 2022 review of ACED concludes that the necessary modelling of concrete structures is still pending.[403] In some computer simulations, with a thin young cement (5 cm), complete dissolution of the portlandite mineral in the cement occurred following increased temperatures. The study identified the driving force as the chemical destabilisation of the concrete by the clay. Expected gas generation from canisters containing ILW has yet to be incorporated in these experiments (see Section *4.2.2. Corrosion of intermediate-level waste packaging*). Another research project, 'Chemo-mechanical evolution of concrete barriers' (MAGIC), had not reported results at the time of the review.

4.3.3. Effects of gas on the clay barrier and surrounding rock

Corrosion of steel in the repository (see Section *4.2.4. Steel corrosion and hydrogen gas generation*) leads to the generation of hydrogen gas in the backfilled tunnels. This gas could seriously affect repository safety if pressure build-up were to force fast routes through the bentonite or host rock or explosively damage their structure. Some of this gas will be radioactive. Fractures opened due to high gas pressure might also create a fast route for the release of radioactive groundwater.

Hydrogen is one of the main gases released from the corrosion of steel in the repository in the absence of oxygen, in reactions that can occur with or without the presence of bacteria (see Section *4.2. Corrosion of canisters, wastes, and repository structures*).[404] When it is released, hydrogen could carry radioactive carbon-14 into the atmosphere in the form of methane (CH_4).[405] Some long-lived intermediate level wastes (ILW) are intended to be co-disposed with high level waste (HLW) or spent nuclear fuel (SNF) in underground repositories (usually in a separate section). ILW can contain organic material which may give off gases (as happens in landfill sites).[406] For example, ILW containing cellulose can generate hydrogen, carbon monoxide, carbon dioxide and methane gases.[407] Radioactive carbon (C-14) from the wastes could be incorporated into these gases and thus be released in gaseous form from the repository. In addition, gases may be released due to the effect of heat on clay rocks. Boom clay contains more organic matter than other clay rocks, which may degrade when heated, releasing carbon dioxide gas (CO_2) and making the groundwater more acidic (reducing the pH).[408] In a study performed in the Opalinus clay in Switzerland, carbon dioxide and hydrogen sulphide were the most prominent gases released.[409]

Researchers in France have concluded that hydrogen gas generation due to steel corrosion may be insufficient to damage the surrounding clay rocks, with fractures in clay rocks recovering sufficiently to allow gas escape but hinder water transport, without compromising the rock integrity.[410,411] However, there are many uncertainties (including the corrosion rate, see Section *4.2.4. Steel corrosion and hydrogen gas generation*). Thus, a key issue of concern still being investigated by researchers is whether gases can move through bentonite and clay rocks without creating over-pressure and rock damage.[412,413] Gas breakthrough in bentonite can take place in either a sudden or a gradual way.[414] Results from these experiments suggest that in saturated bentonite, gas pressures higher than the swelling pressure of the bentonite would have to build up before gas can move away. As well as impacting the bentonite used in most repository designs, researchers recognise that this is a key issue for a repository in clay rocks because their low permeability can also lead to the build-up of gases formed by the corrosion of containers or degradation of wastes.[415,416] According to one study, as the gas permeates the clay it results in a significant increase in the clay permeability (by two orders of magnitude), that can profoundly impact the migration of radionuclides within the clay.[417] Long-term deformation of the bentonite by gas has also been observed and models require a lot of calibration to reproduce experimental results.[418]

Although experiments in rock laboratories can help improve the understanding of gas transport, there remain fundamental challenges in scaling up results from small-scale tests to the size of a repository, and it is often difficult to reproduce experiments.[419] Uncertainties and/or variations in structure (heterogeneities) can cause a wide range of responses for the same experimental conditions.[420,421] The self-sealing capacity of clay rocks is higher in those with higher clay content.[422] However, clay content can also be affected by heat, radiation and chemical processes occurring in the repository, e.g., due to the presence of cement (see Section *4.3. Damage to bentonite and clay rocks*).

The problem of gas also raises a fundamental contradiction in the safety case. If gas release does not occur through fractures, the pressure build up could lead to significant rock damage. However, gases may also be radioactive (e.g., containing carbon-14 or tritium – radioactive hydrogen) and thus their release may present a radiological hazard.[423]

Four principal mechanisms have been identified by which gases can move through clay barriers:[424,425]

- two-phase (water plus gas) advective flow (i.e., bulk motion through the rock), under the influence of a combination of capillarity (the pull through the clay pores

due to the attraction of molecules to the clay) and hydraulic gradient (difference in pressure)
- diffusion of gas through intervening fluid to neighbouring voids in the clay with lower gas concentration
- deformation of the clay, creating larger pores to accommodate gas flow
- fissuring and fracturing caused by gas breakthrough if the gas pressure becomes too high (i.e., if it does not dissipate fast enough through the other mechanisms).

Gas will accumulate until it builds up enough pressure to be able to escape and migrate away from the waste package, either by dissolving in the groundwater, moving together with water through the pores in the rock (known as 'two-phase flow'), pushing through existing fractures, or creating new ones. Due to the complexity of all these processes, the predictive value of gas transport models is still limited, and the basic mechanisms of gas transport in bentonite are still not well understood.[426,427]

Experimental results at room temperature confirm that gas release opens fissures in clay rock and causes large-aperture fissures to develop along the weaker bedding planes. The intrinsic permeability of the rock increases during the gas pressure dissipation stage.[428] These cracks do not completely heal and a second episode of gas release could re-open fissures, although more research is needed to confirm this.[429] Gas transport through clay rocks seems to be controlled not only by the hydraulic and mechanical properties of the intact rock (its permeability, porosity, strength, etc.) but also by the gas pressure and the paths for its release (e.g., through fissures and fractures which form preferential pathways for gas release).[430] Gas transport through clay rocks also appears to be controlled by the different pore size distributions within the clay, which may vary in different directions (anisotropy). Thus, gas transport parallel to the bedding plane might occur without damaging the rock, whilst gas transport perpendicular to the bedding plane will cause a mechanical response. In a computer modelling exercise, water displaced during the formation of a gas path varied between 5% and 10% by volume. [431] In a future repository, displaced water might contain radioactive substances, especially if canisters have leaked. When water re-enters, some gas may still remain in the pore spaces in the clay rock. Fracture roughness and closure mechanisms can also influence gas transport in clay rocks and fracture closing mechanisms (due to the swelling of the clay) may become ineffective as the pressure increases.[432] The combined effects of gas and heat in the repository need further investigation.[433]

Gas transport is likely to occur through the excavation damaged zone (EDZ) created when the shafts, tunnels and deposition holes of the repository are excavated (see Section *4.5.2. Excavation damage*). In clay rocks the network of cracks in the EDZ desaturates the rock and may cause it to lose its self-sealing properties. In a study of COx clay (the proposed host rock in France), gas flow delayed the fracture healing process – as did heat – but no experiments studied the combined effects of high heat and gas that might be expected in a repository.[434] Bentonite and clay rocks are also expected to be partially de-saturated (i.e., dried out) due to the high temperatures caused by heat generated by the radioactive wastes. Further work is needed to study gas transport in such de-saturated clays.[435]

The interactions of gases with water and the clay surface strongly influence the mobility of water, even in the clay pores.[436] If desaturation (drying out of the clay) is considered, different results may be obtained as a water film is absorbed on the outer surface of the clay particles during desaturation, and this water film may be the main transport pathway for dissolved radionuclides.[437] More work is needed to scale up these findings.

In the Swedish repository concept, it has been assumed to date that corrosion of copper in the absence of oxygen will not occur and that the design life of the copper canisters is 100 000 years. If these assumptions are correct, hydrogen generation will be limited until the iron inside the copper canisters is exposed much later in the lifetime of the repository. If, however, corrosion of copper by water can occur in the absence of oxygen (see Section *4.2.1. Corrosion of copper*) the hydrogen generated by this reaction might also have significant implications for the safety case.

Additional steel and/or cast iron may be introduced into a repository for other reasons, e.g., as structural support during excavation (necessary to keep structures open in the case of clay rocks[438,439]); or in the form of steel barrels containing long-lived intermediate-level wastes. Hydrogen generation from the corrosion of this steel also needs to be considered in the safety case.

4.3.4. Effects of microbes on bentonite and concrete

Potential effects of microbes on the backfill, in particular their alteration of the mineral composition of bentonite or their generation of gases, may have significant implications for a repository's safety case.[440] Microbes such as bacteria often play an important role in the production of minerals in a process known as biomineralisation.[441,442] In particular, microbes can de-stabilise smectite and convert it to illite (which also occurs with heat, as described in Section *4.3.1. Effects of heat and mineral changes on bentonite and surrounding rock*, or in the presence of cement, see Section *4.3.2. Effects on clay of chemical disturbance due to corrosion*).[443] The conversion of montmorillonite to illite in the bentonite backfill (or surrounding clay rock) may have significant impacts on a repository's safety case, as described above. Findings that micro-organisms can dissolve smectite at room temperature have been described as a major challenge in the context of deep geological disposal, since they suggest that this process may happen much faster than predicted, even in the absence of significant heat.[444] This can result from the presence of iron-reducing bacteria or from hydrogen sulphide produced by sulphur-reducing bacteria (SRB) that corrode metals as described in Section *4.2.3. Role of microbes in corrosion*. Further research is still required to characterise the microbial community in deep repositories and its potential effects on bentonite.

Microbes may also degrade concrete structures, reducing their strength and increasing leaching, and these adverse effects may be exacerbated by the intense heat in the repository.[445]

Microbes can both produce and consume gases in the bentonite backfill and microbial gas production could cause a build-up of gas in a repository (the effects of gas build-up are discussed further in Section *4.5.3. Gas flow*).[446,447,448,449] The generation gases could also enhance radionuclide solubility and transport (see Section *4.4.4. Release of radioactive gas*).[450] Microbial processes could in addition affect adsorption/precipitation of radionuclides, chemical conditions and the creation of colloids (see Section *4.4.2. Colloids and complexation*).

4.3.5. Summary of damage to bentonite and clay rocks

The effects of intense heat on the bentonite backfill and/or clay rocks of a repository could seriously damage the physical and chemical structure of clay (e.g. its swelling pressure) and/or its ability to trap some radionuclides. Chemical and physical disturbance due to corrosion, gas generation and the effects of microbes could also adversely affect the properties of the bentonite backfill or clay rocks. Build-up of gas pressure in a repository could damage the barriers and force fast routes for radionuclide escape. A particular concern is the impact of alkaline cement water, from the widespread use of concrete and cement in repository designs, which could result in a significant loss of the properties of bentonite (swelling capacity and ability to retain some radionuclides through sorption). Concrete/cement structures may also be damaged by the presence of the clay.

4.4. Solubility, sorption and transport of radionuclides

The transport of radionuclides from the nuclear wastes in the repository depends strongly on the chemical conditions. Chemical changes that occur in the repository over time are extremely complex. For example, they may include changes in pH due to the presence of cement water, or the creation of acidic conditions due to the release of carbon dioxide or other chemicals from reactions occurring within the wastes, backfill or rocks, see Section *4.3.2. Effects on clay of chemical disturbance due to corrosion*. Hydrogen produced by the corrosion of canisters and overpacks could act as a reducing agent (i.e. changing the redox potential, Eh).[451] In contrast, the effect of radiation at the surface of the spent fuel is expected to produce oxidising species (mainly hydrogen peroxide, H_2O_2) through the radiolysis of water (radiolysis is the dissolution of molecules by ionizing radiation).[452]

4.4.1. Geochemistry and backfill chemistry

One function of clay in the repository (bentonite backfill and/or clay rock) is to slow the release of radionuclides. The longer it takes for a given radionuclide to diffuse through the clay, the lower the rate of release of that radionuclide from the near-field engineered barrier system will be, due to radioactive decay.[453] Radionuclides released from the waste will precipitate when their concentrations in the pore water exceed their solubility in the water. This will limit the concentrations of many radionuclides and thus their release rates to the surrounding rock.

The speciation of radionuclides is the distribution of a radionuclide among different chemical species in a system. Species are defined by a wide variety of properties, such as charge, oxidation state, structure and degree of complexation (i.e., the extent to which it is connected to other chemicals).[454] The safety of a repository could be significantly affected by issues such as whether radionuclides exist as particles (which may be more easily trapped in the host rock or backfill), or colloids (which may be much more mobile, see Section *4.4.2. Colloids and complexation*).

Bentonite slows the release of positively charged (cationic) species, however this process is complex and not fully understood.[455] A similar process occurs in clay rocks, if this is the type of bedrock chosen for the repository.[456] Some studies suggest that even the more mobile species of plutonium may be contained within clay rocks.[457] However, the timescale of this experiment is again short (one month) compared to repository timescales. Anions (negatively charged species, such as chlorine-36, see Box 5) are not retarded by clay.[458] In countries that are not yet committed to a particular disposal concept, such as South Korea, some research has taken place with the aim of enhancing the anion removal capability of bentonite.[459]

Estimates of the transport of radionuclides from a repository require careful prediction of the chemical and physical interactions of the radioactive waste with the bentonite (or other backfill materials) and surrounding rock over extremely long periods of time. Many different complex mechanisms are involved under different temperatures and pressures. Preliminary safety assessments have assumed that the chemical retardation of radionuclides in clay can be calculated using a constant retardation factor, K_d. However, more sophisticated computer modelling of the interactions between the different chemical species and the bentonite suggest that using the K_d approach does not provide a good approximation of contaminant transport and can result in significant errors.[460] In particular, temperature has a great impact on the expected concentrations of contaminants in groundwater. Coupled thermo-hydro-mechanical-chemical (THMC) processes will occur, which require complex and difficult modelling.[461] Selection of suitable conditions is generally not straightforward because of the multitude and complexity of the reactions involved.[462] The chemical parameters used in reactive transport models are not known accurately and there can be multiple alternative conceptual models, none of which explain the data.[463] There are still significant shortcomings to geochemical modelling and its applicability to real-world repository conditions.

In Canada a computer model has been developed and used to explore the impact of the thermal gradient (due to heat from the radioactive wastes) and coupled thermal-hydro-mechanical (THM) on the migration of dissolved radionuclides (solutes) in clay rock, comparing with experiments in Switzerland and France (the latter experiment is ongoing, so final results were not available).[464] The temperature gradient plays a role in solute transport, causing the thermo-diffusion effect (or the Soret effect), where solute particles tend to move from warmer to colder zones. However, in this modelling exercise this effect (which depends on the temperature gradient) was found to be negligible in the larger-scale (rock laboratory) experiment. In both situations (small-scale laboratory and rock laboratory), the increase in solute diffusion coefficients with increasing temperatures significantly impact solute transport. Numerous trial-and-error simulations were required to find suitable values for the thermal conductivity coefficients (in both the intact rock and excavation damaged zone, EDZ) needed to achieve satisfactory agreement between the simulation and the actual measurements. The authors emphasise the necessity of incorporating the EDZ into the computer model (see also Section *4.5.2. Excavation damage*), and of including other processes not yet in the model.

Recent research has highlighted the importance of the presence of an electric double layer (EDL) – the formation of a diffuse layer bordering negatively charged clay particles – on radionuclide transport. The EDL leads to partial anion exclusion and a cation accumulation within these layers, which is crucial for accurately simulating the transport of charged species, including significant anionic activation and fission products like chlorine-36, iodine-129, technetium-99, and selenium-79.[465] The authors use a computer model to simulate the cement-clay interface as a 1 cm thick skin, to study the influence of the EDL developed in the Opalinus clay on radionuclide transport. During the first 450 days of the simulation the plume is primarily contained within the cement, while after 450 days the anisotropy of the Opalinus clay and the negative net charge of the clay matrix begins to impact the charged solute's transport. The findings reinforce conclusions drawn in earlier studies that electrostatic effects on radionuclide (especially anionic) transport in clay-rich rocks cannot be neglected.

Sorption of radionuclides in crystalline rocks is not as significant as in clay rocks, nevertheless some radionuclides are trapped when they diffuse into the rock. The large volume of accessible pores in fractured granitic rock may retard the migration of radionuclides through sorption onto the rock.[466] However, the effects depend on the radionuclide, with experiments in Sweden suggesting that some actinides are retarded in the rock, while others may pass through with hardly any retardation.[467] There are significant uncertainties in sorption coefficients and how radionuclides may be transported in reality (including as colloids, see Section *4.4.2. Colloids and complexation*).[468] Sorption coefficients for different radionuclides (a measure of the extent to which they are retained by the rock) are hard to scale up because a small piece of rock may not have the same properties as a large one (for example, it may not contain as many fractures, or may contain only small fractures).[469] Experiments in China show that under high flow rates, fractures became the preferential channels for rapid migration of strontium-90, cesium-137, uranium-238 and plutonium-238, reducing their interaction time with the granite matrix and impeding their diffusion into the granite matrix.[470]

4.4.2. Colloids and complexation

A colloidal system is a type of mixture in which one substance (the colloid) is dispersed evenly throughout another as microscopic particles. Milk is an example of a colloidal system, consisting of globules of fat dispersed in a water-based liquid. Colloid particles have diameters ranging from 1 nm to 1 µm and have a high surface area.[471] Many radionuclides easily attach to (sorb) onto colloids suspended in water and this can make them highly mobile and more easily transported through rock. Computer models that do not account for transport by colloids can therefore significantly underestimate the rate of transport of radionuclides in groundwater.[472]

Particle swarms contain millions of colloidal-sized particles in a drop. They are dilute suspensions of tiny (nano- to micro-scale) particles that exhibit coherent behaviour enabling a group of particles to travel 10 to 1 000 times faster under gravity than single particles.[473] Particle swarms have been observed to reconfigure their shapes to enable transport through narrow pore constrictions and tend to follow the dominant flow path. Understanding and predicting the fate of radionuclides in colloids requires additional analysis of fracture geometry and fracture-matrix interactions, beyond determining groundwater flow paths.[474]

A significant fraction of radionuclides is expected to be carried by groundwater in colloidal form. Colloids are a concern because they can be much more mobile than radionuclides dissolved in groundwater. However, it is also expected that some colloids will be trapped and retained inside the rock, if the diameter of the pore channels in the rock is smaller than the diameter of the colloidal particles. Laboratory experiments in Russia suggest that 99% of the colloidal form of actinides can be mechanically retained in the rock of the Nizhnekanskiy Massif.[475] However, the permeability of the rock at the repository site is estimated to be almost three orders of magnitude higher than measured in the laboratory, due to fractures in the rock.[476] Because many of the fractures are thought to be disconnected (i.e., not forming a connected network), retardation of radionuclide-retaining colloidal particles is still expected. However, this illustrates the complexities and uncertainties involved in using laboratory experiments and computer modelling to try to predict the spread of radionuclides from a repository in granite rock.

Migration on colloids is of particular concern in the case of actinides, such as plutonium, which can be transported large distances in groundwater on colloids, and as a result could potentially be washed out of the bentonite in a repository, rather than being retained there.[477, 478,479] There are still significant gaps in the understanding of the transport of actinides bound to minerals and colloids. In crystalline rocks, the uncertainty of applied models and estimated predictions of radionuclide transport at the field scale of a repository is increased significantly by colloid migration and colloid chemical interactions.[480]

Humic matter is decayed organic matter. Clay is an important source of humic colloids, which can have significant effects on radionuclide migration.[481,482] The bentonite backfill of a repository could generate colloids, which could adsorb radionuclides and transport them over long distances, or retain them by interaction with mineral surfaces or by agglomeration (the process of gathering together as a mass).[483,484,485] Bentonite colloids can diffuse within granite.[486]

Both solid particles and colloids could be detached from bentonite at the bentonite/granite interface in a repository and mobilised by the water flow. It has been shown that these colloids are very stable in low saline and alkaline waters, and could facilitate radionuclide transport in the fracture network of the excavation damaged zone (EDZ) in the granite around a repository.[487]

Naturally occurring rare earth elements can be used as chemical analogues for studying the behaviour of actinides. Preliminary studies at the Swedish Forsmark site suggest a strong association of rare earth elements with colloids in the groundwater in the overlying aquifer but limited mixing and no evidence of transport from the bedrock groundwaters to the aquifer.[488]

The presence of oxidants can enhance actinide transport significantly, due to the formation of complex species, which may increase solubility by orders of magnitude and potentially enhance mobility.[489]

In intermediate level wastes (ILW), cellulose present in the wastes can exacerbate the above difficulties by forming organic compounds, which may then form complexes with actinides.[490]

4.4.3. The role of microbes

Microorganisms (also known as microbes) can colonize fractures and alter the chemistry of the fluids flowing through them, leading to changes in mineral composition. These processes can have a significant impact on the long-term behaviour of the rock mass, including its stability and permeability. Therefore, the coupled processes that need to be understood and modelled when evaluating potential repository safety need to be extended to include microbial activity.[491] As well as corroding containers (leading to gas generation) and eroding bentonite (see Section *4.2.3. Role of microbes in corrosion* and Section *4.3.4. Effects of microbes on bentonite and concrete*), microbial activity can indirectly influence solubility, and hence the mobilization of radionuclides, by the alteration of the geochemical conditions within the repository.[492,493]

Many different kinds of microbes (including, but not limited to, bacteria) have been found in the crystalline bedrock intended to be used for deep geological disposal in Sweden and Finland.[494] For example, diverse fungal communities exist in the crystalline bedrock, but their possible effects are largely unexplored. Although studies have focused on bacteria, viruses are also present and appear to affect bacterial cell numbers and alter the structure of the microbial communities. Biogeochemistry involves the study of chemical, physical, geological, and biological processes and associated chemical reactions. Biogeochemical processes in the deep biosphere are in many cases connected to one another and include multiple different processes. Thus, as well as corrosion processes such as MIC (Section *4.2.3. Role of microbes in corrosion*) and illitization of clays (Section *4.3.4. Effects of microbes on bentonite and concrete*), many other microbial processes may or may not be relevant to the changing chemical conditions underground. For example, biological hydrogen production through fermentation may be common under anoxic conditions (i.e., after the oxygen in the repository has been used up) and fungi may be a considerable hydrogen producer.

Microbiological processes must be taken into account when modelling groundwater hydro-geochemistry. Such processes are expected to be involved in many reactions which would not occur in a lifeless underground environment. The presence of bacteria is important because microbes can affect the mobility of radionuclides in a number of ways.[495,496,497] For example, microbes can introduce complexities in uranium speciation and environmental mobility in a geological repository and microbial interactions with plutonium have also been reported.[498] In addition, microbial processes may have a significant impact upon the transport of radioactive iodine, potentially increasing the environmental mobility of iodine-129. Sorption of radionuclides to planktonic microbial cells may cause higher migration of the radionuclides, whereas sorption to biofilms (a thin layer of microbes on a surface) may immobilize the radionuclides.[499] Microbial reactions that reduce radionuclides (changing their chemistry) may make them less likely to be transported out of the repository, but gas-generating microbial processes may increase radionuclide mobility by producing gas bubbles. Biogeochemical computer models have been developed for low level nuclear waste repositories (e.g. shallow trenches), but the full complexity of biogeochemical processes in a deep geological repository has not been incorporated.[500] A deep geological repository involves complex, evolving physical and chemical conditions over an extremely long period of time, where the activities of microbes cannot be directly measured.

Packages of intermediate level waste (ILW), which are to be included in some repository designs, are more likely to be directly affected by microbial activity than spent fuel and vitrified high-level waste (HLW) because they contain organic materials that may be used in microbial processes, including bitumen (sometimes used to package ILW, especially in Belgium and France) and materials such as plastics and cellulose (particularly common in reprocessing wastes, e.g. from France and the UK).[501,502] The main concerns include the generation of gases (particularly methane) and the potential to increase the mobility of radionuclides.

4.4.4. Release of radioactive gas

The principal source of gas in repository designs that use steel waste containers is expected to be hydrogen produced by the corrosion of steel (see Section *4.2.4. Steel corrosion and hydrogen gas generation*). Higher burn-up fuel is expected to lead to increased gas release.[503] There are concerns relating to any damage to containment that might be caused by pressure build-up and to the potential role of the gas in pushing radioactively contaminated water upwards out of the repository (see Section *4.3.3. Effects of gas on the clay barrier and surrounding rock* and Section *4.5.3. Gas flow*). However, in addition, carbon dioxide and methane are likely to contain radioactive carbon-14 and may pose a radiological hazard in themselves as they leak from the repository. Carbon-14 has a high production rate in nuclear reactors and is released to the environment in discharges as well as through the disposal of radioactive waste.[504] It has a long half-life (5,730 years) and high mobility in the environment. Methane (CH^4) containing radioactive carbon-14 is one chemical form in which hydrogen from the corrosion of irradiated steel can be released. The largest portion of the carbon-14 inventory in irradiated steel (around 80%) is expected to be released as methane gas.[505] Thus, radioactive carbon-14 from the repository could enter the environment as gas, and ultimately reach humans and the human food chain. As one example, in the German generic safety case for a potential repository in clay rock, the release of carbon-14 in gas at the drift seal starts after about 1 000 years and decreases again after several tens of thousands of years, due to its decay.[506]

Repository designs require bentonite seals in certain places to limit water flow. However, several experiments have shown that gas breakthroughs can occur through seals, most likely at the interface between the bentonite seal and the rock, or in the excavation damaged zone (EDZ).[507] Gas flow through the interface between bentonite blocks may depend on the extent to which it is saturated.[508]

4.4.5 Criticality

Calculations show that the possibility of a nuclear chain reaction (nuclear fission) occurring in a deep underground repository (known as criticality) cannot be ruled out.[509] Nuclear waste disposal canisters are designed so that nuclear fission products cannot reach criticality whilst they remain in their original configuration in the canisters.[510] However, doubts remain about what might happen after the canisters are breached.

Even if contained, a nuclear chain reaction could create new fission products (i.e., new radionuclides) even outside the barrier system and perhaps nearer to the surface where they might more easily contaminate the biosphere. In a worst-case scenario, a nuclear explosion could occur, spreading large quantities of radioactivity into the environment. For criticality to occur, firstly, sufficient enriched uranium or plutonium must be placed in the repository to achieve a critical mass (sufficient to sustain a nuclear chain reaction). This is undoubtedly the case. Secondly, this material must be released from the nuclear waste containers and travel through the repository in such a way that this critical mass actually forms (i.e., the fissile plutonium or uranium is lumped together and a nuclear chain reaction can begin). In addition, criticality can only occur if a critical mass of fissile material is present with sufficient water (or another moderator).[511] A moderator is a material used in nuclear reactors to slow down fast neutrons, making them more likely to cause further fission reactions, i.e., to create a chain reaction.

Based on calculations using the expected inventory on spent nuclear fuel for disposal in Japan, assumed to be buried in a repository in granite, it is clear that sufficient fissile material (uranium and/or plutonium) will be buried in the repository to potentially form a critical mass.[512] The repository is also likely to be wet over a long period. Whether criticality will actually occur is much less certain, due to uncertainties about how released fissile materials will spread or lump together in the rock once the containers have been breached. This is a long-term process (taking perhaps hundreds of thousands or millions of years), however it is potentially a very serious hazard to future generations.

In Switzerland, it is a regulatory requirement to assess the risk of criticality over a period of a million years. Some preliminary calculations have been undertaken in relation to different scenarios for the erosion of a single fuel canister, however, no conclusions regarding the risk of criticality were drawn in this study.[513] It should be noted that the fissile content of a repository can increase over a period of millions of years.[514]

4.4.6. Summary of solubility, sorption and transport of radionuclides

Chemical changes that occur in the repository over time are extremely complex and could affect the ability of bentonite and/or host rocks to retain radionuclides. Poorly understood chemical effects, such as the formation of colloids and the role of microbes, could speed up the transport of some of the more radiotoxic elements such as plutonium. Radioactive gases (carbon dioxide and methane) will be released. The possibility of a nuclear chain reaction (criticality) occurring in a deep geological repository has not been ruled out.

4.5. Bedrock properties and hydrogeology

4.5.1. Groundwater flow in the bedrock and fractures

There is little doubt that different hydro-geological properties can have significant impacts on the safety case for a future repository.[515] Important hydro-geological criteria for a repository include:

- slow regional and local groundwater movement,
- long groundwater pathways before discharge,
- groundwater that progressively mixes with older deeper waters,
- separation of deeper groundwater systems (where the nuclear wastes will be placed) from near-surface ones (which may include aquifers for drinking water, or seas or lakes for fishing).

However, geology is complex and details of the geology and site characteristics at each repository site cannot be known completely due to practical limitations regarding what can be measured.[516]

When choosing a geological site there are two types of uncertainty. Uncertainty in natural barrier performance arises from:

- uncertainty about the occurrence of future events such as earthquakes, glacial events and human intrusion (see Section *4.6. Human intrusion and human error*; Section *4.7. Glaciation*; and Section *4.8. Faults, seismicity and earthquakes*) and;

- incomplete knowledge about the physical properties of a system such as the location or occurrence of a fault, or the permeability of rock formations.

Changing assumptions about permeabilities, for example, may change not only the time taken for radionuclides to be released, but also the pathway that they take (e.g., directly to the surface versus remaining longer within the rock formation).[517]

Crystalline rocks contain fractures and faults, which are of critical importance in determining the flow of radionuclides out of a repository, although diffusion through the rock is also an important process.[518] In contrast, for clay rocks, used in the French concept, a key assumption of the safety case is that transport would be by slow diffusion through the clay, rather than through cracks and fissures, which are assumed to be self-healing.[519] In both cases, some radionuclides are expected to be trapped by the rock in a process known as sorption (see Section *4.4. Solubility, sorption and transport of radionuclides*).

Three different clay rock formations are being considered for repositories in Europe (Boom Clay in Belgium, Callovo-Oxfordian clay – known as COx - in France and Opalinus clay in Switzerland) and each has different properties and behaves somewhat differently, e.g., in response to heat. [520] Boom clay is younger than the others with a higher hydraulic conductivity, lower heat conductivity and less stiffness. It is known as a poorly indurated (i.e., less hardened) clay. Opalinus clay has a more marked effect of the direction of the bedding plane on its properties (i.e., it is more anisotropic) than COx clay, whereas COx clay has a higher calcium carbonate content, which may limit its self-healing properties, particularly when heated.[521,522, 523] In the proposed repository area in France, the COx clay can be described approximately of consisting of 3 layers: at the bottom there is a so-called 'clay unit' with about 45-50% clays, 27% carbonate and 24% quartz: above is a so-called 'transition unit' with between 30 to 40% clay content (20 to 30% carbonate content), and above this is a so-called 'silto-carbonated unit' (the most carbonated one, with porosity of 15%).[524] Both Boom clay and Opalinus clay have lower stiffness in the direction perpendicular to the bedding layers, but Boom clay tends to fail through ductile behaviour (shear failure along bedding planes), whereas Opalinus clay is more brittle (with tensile failure along bedding planes and buckling).[525] Boom clay also contains more organic matter, which may degrade when heated, releasing carbon dioxide (CO_2) gas and making the groundwater more acidic (reducing the pH).[526] In clay rocks, flow paths for potentially contaminated groundwater or gas could be created by reactivation of faults through mechanical, hydraulic or thermal disturbance.[527] The possibility of increased permeability due to fault slip, generating new pathways for the escape of radioactive wastes, also remains a major risk.[528] Re-activation of faults is discussed in more detail in Section *4.8. Faults, seismicity and earthquakes*).

The effect of heat, chemical process and microbes on clay rock have been discussed in Section *4.3. Damage to bentonite and clay rocks*. Studies on clay rock were included in that section due to the similarities between clay rock and the bentonite clay used as a backfill in most repository designs. In the following discussion in this section, effects of heat on crystalline rock are included, which were not previously discussed. The presence of an excavation damaged zone (EDZ) must also be considered, see Section *4.5.2. Excavation damage*.

Groundwater flow through crystalline rock takes place mainly through fractures as the rock itself has very low permeability. However, flow through both fractures and porous rock needs to be considered in a safety assessment. This poses particular problems because of the very large degree of structural variation (known as heterogeneity) in the fracture systems, which means that the permeability of each piece of rock is different, and varies in different directions.[529] The hydraulic conductivity can vary by one or two orders of magnitude at different points, leading to very different thermo-hydro-mechanical (THM) properties at different points in space. Fractured rock systems are challenging to characterise and predict because they are inherently complex, rock is opaque (making it difficult to see inside) and fracture flow and transport properties are highly sensitive to coupled thermal, hydrologic, mechanical and chemical (THMC) processes.[530] The measurement and observation of the chemical behaviour of fractures and faults (relevant to corrosion processes and the transport of radionuclides once released) also remains very challenging at the field scale. A 2022 review finds that, "*despite significant progress, we lack a definitive prediction of flow and transport based on geometry and that a cohesive framework for interpreting fracture permeability measurements across different fractures in different rock types is lacking. These are significant obstacles to the development of a more predictive understanding of coupled processes*".[531] This review goes on to state that, "*A method of predicting (or even ballpark estimates) subsurface fracture permeability based on knowledge of rock type, fracture type, fracture history, and stress conditions remains elusive and maybe unachievable due to variability at multiple scales*". In the field of nuclear waste disposal, this review also highlights how thermal-hydro-mechanical-chemical (THMC) processes dynamically change the fracture network, due to heat generation from the wastes, adding additional complexity. Subsequently, multiple computer models, created by teams from different countries, have been compared with each other in a benchmarking exercise to simulate flow and transport through a 1 km^3 block of fractured rock.[532] However, these models are described as "*preliminary or under development*" and the highest agreement was found for the simplest problem (limited to four fractures).

A 2021 review of the expected behaviour of radionuclides and water flow in fractured crystalline rocks highlights three main issues:

- determining parameters of radionuclide transport models in various scales from laboratory- to field-scale experiments,
- upscaling physical and chemical parameters across scales, and
- characterizing fracture structures for radionuclide transport simulations.[533]

Relevant parameters are values such as the permeability of the rock (a measure of how easily water passes through it) and sorption coefficients for different radionuclides (a measure of the extent to which they are retained by the rock – see Section *4.4. Solubility, sorption and transport of radionuclides*). Producing accurate models of fractures in the rock – through which radioactive water and gas can flow – is difficult because it is hard to extrapolate from measurements on the surface of a block of rock in order to correctly describe the network of fractures inside it. This means that markedly different fracture densities, hidden in the rock, could be consistent with the same experimental data.[534,535]

The importance of fractures for understanding and predicting fluid flow in crystalline rocks is widely recognised. Nevertheless, there remain considerable differences in the assessment of which properties of fractures and fracture networks are most essential, how to best characterize them, and how to properly include them in a representative and efficient manner in a numerical model.[536] In particular, it remains unclear which fracture characteristics need to be determined with high accuracy, and how they may be best included in a numerical model. Discrepancies and errors occur even in modelling exercises of rock laboratory experiments (which occur on a short timescale compared to the evolution of a repository) and in the absence of perturbations such as heat. The (lack of) feasibility of mapping fractures and water flows at full-scale at a repository site also needs to be considered.

A modelling study based on a fictitious repository located in a geological setting inspired by the Olkiluoto site in Finland, has considered how radioactive iodine-129 tracers might travel through fractured crystalline rock.[537] Breakthrough of radioactive tracers in the host rock is observed after 1 000 years, but most of the tracer is retained in the repository, particularly within the engineered barrier systems. However, the model assumes that the repository is fully saturated and that the bentonite backfill performs as expected with no damage due to heat or other processes. Computer modelling of tracers involves many assumptions and uncertainties and different approaches give different results.[538] Comparing multiple computer models has highlighted the importance of explicitly including drifts and backfill.[539] If the backfill performs as expected, it greatly reduces release of radionuclides from the repository. However, the effectiveness of the backfill can also be questioned if it is damaged by heat, gas release or chemical reactions (see Section *4.3. Damage to bentonite and clay rocks*).

The effect of heat on clay rocks is discussed in Section *4.3.1. Effects of heat and mineral changes on bentonite and surrounding rock*. However, heat can also damage hard rocks. As noted in that section, one study in granite has estimated a maximum uplift at the surface due to heat from a repository of 17 cm after 2 000 years.[540] In the study, stresses are expected to be high enough to fracture the wall of the vault.

Heat can damage crystalline rock due to the uneven expansion of minerals in the rock, or chemical changes in such minerals which can occur with heating.[541] The thermal stress on the rock depends on the size, shape and arrangement of the mineral, and the strength of the heated rock decreases with larger and less uniform grain sizes (i.e., heterogeneity). Experiments in China which examined the impact of heat and pressure on granite identified a coupled effect in which increasing pressure and then temperature led the peak shear strength of the rock to drop.[542] The proportion of hard minerals in the granite governs its thermal expansion capacity, while the proportion of soft minerals affects its ability to absorb expansion. External factors, such as the coupling between temperature and stress, also impact the ability of the rock to absorb expansion. Experiments in India, which involved heating granitic rocks to much higher temperatures than expected in a repository (up to 350˚C) are nevertheless informative because they show that mass loss due to heating (as the result of evaporation of water) also occurs at expected repository temperatures of up to 100˚C.[543] Rock fractures or faults in granitic rocks could be reactivated by the thermal stress generated during the decay process of the high-level radioactive waste.[544] This thermally-induced fracture slip, can lead to large shear movements exceeding 5 cm on fractures intersecting the deposition holes and thus may damage the waste canisters. Induced shear dilation could also cause an increase in the repository permeability. Thermal stress can cause spalling as well as shear activation of fractures in the host rock and tensile failure around emplacement tunnels.[545] These thermal stresses may peak several thousand years after repository closure. The impacts of heat on faults is discussed in more detail in Section *4.8. Faults, seismicity and earthquakes*.

In Finland, Posiva argues that it will be able to place the disposal holes in unfractured regions of the bedrock.[546] Similarly, in Sweden, researchers argue that potential deposition holes with high groundwater flow should not be accepted for final deposition of radioactive wastes.[547] However, it remains unclear whether this is possible in practice.

4.5.2. Excavation damage

Construction of a deep repository creates an excavation damaged zone (EDZ), with cracks and fractures in the rock, which may create fast routes for radionuclides to escape in future water or gas flows.[548,549]

Excavation causes significant stresses in rock and can change the aperture of fractures, which are important for determining the future groundwater flow through the wastes in a repository and the surrounding rock.[550, 551] Reduction of pore pressure will also occur during excavation as water is taken out of the system and gases that were under pressure in the water are released. These processes can influence fracture size and permeability, making it harder to predict water and gas flows after closure. After closure, it is not expected that the system will return to pre-excavation conditions, because of mechanical hysteresis (the effects of past stresses retained in the system).

Excavation damage depends on local geological conditions and the excavation method. For example, in crystalline rock, it is greater in the case of drill and blast excavation than with mechanical excavation using a tunnel boring machine.[552] The EDZ consists of a failed zone, in which blocks or slabs may detach completely from the surrounding rock; a damaged zone containing micro-cracks and fractures; and a larger disturbed zone where rock stress and water pressures may be altered. If high groundwater flow occurs in the EDZ, concerns include the possibilities that harmful chemical species may be transported from the surface to the engineered barriers, diffusion of radionuclides from the wastes into groundwater will be increased, and fast routes for release of radionuclides could be created.[553,554]

Complex 3-dimensional computer models have been developed to attempt to predict the opening of single fractures in crystalline rock, and the water flow through them, as they are created, propagated and deformed by the disturbance due to excavation. These models can reproduce small-scale experiments reasonably well, but have yet to be applied to more complex cases on the scale of a repository.[555]

When the stresses on the boundary of an underground excavation reach the rock mass strength, failure occurs. At depth, it is likely that the excavations will induce stress concentrations above the rock mass strength. In addition, the heating from the spent nuclear fuel in a repository will increase stresses due to thermal expansion of the rock. Together, these stresses could affect the stability of the rock mass pillars that surround the canisters and must be taken into account in the design.[556]

In good-quality hard rock, the failure process involves splitting and cracking, known as spalling. Early calculations in Sweden suggest that the probability of spalling is low down to a depth of about 550 m but that the probability increases below this.[557] Explosive spalling (rock bursts) can occur in hard, brittle rock at these depths. However, more recent work shows that the effects of heat can exacerbate this problem, causing thermo-mechanical damage to the rock. Computer modelling of crystalline rock suggests that vertical deposition holes are vulnerable to thermally-induced compressive spalling failure, whereas sidewalls of tunnels are vulnerable to thermally-induced tensile stress and fracturing.[558] At the Forsmark site in Sweden, a brittle spalling zone of enhanced permeability could occur along the deposition holes.

Repository construction will require the excavation of many underground openings. In the Swedish concept these range in size from the 1.8 m diameter emplacement holes for the spent fuel, of which about 4 500 are needed, to an 8 m wide x 15 m high cavern required for the underground operations needed to move spent fuel to different locations in the repository. In granite, the excavation-induced stresses form an EDZ in which hydromechanical and geochemical modifications induce significant changes in flow and transport properties.[559] Strength degradation of the rock may occur over time due to micro-cracking or micro-fracturing.[560]

As noted above, the construction of a repository in clay rock is challenging, due to the need to support shafts and tunnels with steel/iron and/or concrete.[561] In clay rocks, methods are being developed to limit the flow of groundwater through the EDZ by creating radial slots filled with bentonite to interrupt the flow.[562] Clay-based seals may become key components in repository designs.[563,564,565]

In clay rocks studied in France and Belgium, an unpredicted hydraulic perturbation was found at a large distance (greater than 30 m) from excavation in both clays. Herringbone fractures were observed ahead of the gallery excavation front and around boreholes, and eye-shaped fracture patterns were also observed around boreholes.[566]

Computer modelling has been undertaken of the hydromechanical response and induced damage zones around an experimental gallery at the underground research laboratory (URL) in clay rock at Bure in France.[567] Both tensile and shear cracks can be generated, involving complex cracking processes. In this computer model, a strong tensile damage zone is localized close to the gallery wall. The shear damage has a smaller amplitude than the tensile one but extends to a larger zone. More work is needed to develop a 3-dimensional model and apply it to other excavation experiments.

In some studies, a significant proportion of gas flow, including the release of radioactive gases, is expected to occur through the EDZ (see the next section, Section *4.5.3. Gas flow*).[568]

4.5.3. Gas flow

It is now recognised that the ability to understand and predict underground gas migration is crucial to the design and management of nuclear waste repositories. Considerable complexity exists due to the highly different porous media that may surround the gas-generating waste packages, including concrete, bentonite backfill, and damaged or fractured zones in different host rocks. Effects of gas on bentonite are discussed in Section *4.3.3. Effects of gas on the clay barrier and surrounding rock*. This section looks more broadly at how gas may migrate through rock. Heat-damaged (cracked) bentonite backfill or clay rock and excavation-damaged or fractured rock may provide fast routes for gas escape

Investigating gas flow involves developing computer models of the migration of gas, produced by corrosion of metals, microbial degradation, and radiolysis of water, within geological and clay-based engineered barriers, including the role of gas in fracturing clay-based barriers.[569] Such models can be compared with each other in so-called benchmarking exercises and with experimental data from rock laboratory experiments. However, computer models of combined water and gas migration (known as two-phase flow) in an underground nuclear waste repository are still under development.[570,571,572,573,574,575,576] Different models yield different outcomes when reaching critical values leading to fracturing of clay rock by gas, which strongly depend on how the mechanical part influences the hydraulic response through the changes in hydraulic properties.[577]

Recently, models have been enhanced to include coupled water and gas flow, but this is still not coupled to mechanical changes, so cannot replicate the effects of changing pressure on gas flow.[578] More recently, mechanical coupling has been introduced showing that the initial stress state of the clay rock, anisotropy, and rock damage effects all influence the behaviour of gas flow.[579] However, this is a 2-dimensional model only. In addition, computer model results can only be compared with a limited number of experiments. In clay rocks, gas may travel through cracks in the excavation damaged zone (EDZ) and may also open new flow paths.[580]

Computer models have been used to seek to reproduce experiments studying gas flow through bentonite in the Swedish rock laboratory (the Lasgit experiment).[581,582] However, further developments are still needed to address discrepancies between the experiments and modelling, and no heating was applied in this experiment.[583] Fracture behaviour is critical in determining the system's hydro-mechanical response (small changes in fracture properties or dilatancy assumptions can lead to significant differences in stress and pore pressure evolution) and the characteristics of the gap and transition materials significantly influence the resulting gas pressure, both pre- and post-swelling of the bentonite.[584] One of these models, calibrated with data from the Lasgit experiment, was subsequently applied to simulate migration of hydrogen gas generated within a breached nuclear waste canister over 10 000 years, involving migration of much larger gas volumes.[585] In the Lasgit experiment, gas migration occurred along interfaces (between compacted blocks and along the canister surface), requiring these to be included in the model. Consistent with the Swedish repository design, in this study, hydrogen was assumed to be the sole gas generated from the corrosion of the cast iron insert within a breached copper overpack (note, if copper corrodes in pure water, this process would also release hydrogen, see Section *4.2.1. Corrosion of copper*, but this is not included in this model). For the gas generation rate and host rock properties considered, the gas could migrate through the bentonite and be released into the surrounding host rock at a maximum gas pressure somewhat higher than the initial total stress, though a significant amount of hydrogen also remained within the backfill surrounding the container. In this study, out of the 5 kg hydrogen generated during 10 000 years, about 1.3 kg remains in the backfill after 20 000 years, with about 60% of the 1.3 kg stored as pressurized gas, while about 40% is stored as hydrogen dissolved in water. In this model, at 10 000 years, the gas plume expanded significantly within the backfill, but also along the interface between the backfill and the rock, connecting with five horizontal fractures in the model, where some of the hydrogen gas can be released. The authors argue that, for the safety assessment, much more detailed calculations are needed and field experiments involving much larger gas volumes would be beneficial. In this study, the bentonite is assumed to maintain its safety functions, however, it is unclear if this would be the case after significant stresses due to heating, and chemical damage due to alkaline cement water and/or the effects of microbes (see Section *4.3. Damage to bentonite and clay rocks*).

Hydrogen from the corrosion of radioactive steel could carry radioactive carbon-14 into the atmosphere in the form of methane (CH_4), as described in Section *4.4.4. Release of radioactive gas*.[586] In addition to steel corrosion (see Section *4.2.4. Steel corrosion and hydrogen gas generation*), radioactive decay of the waste and radiolysis of water can also generate gases in the repository.[587] Total system performance assessment models in most national programmes considering clay host rocks and/or barriers do not currently directly represent the effects of gases on radionuclide transport – at least on soluble radionuclide transport – and thus their potential radiological impact on the safety case.[588]

The risk of ignition of gas mixtures is included as one of the processes for risk assessment in repository design in Germany. [589] Some researchers have argued that generation of hydrogen through corrosion in the repository may lead to the production of hydrogen-air layer and the accumulated hydrogen may cause a hazardous flame propagation resulting from any potential ignition sources.[590] However, this appears highly unlikely as hydrogen generation is expected only after all the oxygen in the repository has been used up. However, this research illustrates the importance of understanding the evolution of repository conditions with time, as discussed in Section *4.1 Changing repository conditions*).

4.5.4. Summary of bedrock properties and hydrogeology

Unidentified fractures and faults, or poor understanding of how water and gas will open up and/or flow through fractures and faults, could lead to the release of radionuclides in groundwater much faster than expected. Excavation of a repository could create fast routes for radionuclide escape through the part of the rock damaged by the excavation. Both gas and water flow are important for the safety case.

4.6. Human intrusion and human error

Other scenarios which should be considered in the safety case for a deep geological repository include human intrusion, which can be accidental or deliberate (in order to obtain nuclear materials for military use).[591] If human intrusion takes place in the form of underground drilling, radioactive wastes could be rapidly released. Solid material, which might be highly radioactive, could be rapidly ejected from a repository into a borehole during an exploratory drilling operation if the gas pressure in the repository exceeded the pressure of the column of drilling mud.[592]

Spaces deep below ground may be subject to hydrocarbon or mineral extraction and increasingly used for geothermal energy production or for storage (for example, storage of gas, or of carbon dioxide (CO_2) as part of planned carbon capture and storage systems).[593] This raises the possibility that future generations seeking to access such spaces may inadvertently drill into a repository and be exposed to potentially high levels of radiation. Repository sites are supposed to be chosen to minimise the risk of human intrusion by avoiding sites likely to be subject to the extraction of raw materials (minerals, coal, oil, gas) or drinking water or use for geothermal energy production.[594] However, in practice it may be impossible to anticipate how future generations will wish to use underground space and resources.

If the function of the repository is forgotten by society, and the future technology for radiation detection is limited, it is also possible that accidental intrusion could occur due to human curiosity about what may appear to be an interesting historical site.

Deliberate intrusion is also possible in that the contents of repositories could be attractive to some – some of the wastes would be suitable for the manufacture of nuclear weapons and dirty bombs (i.e., bombs in which radionuclides are dispersed using conventional explosives) for thousands of years, and the sites will also contain very substantial amounts of precious raw materials (e.g., copper).[595] If deliberate intrusion led to the proliferation of nuclear weapons and nuclear conflict this would obviously have significant societal, environmental and human impacts.[596]

Human error during the process of disposal is one of the hardest scenarios to evaluate. Issues include the use of damaged canisters or overpacks and the disposal of poorly catalogued materials. If fresh, rather than irradiated, nuclear fuel were buried, it could undergo a nuclear chain reaction (criticality) while underground, potentially causing significant damage to the engineered barriers and the surrounding rock (see Section *4.4.5 Criticality*).[597] Other future human actions could include abandoning a repository before completion, with tunnels and boreholes left open.[598]

Some nuclear waste disposal programmes are investigating the best way to leave warning signs for future generations hundreds of thousands of years into the future.[599] In 1989, the US Government initiated research into how future generations could be warned and protected against the hazards of an isolated high-level nuclear waste disposal site.[600] The first study concluded that in the long-term human intrusion of the waste disposal site was unavoidable, while the second study looked at how markers could be used to prevent such human intrusion. However, it is hard to imagine how the world will look some 10 000 years from now, let alone in 100 000 years or longer.

4.7. Glaciation

One of the greatest long-term threats to the integrity of deep repositories may be the effects of future glaciation. The weight of the ice can increase rock stresses, potentially leading to canister failure and/or it can cause faulting and higher erosion rates, and also create new channels for water flow at depth.[601, 602] Changes in any single process due to glaciation will also inevitably affect other processes. Glaciation can also re-activate faults far from the ice sheet (see Section *4.8. Faults, seismicity and earthquakes*).

A glacial period is an interval of time within an ice age that is marked by colder temperatures and glacier advances. Despite global warming, the next glaciation is expected to occur at 10 000 to 100 000 years in the future, and glaciation/deglaciation is likely to cause the most significant perturbation to a repository in this timeframe.[603] There have been at least five ice ages in earth's history. Several factors are thought to be important in causing them, including changes in the earth's orbit around the sun and variations in the sun's output. The last glaciation ended more than 8 000 years ago but its effects on geology and groundwaters are still visible. Post-glacial rebound – the slow upward movement of rocks which occurs after the weight of the ice has been removed – is still occurring in regions that were under ice sheets, such as northern Europe and Canada. Repository sites in Europe and Canada could be affected by future glaciations because future ice sheets are likely to extend over similar regions to those in the past.[604] Research using samples of brines occurring in crystalline rocks in Canada, Finland and Sweden suggests that these waters have been concentrated from seawater, by freezing during glacial times.[605]

At the Forsmark repository site in Sweden, the groundwaters that have been sampled using boreholes show that there have been a series of mixing events resulting from the recharge of different waters over time. These include the intrusion of glacial meltwaters, probably from several different glaciations (the last one peaked around 20 000 years ago) as well as sea water from the Baltic around 7 000 years ago.[606,607] In the Swedish Safety Case, the primary hydraulic driving force for groundwater flow during periods of glacial and periglacial (i.e., at the edges of glacial areas) conditions is the hydraulic gradient resulting from the existence of an ice sheet.[608] Computer modelling predicts that the flux of water through the repository could increase by two orders of magnitude during glacial conditions when an advancing ice-sheet margin is located right above the repository.[609] Discharge of particles released at repository depth occurs very close to the ice-sheet margin if permafrost is omitted from the model. If the presence of permafrost is taken into account, the discharge mainly occurs into taliks (areas of unfrozen ground). In this computer modelling exercise, the glacial meltwater penetrates between 500 m and 1 000 m depth, consistent with observations from the last glacial period. At Forsmark, there is also evidence of extensive rock damage due to glaciation, mostly in the uppermost 4 m of rock, but extending to depths of 13 m. This has been interpreted as likely due to high pressures under glaciers during rapid melt of the ice sheet.[610]

Ice meltwater, which is alkaline, could significantly change the composition of the pore water in a repository and the chemistry of the bentonite.[611]

In the Swiss host rock, Opalinus clay, investigations suggest that the site was not glaciated during the last glacial period, however it was covered in ice at an earlier glaciation around 500 000 years ago. It is thought that the ice front reached only a few kilometres beyond the site and was likely thin.[612] In Canada, NWRO assumes that the effects of glaciation can be disregarded, stating that "*There is no evidence in Canada for the injection of dilute and possibly aerated, glacial meltwaters to repository depth*…".[613] Similarly, in Germany, the generic safety case produced for clay rock types assumes that glacial channel formation will not reach the depths of the repository.[614]

A study of the release of uranium from the Palmotto natural uranium analogue site in Finland suggests that release occurred in two or three violent episodes in the last 300 000 years, probably due to repeated inflows of oxic glacial meltwater.[615] At the UK Sellafield site (which was rejected but may be re-visited), borehole measurements suggest that cold climate recharge of glacial meltwaters (influx of cold waters) occurred at depths of about 700 m, probably during the Pleistocene glacial periods between 2 million and 10 000 years ago.[616]

The long-term effects of glaciation on repository safety could be very serious, potentially involving a large release of radionuclides due to glacial flushing from a damaged repository zone. Future glaciations could cause faulting of the rock, rupture of containers and penetration of surface and/or saline waters to the repository depth, flushing out radionuclides as the ice melts. Future glaciations therefore place a serious limit on the predictability of containment of the buried wastes.

4.8. Faults, seismicity and earthquakes

Inactive faults may be reactivated during the lifetime of a repository and earthquakes could severely damage the containment system, including the canisters, clay backfill around the containers, tunnel backfill and the rock. Faults can also provide fast routes for the escape of radionuclides to the surface. Until recently, the main concern identified by researchers was the re-activation of faults due to glaciation. However, it has also been proposed that rock fractures or faults in granitic rocks could be reactivated by the thermal stress generated during the decay process of the high-level radioactive waste, or by permafrost, and this could lead to the creation of fast routes for radionuclide escape, or to seismic events (earthquakes).[617,618,619] Stress changes caused by temperature and thermal pressurization of a rock mass around the emplacement tunnels may trigger a slip event on a fault plane in proximity of the geological disposal site in clay or granite rocks. Even small stress increments due to heat transfer can induce fault reactivation in the repository area.[620] There are major discrepancies between experimental and computer modelling results due to problems simplifying continuous rock fracture surfaces, which can lead to underestimated fracture displacement. There are numerous issues regarding scaling up effects (currently based on modelling a single fracture and comparing with laboratory experiments) to the repository scale. In granite, rock joints could also be preferential pathways for radionuclide migration and the heat generated from the waste can itself induce shearing of the joint.[621]

In clay rocks, fault ruptures can begin at depth, hundreds of meters below (or above) the repository.[622] A study in the Opalinus clay formation in Switzerland, where an old quiet tectonic fault is known to be present, suggests that fault slips could occur up to a distance of 600 m from the outermost tunnel. Prompted by recent evidence of earthquakes caused by fracking, computer modelling suggests that such ruptures could take place during the first 1 000 years after emplacement of the waste, with a fault about 200 m from the repository rupturing for a length of about 1 km, with slip of the order of 1 cm. Reactivation may be delayed for faults further from the repository, but delayed reactivation is expected to affect a slightly larger section of the fault. A 2024 study analyses the shear slip potential and ground uplift around high-level radioactive waste (HLW) repositories using coupled thermo-hydro-mechanical (THM) numerical models, finding that slip can occur within 10 000 years of waste emplacement if a fault is located within 2 km of a repository.[623] These researchers state that "*studies on the shear slip potential around a geological repository are at an embryonic stage, and further studies considering various geological and HLW disposal conditions are needed*". Predicting the shearing of intersecting faults and fractures poses even greater challenges and, to date, model comparisons (benchmarking) have only taken place for 2-D models, not 3-D.[624] When more than one fracture or fault intersects with another fracture/fault in three dimensions, it could lead to mechanistically different shearing behaviour from the simplified 2D cases studied so far. A recent modelling exercise concluded that considering failure along the weak planes in the clay rock enables more accurate predictions of fracture development.[625] This research did not consider the complex interaction between rock failure and permeability, as the permeability was assumed to remain constant.

In comparison with results from studies in rock laboratories, different modelling teams show significant discrepancies with experimental results when modelling shear displacement evolution.[626] Plastic deformation of rock around a fracture changes the local stress field and can lead to the formation of new fractures or reactivation of existing fractures, potentially increasing rock permeability. However, this is not currently included in these models or experiments. Coupled thermal-hydrological-mechanical (THM) processes are also not included in the models yet.

In Finland, Antti Joutsen, principal geologist with Posiva, is reported as acknowledging that, "*There will be several ice ages in the next million years and they will pose a risk of earthquakes. There will be a 2-3km (1.2-1.9 mile) thick ice sheet on top of Onkalo that will push the Earth's crust downwards by hundreds of metres. Onkalo's been built to withstand that*."[627] When the ice age ends, the crust will start rising again, which is when earthquakes with the power to break up the canisters could happen. Joutsen states, "*To prevent that, we're putting them in the best possible locations: the disposal holes are in unfractured sections of the bedrock*." Post-glacial (glacially influenced) faults are well documented in Sweden and Finland and many continue to produce small earth tremors (known as 'micro-seismicity'). In Sweden, thirteen fault systems are believed to have ruptured to the surface before or after deglaciation and some faults are known to have ruptured multiple times. At least two postglacial faults are known to have ruptured below water in the Baltic Basin and there has been controversy regarding whether these could have caused tsunamis (known as paleo-tsunamis), with possible implications for the Swedish Safety Case for the proposed repository at Forsmark. A recent review of the evidence suggests that geological evidence for this is lacking.[628] However, the authors conclude, "*the authors of this study do not claim there were no paleo-tsunamis in Sweden, rather we claim there is no credible evidence of paleo-tsunamis in Sweden*".

Russian researchers have considered the effects of tectonic activity on the safety of the geological repository at the Yeniseisky radioactive waste repository (Nizhnekansky massif, Krasnoyarsk Krai, Siberia).[629,630] They argue that tectonic activity will most probably lead to the renewal of old faults, and not to the formation of new ones. Existing faults at the site are highly permeable, some run South to North (meridional) and some run West to East (latitudinal). Using 3D (i.e., 3-Dimensional) modelling of potential water flows, these researchers find that a "tongue" of contaminated groundwater is drawn towards the river Shumikha (a tributary of the Yenisei) from the northern part of the area along the Shumikhinsky fault. This leads to an inflow of radionuclides into the Yenisei River. Thus, the latitudinal faults can represent a significant ecological hazard at this site, depending on the distance from the repository to the faults.

In Japan, some scientists argue that geological disposal in Japan is impossible as it is one of the world's most tectonically active zones (see also Box 15).[631] Earthquakes also occur frequently in the South Korea Plateau.[632]

However, in many other countries it is assumed that earthquakes will not take place or, if they do, that they will not disturb the repository at depth. This is based on geological data at proposed repository sites, suggesting that past glaciations have not led to changes in the groundwater types contained within the rock. For example, in the German generic safety case for a repository in clay rock it is assumed that the repository will not be affected by future earthquakes, volcanic activities or tectonic processes.[633] However, this assumption is likely incorrect as: (i) the heat of the nuclear wastes in the repository itself can reactivate faults up to 2 km from the repository (as discussed above); and (ii) more recent research suggests that, unlike the effects on water flow directly below the ice sheet (discussed in Section *4.7. Glaciation*), glaciation can re-activate faults far from the ice sheet.[634] This is important because this effect could occur more widely than previously assumed. For example, during the last ice glaciation (about 70 000 to 20 000 years ago), a large part of northern Europe was fully covered by the Scandinavian ice sheet, which extended up to the British Isles and some parts of Poland and Germany, and, in central Europe, the Alps were also almost fully glaciated.[635] Similarly, the Laurentide ice sheet covered most of Canada and a large portion of the Northern United States. During glacial periods, the weight of the ice pushes the Earth's crust down and, as the ice retreats, it then rebounds, a process taking thousands of years. This can reactivate faults in crystalline rock, speeding up the release of radionuclides by channelling the flow. If two faults interact, this can make this situation worse, leading to the rapid spread of radionuclides in two directions. [636]

4.9. Transport of radionuclides in the biosphere

As described in Section *4.2.3. Role of microbes in corrosion*, there is a deep geological biosphere where microbes are now known to live. However, in the context of safety assessments for geological disposal, the term biosphere is normally taken to mean the region at or close to the surface of the earth – including soils, rivers, lakes and oceans, forest and farmland - when humans and other animals live (with a focus on those that are part of the human food chain).

Although public communications emphasise the 'containment' of radioactive wastes in a deep geological repository, safety cases include calculation of potential doses of radiation to future generations. For example, in Finland's safety case calculations, carbon-14 is assumed to be released as gas and other radionuclides (such as chlorine-36, iodine-129, strontium-90, molybdenum-93 and silver-108m) are discharged into the sea, lakes and soils in contaminated groundwater.[637,638] Although the doses predicted by Finland's nuclear waste management, Posiva, are very low, these calculations depend on numerous assumptions.

Once radionuclides reach the biosphere, they may expose humans to radiation in a variety of ways. As part of the safety assessment of a proposed repository, computer models are used to calculate expected doses to humans via pathways such as ingestion of radionuclides in drinking water and food, inhalation of radionuclides, and external radiation from radionuclides in soils.[639] Prediction of the consequences of radioactive contamination of the environment is increasingly recognised as being a complex multidisciplinary scientific problem.[640] More than two decades after the Chernobyl nuclear accident, there is no consensus on the health effects because increases in cancers are difficult to measure and attribute to radionuclide exposure. Estimates of cancer mortalities therefore vary from a few thousand to 40 000.[641] Nevertheless, several thousand thyroid cancer cases can be attributed to radiation effects among children and adolescents, as can an increase in leukaemia cases among the 'liquidators' who dealt with the immediate aftermath of the accident.

Computer models of the behaviour of relatively well-known radionuclides in scenarios such as a nuclear accident can give reasonable predictions. For example, a comparison of nine computer models of ecological transfer and thyroid doses resulting from the release of iodine-131 following the Chernobyl nuclear accident found agreement within a factor of ten with dose measurements.[642] However, different radionuclides move in different ways in the near-surface environment, including in soils, lakes and streams.[643] There may be multiple migration mechanisms involved, including transport by air, water, particulate matter and biota, which further complicate dose estimates.[644] It is possible that estimates of the effects of radionuclide exposure on health may also be revised in future as scientific understanding improves (see Section *2.1. Harmful effects of radioactive wastes*). There is no direct comparison between radionuclides released in past accidents, or from nuclear weapons' tests, with how radionuclides will behave when released from a deep geological repository.

The safety assessment for a nuclear waste repository involves developing computer models of the biosphere, in order to show that the dose limit to a person living in the far future, set by regulations, is likely met (see Section *3.1. Safety assessment*). Although the idea of 'isolation' and 'containment' of wastes is often used to describe deep disposal, the safety assessment also relies on 'dilution and dispersion' at or near the earth's surface (particularly of highly mobile radionuclides which are expected to escape the repository).[645] Developing such models involves understanding in more detail what happens in the top few tens of metres where upwelling groundwaters interact with surface water bodies (e.g., rivers and lakes), or aquifers (which may be drinking water sources). There are substantial challenges due to the extremely long timescales involved and the range of potential ecosystems and human behaviours (which will all change with time). For example, this can include sea level change at coastal sites (e.g., in Sweden). There are significant uncertainties in these models of highly complex processes. For example, the high mobility of chlorine in underground water suggests that chlorine-36 (half-life 300 000 years), released from a radioactive waste repository would readily contaminate the biosphere. However, there is large uncertainty regarding the degradation of chlorinated organic compounds in soil, which has a major impact on the accumulation of radioactive chlorine in ecosystems.

The speciation of radionuclides (i.e., their chemical form) is of great importance for biological uptake, accumulation and biomagnification.[646] Bioaccumulation is the gradual buildup in an organism over time. Biomagnification is the increase in concentration of a substance higher up the food chain. Radionuclide transfer from soils to food crops can vary considerably with the radionuclides, plant species, soil types and times of deposition, and there is considerable uncertainty regarding these transfer factors.[647] Soil-to-plant transfer factors need to be estimated for each radionuclide, which differ depending on the soil properties, climate conditions, plant species and land use and management.[648] Depending on the plant, radionuclides may accumulate mainly in the roots or also above-ground (e.g., in leaves).[649] A 2023 study explores the relationship between radionuclide fallout from nuclear weapons' testing and vegetation distribution in China.[650] The authors suggest that the higher inventories of radionuclides (cesium-137, plutonium-239, plutonium-240, neptunium-237, and americium-241) found in the Changbai Mountain area suggest that the environment and latitude there contribute to preserving radionuclides in some way.

Many data gaps also remain in factors governing the transfer of radionuclides in animal feedstuffs to domestic farm animals, which will contaminate the human food chain via meat and milk.[651,652] Many species of fish also bioaccumulate radionuclides, so that their concentrations become higher than in the surrounding water.[653,654,655] Concentrations depend on the radionuclide, the species of fish, and are different in different organs: for example, radioactive caesium-137 and potassium-40 can build up in the muscle of the fish, whereas concentrations of plutonium tend to be highest in bottom-feeding fish. Repositories located near to the coast are expected to discharge some radionuclides into the marine environment and here too there are uncertainties regarding the bioaccumulation of radionuclides in different species of fish and shellfish, and particularly in the rates of sorption and re-release (desorption) of radionuclides into and from seabed sediments over long timescales.[656,657]

Radionuclides can also accumulate in humans. For example, strontium-90 has been detected in the baby teeth of children born during above-ground (atmospheric) testing of nuclear weapons (1946-1965), highlighting past exposures to fallout in the womb and during infancy/childhood, when exposures pose the greatest health risk.[658] Radioactive iodine can accumulate in the thyroid gland of humans (and animals), increasing the risk of thyroid cancer.[659] Consumption of milk contaminated with radioactive iodine-131 has been identified as dominating the ingestion dose of the local population after the Chernobyl accident.[660] Although iodine-131 is a short-lived radionuclide, with a half-life of about eight days, the much longer-lived iodine-139 has a half-life of around 16 million years, and is highly mobile, so is expected to be one of the radionuclides released from a repository (see Box 5).

Radionuclides that are trapped in soils or sediments can be released at a later date. For example, much of the plutonium discharged from reprocessing at the Sellafield nuclear site in the UK stuck to the mud in the estuary and off the coast. However, radionuclides from the mud have been re-dispersed via particulate transport in fine-grained estuarine and intertidal sediments to the North-East Irish Sea.[661]

Studies of the US plutonium-contaminated site at Savannah River have shown that a large proportion of the buried plutonium unexpectedly migrated upward. Simulations indicate that because plants create a large water flux, small concentrations taken up in plants over long periods may result in a measurable concentration of plutonium on the ground surface.[662,663] Researchers warn that animals such as rabbits could consume grasses containing plutonium and move it further into the food chain. This finding will not be relevant to repository safety if actinides are contained by sorption in the bentonite backfill deep in the repository. However, the concentration of plutonium by plants could be an issue of concern if it is transported to an aquifer faster than expected, perhaps in the form of colloids (see Section *4.4.2. Colloids and complexation*), or if the backfill fails to perform as expected (Section *4.3. Damage to bentonite and clay rocks*). The unexpected nature of the findings at Savannah River also illustrates how complex processes can be misunderstood, leading to erroneous conclusions. Plutonium has also been detected in groundwater in the prevailing flow direction in a borehole close to the vault at the Maišiagala shallow radioactive waste repository in Lithuania.[664]

In the USA, beginning in the 1940s, radioactive waste from the nuclear weapons programme was stored in the open in St Louis, Missouri, and over several decades contaminated nearby Coldwater Creek. In a 2025 cohort study of 4 209 participants, living near Coldwater Creek as a child was associated with an increased risk of overall cancer during long-term follow-up, with evidence of a dose-response association.[665]

Safety assessments for nuclear waste repositories focus on the expected future doses to humans. However, ecosystems may be affected in complex ways (and this may also lead to impacts on humans in the future). The current approach to radiological protection is based on simplification of systems, rather than acknowledging and addressing complexity.[666] A more ecosystem-focused approach would recognise multiple feedbacks (such as the ways that organisms can affect environmental concentrations of radionuclides, as well as vice versa), the limitations of extrapolations and the potential importance of indirect and ecosystem effects over long timescales.[667] Irradiation can result in disruption of ecological relationships and radioactive contamination can stress natural populations, leading to unexpected consequences due to the complexity of ecosystems.[668] Since organisms compete with one another, the effects of radiation on ecosystems may differ from those on individual species. The effects of long-term exposure may differ from short-term ones, as ecosystems are exposed to multiple stressors. One example of an area that has received limited study is the accumulation of radionuclides in invertebrates, including beetles, ants, butterflies, spiders and millipedes, which are a major dietary component of many animals and therefore one potential route into the human food chain.[669,670,671]

Impacts of radiation on many animals is poorly understood. One computer modelling study, based on data available in databases for different species of mammals and birds, concluded that differences in population sensitivities of warm-blooded animal species to ionizing radiation generally depend on the metabolic rate and longevity of organisms, and also on individual radiosensitivity of biological tissues.[672] Among species studied, the greatest adverse impacts were estimated for elephants, followed by humans and then larger mammals such as deer, horses, wolves, pigs, wild boar and sheep.

Climate change – including both global warming and future glaciation – will change ecosystems significantly, including drastic changes from aquatic to terrestrial systems and vice versa as sea levels rise or fall at a particular location. This prospect poses additional challenges for radiological protection.[673] Currently, different climate states are considered in safety assessments, but not the transitions between them. This means that some scenarios that might result in higher releases – such as the accumulation and then release of radionuclides below an ice shield during a glaciation event – are not included in the models.[674]

A typical scenario for future exposures presumes the existence of a group of people living above a repository and deriving all its water from a well in the aquifer above the waste. The water is used for drinking by humans and animals, exposing people directly via the water and via meat, milk and eggs from the livestock. The water is also used for irrigation, exposing people via soil contamination, plant uptake, and ultimate ingestion of soil and plants, as well as via external exposure and inhalation of suspended soil.[675] There are significant social uncertainties regarding future human behaviour, as well as uncertainties in the physical, chemical and biological behaviour of each radionuclide. Further, because radionuclides are assumed to be diluted in the well, the above scenario may not always be the highest exposure route for future generations, compared with, for example, consumption of fish or shellfish in which radionuclides have bioaccumulated.[676]

5. Overarching unresolved issues

5.1. Safety assessment: the evidence base, the methodology and their limitations

The literature review set out above suggests that significant releases of radioactivity from a deep underground repository could occur in a number of ways:

- Copper or steel canisters and overpacks containing spent nuclear fuel or high-level radioactive wastes could corrode more quickly than expected.

- The effects of intense heat generated by radioactive decay, and of chemical and physical disturbance due to corrosion, gas generation, cement water, and resulting changes in mineral content, could impair the ability of backfill materials to protect the canisters from stresses in the rock and to trap some radionuclides.
- Build-up of gas pressure in the repository, as a result of the corrosion of metals and/or the degradation of organic material, could damage the barriers and force fast routes for radionuclide escape through crystalline rock fractures or clay rock pores.
- Poorly understood chemical effects, such as the formation of colloids, could speed up the transport of some of the more radiotoxic elements such as plutonium.
- Unidentified fractures and faults, or poor understanding of how water and gas will open up and flow through, excavated tunnels, fractures and faults, could lead to the release of radionuclides in groundwater much faster than expected.
- Excavation of the repository will damage adjacent zones of rock and could thereby create fast routes for radionuclide escape.
- Future generations, seeking underground resources or storage facilities, might accidentally dig a shaft into the rock around the repository or a well into contaminated groundwater above it; or deliberately seek to extract canister materials or nuclear materials for military use.
- Future glaciation could cause faulting of the rock, rupture of containers and penetration of surface waters or permafrost to the repository depth, leading to failure of the barriers and faster dissolution of the waste.
- Faults could be re-activated, creating fast routes for radionuclides to escape or leading to earthquakes which could damage containers, backfill and the rock.

Although computer models of some of these processes have undoubtedly become more sophisticated, fundamental difficulties remain in predicting the relevant chemical and geochemical reactions and complex coupled processes (including the effects of heat, mechanical deformation, microbes, changing chemistry, and coupled gas and water flow through fractured crystalline rocks or clay) over the long timescales necessary.

In particular, there is increasing recognition of the importance of ‘coupled’ thermal-hydro-mechanical-chemical-biological (THMCB) processes, where each process potentially affects and is affected by the initiation and progress of all other processes. This introduces considerable complexity and also undermines the ‘multi-barrier concept’ in which each barrier (waste containers, backfill and rock) is presumed to act independently to contain the wastes. For example, corrosion of canisters and wastes generates gas which can damage both the bentonite barrier and surrounding rock, as well as carrying radionuclides up to the surface. Mineral changes to bentonite (due to heat, microbes or cement water) may mean it cannot prevent nuclear waste containers from corrosion or from being breached due to high stresses in the surrounding rock.

In contrast to the simple picture often presented publicly, of stable, unchanging rock formations containing wastes over geological timescales, the scientific literature highlights the significant disturbance to the rock caused by excavation of the tunnels and the extreme heat and radioactivity emitted by the wastes, a disturbance expected to last around 100 000 years. Numerous attempts have now been made to replicate (some) expected future repository conditions in rock laboratories and to model the relevant processes using complex computer models. However, both experiments and models have numerous limitations, as the repository conditions can never be exactly reproduced. Many expected stressors (particularly the presence of the radioactive wastes themselves) have to be omitted from experiments, which take place over timescales that are extremely short in comparison to timescales of hundreds of thousands of years. Thus, computer models cannot be validated by comparing with the real-world conditions that will actually exist underground in the far future. In the long-term, the concept of deep geological disposal remains dependent on the idea of passive safety.[677] Yet, passive safety is impossible to guarantee over such long timescales.

Fundamental difficulties in resolving these issues are discussed below.

5.1.1. Unknowns, uncertainties and model validation

A landmark paper published in 1994 argued that verification and validation of numerical models of natural systems is impossible.[678] This is because natural systems are never closed and because model results are always non-unique. Models can be confirmed by the demonstration of agreement between observation and prediction, but confirmation is inherently partial. Computer models can only be evaluated in relative terms, and their predictive value is always open to question. In the case of nuclear waste repositories, validation is impossible because there are no measurements of what happens in reality over the extremely long time-scales involved. Instead, researchers rely on ‘benchmarking’ exercises (comparing computer models with each other), in an attempt to reach a common understanding, or on trying to reproduce much shorter-scale experiments.[679,680] It is important to remember that the repository conditions will evolve over time over the order of 100 000 years before returning to the steady state of the undisturbed geology (assuming no major disturbances, such as earthquakes or human intrusion in that time).[681] Even then, excavation damage will remain and could provide fast routes for radioactive water or gas to leak from the repository and future geological events (glaciation, earthquakes) or human intrusion could change the situation significantly. The underlying challenge is that completeness, i.e., the precise estimation of the risk of the repository, cannot be attained.[682]

Although the aim of experiments in Underground Rock Laboratories (URLs) is to reduce uncertainties, some regulators recognise that, “*such experiments lead sometimes to ‘new’ uncertainties and processes that were not identified before*”.[683] There may be situations where an investigation may provide surprising information, calling for a revised conceptual model of the problem.[684] Or, processes which compromise the safety of a deep geological repository might not be discovered until too late. Historic examples from other fields include collapses in fish stocks, the effects of CFCs on the ozone layer, and the harm to health caused by X-rays and asbestos.[685]

Although it is often difficult to get computer models to reproduce experimental data, another problem is that models that are tuned (calibrated) to reproduce experimental data can still give poor predictions when applied to different experimental or real world situations. This is because many different models may be consistent with the available data.[686] Therefore, even perfectly calibrated models (i.e., those that appear to fit a particular data set well) may have limited or no predictive value (i.e., they may not adequately represent the necessary processes as conditions change with time).[687] Similarly, models that work well in the laboratory may not apply to real-world conditions. For example, the advection-diffusion equation is used to predict the transport of solutes in soils. However, it neglects the possibility of preferential fast transport routes, particularly on colloids, and therefore failed to predict the unexpected pollution of streams and groundwaters with pesticides and other contaminants.[688] Computer modelling requires many judgments about what assumptions are made, both in the methods adopted, and the parameters used to describe the rock, backfill and containers, which are often not well known.[689] A 2022 review of computer modelling for radionuclide flow through fractured rocks highlights that establishing an appropriate conceptual model may be more or at least as important as the acquisition of accurate parameters.[690] This review concludes that the uncertainties of the models come from the inherent complexity of fractured formations, parameter reliability, data quantity, the underlying conceptual-mathematical frameworks, coupled uncertainties in multidisciplinary information, and the scenarios under which a system is assumed to operate. A comparison of different approaches in performance assessment of the long-term safety of a repository for radioactive waste in salt formations, finds that the assumptions made and initial conditions assumed can have a large impact on the results of calculations.[691]

It is possible to attempt to reduce the uncertainty associated with using different conceptual models by getting different computer modelling teams to compare the results of their different interpretations. This can lead to a better understanding of why some models disagree, but it cannot guarantee that all the relevant processes and assumptions have actually been included.[692] In addition, the models can still only be compared with each other or with relatively short-term experiments, not with the actual conditions in the repository as they evolve over hundreds of thousands of years. Thus, uncertainties are likely underestimated.

Another problem is the difficulty in finding a parameter set that adequately represents a given location, because places are unique in their characteristics and boundary conditions and their uniqueness is inevitably to some extent unknowable.[693] This means that a model that has been refined to be ‘fit for purpose’ at one location will not necessarily work at another, or in different future circumstances, if the parameters used to define the new site or circumstances are inadequate to represent important processes.

Theoretically, it should be possible in the modelling of repository safety to take a pragmatic approach which would allow researchers to consider all the possible models that might fit the data and, by hypothesis testing using experimental data, rule out scenarios that breach safety requirements.[694] However, it is by no means clear that sufficient data can be collected, or sufficiently safe sites exist, to rule out scenarios which involve significant radiological releases.

New data-driven models (e.g., ‘machine learning’ and ‘neural network’ models) are being developed, as are new tools such as ‘molecular dynamic’ (MD) modelling (which attempts to model relevant physical and chemical processes at the atomic scale).[695,696,697] However, these will also be limited by the data that is available about repository conditions as they evolve into the far future. ‘Hyper-gravity’ experiments (using centrifuges) speed up the transport of contaminants such as radionuclides through geological barriers, potentially allowing better evaluation of potential releases of radionuclides through rock.[698] However, there are still questions regarding whether this method can replicate the flow and transport processes in real fractured rocks. An approach called ‘hybrid twin’ methodology is also being developed which combines computer simulations (using both machine learning and physics-based models) with sensor data.[699] However, such methodology could only be applied in the relatively short period of time (around 100 years) when monitoring may take place, before repository closure.

5.1.2. Potential for bias in the assessment process

Scientific bias has been well studied in the medical research literature, where several types of interpretative bias (bias in the analysis of data, rather than in the measurements themselves) have been identified:[700]

- confirmation bias – evaluating evidence that supports the scientist's preconceptions differently from evidence that challenges these convictions
- rescue bias – discounting data by finding selective faults in the experiment in order to 'rescue' the original hypothesis
- mechanism bias – being less sceptical when underlying science furnishes credibility for the data, meaning that the interpretation of results is in line with prior expectations
- "time will tell" bias – the phenomenon whereby different scientists need different amounts of confirmatory evidence, because deciding when evidence is sufficient to make a decision is inevitably subjective
- orientation bias – the possibility that the hypothesis itself introduces prejudices and errors and becomes a determinant of experimental outcomes.

In the field of deep disposal, the likelihood of interpretative bias is high and the potential safety implications considerable, because the wastes involved remain highly dangerous for tens of thousands to millions of years and there is no mechanism to validate computer model predictions over the long timescales involved. In systems whose properties are spatially and temporally heterogeneous (variable) at different scales the concept of the observer as an impartial, totally unbiased bystander becomes meaningless.[701] Models of environmental systems, including radioactive waste disposal, involve numerous subjective choices about system structure, boundary conditions, feasible values for parameters, characterisation of input data, scenarios for future predictions and how the performance of the model should be evaluated.[702] Environmental models are mathematically ill-posed or ill-conditioned, meaning that the information content available to define a modelling problem does not allow a single mathematical solution.[703]

Failure to recognise this can easily lead to overconfidence in a particular computer model or the assumptions that underpin it. It is clear from historical and contemporary examples drawn from many fields – an example being the credit crunch of 2007-08 – that highly expert regulators and private risk modellers sometimes exhibit 'herd behaviour' and may fail to anticipate rare and unexpected events. The dangers of such groupthink are greatest when in-depth discussion of the issues is limited to a relatively small group and computer model-building is highly complex and are comprehended only by a highly expert group, because they are then less likely to be open to public scrutiny or challenge by outsiders.[704]

Numerous articles in the medical literature and some in other scientific fields have also found that bias is strongly influenced by commercial interests.[705,706,707,708,709,710,711,712,713,714] This suggests that the selection of a particular computer model and set of parameters may be not only subjective, but also easily biased towards giving the preferred outcomes.

Bias can affect how experimental and modelling results are interpreted, what research is undertaken, or how research results are fed through (or not) to the safety case. Some recent examples of different interpretations of evidence related to deep disposal are described in Boxes 11 to 15. In particular, out-dated assumptions about the evolution of repository conditions, and the behaviour of the materials used (steel, cement, bentonite and copper) under these conditions, appear to be 'locked-in' to the safety case.

Box 11: Intense heat from radioactive wastes not relevant to clay rock repositories?

The Belgian regulator has stated, "*In current safety assessment of geological disposal, the impact of thermal gradients generated by the radioactive high-level waste on the diffusion of radionuclides through the host rock is usually disregarded because the full containment of radionuclides in the waste canister is assumed during the entire thermal phase*".[715] For repositories in clay rocks, the design life-time of the canister is 1 000 years. The assumption that the heat generated by the radioactive waste is not relevant to the safety case appears to rest on a timeline taken from an earlier study showing normal geothermal conditions restored in a clay rock repository after around 1 000 years, and normal hydrogeological conditions slightly later.[716] The source of this timeline appears to be the Swiss nuclear waste disposal company NAGRA (whose repository design is cited), however no source reference or scientific rationale is given for the claimed timeline. This timeline is surprising because spent nuclear fuel remains heat generating for more than 10 000 years and the temperature in the repository is not expected to return to normal until around 100 000 years after closure (see Section *4.1 Changing repository conditions*).[717,718] Thus, there is a need to assess and model complex coupled THMCB (thermal, hydrogeological, mechanical, chemical and biological) interactions as described in Section *4. Literature review of post-closure issues*, due to their importance to the safety case. The purpose of this (expensive) research is undermined if the effect of heat on the engineered barriers and host rock is simply excluded from the safety case.

Box 12: Are cement, steel and bentonite compatible materials?

Chinese researchers have concluded that combining cement and cement-based materials such as concrete with bentonite clay backfill is "*not conducive to the safety of HLW disposal*".[719] This conclusion is consistent with the findings of many other studies which show that alkaline cement water, together with the effects of heat and microbes, will damage the swelling properties of the clay (intended to hold the waste canisters in place and slow the release of radionuclides) (see Section *4.3. Damage to bentonite and clay rocks*). Yet all repository designs combine the use of bentonite with considerable quantities of cement.

Consistent with other research questioning the impacts of corroding steel on bentonite, Chinese researchers have also warned that the products of steel corrosion and radiolysis could also reduce the performance of bentonite, until the entire multi-barrier system fails.[720]

Box 13: **Self-healing in clay rocks?**

A study of self-healing of fractures in COx clay rocks in France concludes that, "*These first results are very promising and give confidence to the positive impact of the self-healing process…*", also claiming that "*To have an effective sealing it is necessary to have a carbonate content lower than 40%*".[721] However, the data in the paper shows that 'self-healing' does not actually occur (closure of the fractures does not restore the rock to its original state) and there is no threshold at 40% carbonate content, but rather a rapid loss of self-healing properties as carbonate content increases. Thus the 40% claim appears to be made mainly to be consistent with the existing carbonate content of 20-30% in the lower two layers of the proposed host rock in France. In this study, closure of larger fractures (0.8 mm compared to 0.4 mm) does not actually occur (with a suggestion in the text of the paper that some sealing material could be torn off due to the water flow, which can occasionally increase the permeability) and heat and gas flow both slow the fracture closure process (with only one test conducted on the effects of temperature or gas, and no tests with both together). Thus, the claim that the results are promising is inconsistent with the actual findings of the research. Similarly, the summary of these and other experiments undertaken in the EU research programme EURAD states, "*Overall, confidence was gained in the positive impact of the self-healing process on the restoration of the self-healing properties of the clay host rock…*".[722]

Box 14: Independent scrutiny in Sweden?

MKG, the Swedish NGO Office for Nuclear Waste Review, is a non-governmental environmental organization established in 2004 to work specifically with nuclear waste issues: however, its funding has now ceased.[723] In 2024, together with the Östhammar Nature Conservation Association, MKG launched an appeal against the decision of the Land and Environmental Court to allow construction of the Swedish repository to proceed.[724] In particular, MKG has drawn attention to expert concerns regarding the corrosion of copper (see Section *4.2.1. Corrosion of copper*) and to the LOT experiments conducted in Sweden's Äspö Rock Laboratory.[725] The LOT experiments involved emplacing seven experimental packages, of copper pipes containing heaters, in the bedrock, surrounded by bentonite, and, after several years, excavating and analysing them. The findings from one of the packages have not yet been reported. Two of the other tests were dismantled in September 2019, and the initial investigations plus an analysis of the copper corrosion have been published by SKB.[726,727] These tests show relatively high copper corrosion rates, which SKB attributes to oxygen having been present in the experimental set-up, whereas critics argue that this is not possible and that the experiments therefore confirm their view that copper can corrode faster than expected in an oxygen-free environment.[728] In addition, SKB finds pitting corrosion in copper samples (coupons) embedded in the bentonite, but claims that the pits were likely in the samples prior to the experiment. SKB admits that the LOT experiments were designed to assess the performance of the bentonite barrier, not the copper, and thus there are important gaps in the analysis. The Swedish Regulator has accepted SKB's interpretation but also notes that: the copper coupons and copper tubes were not characterised before installation (so the extent of any prior pitting was unknown); no measurements of microbial populations in groundwater were made (these would affect how quickly oxygen was used up, and would also contribute to corrosion by sulphides); there was no monitoring of reduction-oxidation (redox) conditions; and radiation effects are not accounted for.[729]

The dispute regarding the corrosion of copper has not been resolved.

Box 15: Earthquakes and faults

In Japan, some scientists argue that geological disposal in Japan is impossible as it is one of the world's most tectonically active zones.[730] There are many known active faults but severe inland earthquakes often occur in places where active faults have not been identified. A report of a meeting in 2024 to discuss these issues concludes that "*there was too little time for a serious scientific discussion, and there were problems with the handling of the proceedings*" and the exercise may have been more about appearing to listen to the voices of experts, rather than changing anything.[731]

Even in countries where faults are mostly dormant, there is increasing evidence that faults may be re-activated by heat from the radioactive wastes, or by the effects of glaciation far from ice sheets (see Section *4.8. Faults, seismicity and earthquakes*).

Availability of alternative expertise and funding, and the level of independent scrutiny required by regulatory processes, can influence whether there are sufficient critical perspectives to identify problems with the safety case for a radioactive waste repository. For example, at the UK Nirex inquiry in 1995-'96, which led to the rejection of planning permission for the first phase of a nuclear waste repository near Sellafield (see Box 7), the objecting groups had a total budget one hundredth that of Nirex.[732] Nevertheless, after hearing extensive evidence over several months, the planning inspector concluded, "*The indications are, in my judgement, still overwhelmingly that this site is not suitable for the proposed repository, and that investigations should now be moved to one of the more promising sites elsewhere*".[733] In a letter to the Guardian newspaper five years later, an anonymous former employee of Nirex describes how, "*We were there to justify a decision that had already been made*" (on political and financial grounds). The writer adds, "*It was easy to suppress any doubts about the correctness of what we were there to promote. With hindsight, the "groupthink" was obvious*". This individual goes on to express concerns that the UK Government's response has been to reduce scrutiny of proposals for nuclear facilities, stating, "*My personal experience leads me to fear for the results*".[734]

Bias can be exacerbated by claims that deep disposal must be workable because 'road maps' towards its implementation exist in a number of countries, significant amounts of research have been done, and other alternatives have been discarded as technically or economically unfeasible or unsafe.[735,736]

It seems likely therefore that there could exist other serious problems with deep repository proposals, which have not been identified due to lack of resources and funds for independent scrutiny of data and assumptions. In each country with a deep disposal programme, regulators are responsible for reviewing safety cases and ultimately for licensing facilities.[737, 738] Although this can include some independent research and development to support decision-making, regulators are in practice largely dependent on the data collection, analysis and computer modelling produced by the nuclear waste disposal companies, or in collaboration with them.

Historically, the majority of the funding for research, development and demonstration (RD&D) in waste management comes from the nuclear industry and follows the research agenda set by the industry's implementing organisations. More recently, there has been increased international research collaboration, involving nuclear waste management organisations, regulators and research entities (e.g., universities). For example, following the adoption of the EU's waste directive (which endorses deep geological disposal[739]), EU research funds have been made available for research on deep geological disposal. However, one of the aims of the EU's radioactive waste research programme EURAD, which is mainly focused on deep geological disposal, is to "*help in gaining and maintaining public confidence*".[740] Other aims include addressing evolving regulatory concerns and "*reducing uncertainties through excellence in science*". This raises questions regarding what happens when science uncovers new uncertainties or results reduce confidence in deep geological disposal (see, for example, Boxes 11 to 15).

5.2. Site selection and public opinion

Whilst making the right siting decision is necessary, it is not necessarily sufficient to meet safety requirements or ensure public acceptability. It should also be remembered that decisions taken regarding a deep geological repository will mostly affect future generations, who have no voice and no power to influence decisions made today.[741]

In repository safety cases, the 'normal' or central scenario, assumes that the canisters, canister and tunnel backfill and host rock retain their integrity as expected and do not suffer any significant changes.[742,743] The design life of canisters is intended to ensure no release of radionuclides until conditions in the rock have returned to the stable state it was in before it was impacted by the intense heat of the radioactive wastes placed in the repository (and, in the case of copper canisters in Sweden and Finland, potentially to survive future glaciations and earthquakes).This is reflected in public communications which emphasise the stability of rock and deep geological disposal as a method of 'containment' of such wastes of timeframes of hundreds of thousands or millions of years.[744,745] There is a notable contrast between this story of geological containment and stability and the scientific research programmes discussed in Section *4. Literature review of post-closure issues*, which focus on the highly dynamic environment expected in the repository over the first 100 000 years or so, in which the critical importance of complex models of coupled thermal, hydrogeological, mechanical, chemical and biological (THMCB) processes, is emphasised. Little public emphasis is placed on the extremely long design lives of the canisters and backfill compared to any previous human engineering works, and the unimaginable timescales involved for the repository as a whole.[746] The tension between the need to ensure the release of gas to avoid repository damage, and the potential for the release of radioactive gases is also generally not mentioned. Some commentators have described nuclear containment as a 'myth'.[747] In addition, differences in expert views are often hidden from the public.[748]

Members of the public may see the issue of safety in different ways.[749] Many authors argue that there is a need for public involvement in terms of a moral responsibility towards society today and towards future societies.[750]

Sweden involved local communities in the decision-making process and gave them a veto at each stage of the site selection process for a deep repository. Following the example set by Sweden and Finland, and the past failures of site selection processes in many countries, there has been a shift in most countries since the 1980s away from seeking the best geological site for disposal towards finding a site that is considered good enough and where repository construction is considered politically as well as technically achievable. The site selection process then takes more account of other factors, particularly acceptability to the local population and proximity to existing nuclear facilities, and the outcome of public participation exercises, or 'volunteerism' based on financial compensation for local communities.[751,752,753, 754] This approach has been successful in some countries, largely by focusing on existing nuclear industry sites.[755] However, other countries have still not made any progress in finding sites, despite numerous attempts (Box 7).

A voluntarist approach to site selection for a deep geological repository presumes that a number of sites that are both geologically suitable and publicly acceptable exist, and that safety will not be compromised by offering financial incentives to poor or marginalised communities. In practice, offering financial compensation may risk undermining the requirement to 'optimise' radiological protection (i.e., to use the best available techniques to minimise radiation exposures in the future). Further, as the European Commission's Joint Research Centre (JRC) acknowledges, a suitable site might simply not exist in a given country seeking to implement the deep disposal option.[756] In Japan, where seismicity is a major concern throughout the country (see Box 15), in 2024, Genkai Town, Saga Prefecture became the first municipality to accept a literature survey for HLW disposal (the first step in the site selection process). In order to facilitate literature surveys, the central government provides up to ¥2 billion (US$12.8 million) over two years to municipalities accepting a survey.[757]

In those countries that have selected sites, the focus of public debate may shift to the merits (or otherwise) of the safety case. For example, in Sweden, this debate has focused on the corrosion of the copper canisters.

According to a 2008 Eurobarometer survey, in Greece, Sweden, France, Germany and Finland around 80% of respondents "*totally*" or "*tend to*" agree that there is no safe way of getting rid of high-level radioactive waste.[758] However, a more recent EU-wide study does not appear to have been undertaken.

5.3. Costs

The construction and operation of a deep geological repository is a major infrastructure project. Costs are influenced by the upfront costs of researching and designing the repository, the fixed costs associated with large-scale underground construction, and the additional costs which depend on the size and scale of the repository. The latter are largely determined by the waste inventory and the need to space heat-generating wastes sufficiently widely to meet the 100°C temperature limit. In addition, there are costs associated with packaging and transporting the wastes. The repository layout will influence costs and, as well as the temperature limit, other constraints include the need to avoid major faults and fracture zones.[759,760,761] Growing evidence that heat from the radioactive waste, or glaciations, could re-activate faults may increase the difficulties in meeting these requirements (see Section *4.8. Faults, seismicity and earthquakes*).

Cost calculations are also based on assumptions about the materials to be used in a repository (e.g. copper, steel, bentonite, concrete/cement), despite serious doubts that many of these materials are suitable for use in a repository, as discussed in Section *4. Literature review of post-closure issues*.

New nuclear reactors could add to the inventory of spent nuclear fuel requiring disposal. The construction of new reactors will increase not only the volume of wastes to be disposed of but also the average level of radioactivity per rod of spent nuclear fuel, since next-generation reactors are likely to use higher burn-up fuel. This may have implications for repository safety cases because of higher radioactivity and heat generation from these fuels.[762,763]

Funding mechanisms for nuclear waste management and decommissioning of nuclear reactors vary in different countries.[764] Part of these funds (or sometimes a separate fund), is intended to cover the costs of a geological disposal facility for spent nuclear fuel, high-level waste, and some intermediate-level waste (other wastes will require different facilities, incurring other costs). Although the 'polluter pays' principle indicates that commercial operators of nuclear power plants should cover the costs of clean-up and disposal of wastes, many countries also require some government (taxpayer) funding, either as a result of design or due to a shortfall. If the funds set aside prove not to be sufficient in reality, the burden of the extra costs is likely to fall on taxpayers.

In all cases, the volume of rock that needs to be excavated is significantly larger than the volume of the waste, due to: (i) the need to reach the host rock (around 500m underground); and (ii) the need to space waste canisters widely in order to meet the temperature limit (intended to reduce the adverse effects of heat on repository safety). The spacing required between the canisters is a major factor in predicted costs.

Calculations of minimum canister spacings required to meet the temperature limit (calculated on the basis of the heat emitted from the spent fuel or high-level waste) vary for various types of spent uranium oxide fuel. In one study, spacings from 3 m to 10 m are given, however some types of MOX (mixed plutonium and uranium oxide) spent fuel require much larger spacings and probably cannot meet existing temperature limits according to this study.[765] In another study, minimum repository footprints per canister are calculated, which are between 16 m^3 and 289 m^3 for spent fuel that has been cooled for 100 years. In this study, spent MOX fuel is limited to one assembly (rather than 4) per canister (because otherwise the temperature limit cannot be met), with a predicted repository footprint of 121 m^3 after 100 years of prior cooling. [766] The necessary spacing will depend on the repository design and rock type, as well as the type of fuel and how long it has been cooled prior to emplacement in the repository. For example, calculations in Brazil considered higher rock temperatures at depth than in many countries, finding that when the bedrock temperature is 45°C, the canister spacing must be at least 15.9 m for uranium spent fuel or 17.8 m for MOX spent fuel.[767] In all cases, the disposal area per canister (and thus the volume of rock that requires excavation) will be much larger than the original volume of the waste.

One study has investigated the effects of spacing on the design of high-level waste (HLW) disposals in a deep underground repository in clay rock (based on the French COx claystone), in which micro-tunnels which incorporate the waste packages are parallel spaced. To investigate the effect of distance between micro-tunnels, five different spacings are analysed: 26 m (the base case), 34 m, 40 m, 60 m and 100 m. Using computer models, this study demonstrates that a larger damage zone (in which heat causes thermal fracturing) develops for cases with smaller parallel spacing between the micro-tunnels.

In Sweden, a capacity of 6,000 canisters is estimated to require excavation of about 1.6m tonnes of rock, with tunnel construction costs alone of 500 million Euros.[768] Uncertainty in calculations of heat generation from spent fuel contributes to uncertainty in the calculations of what spacings are required to meet the 100°C temperature limit.

One study has used data from Sweden to make general predictions about the cost of the disposal of spent nuclear fuel from a single pressurised water reactor (PWR), operating for 60 years, with an energy output of $10GW_e$ and spent fuel storage for a cooling period of 100 years.[769] The central estimates are a fixed cost of 3.18 billion US dollars for the repository construction and a cost of 6.37 billion US dollars for tunnel excavation and disposal. Additional costs are associated with the storage and packaging of wastes, prior to disposal. The use of different types of fuel can increase costs. Research costs are not included in these estimates. In South Korea, costs of the current phase of deep disposal research, scheduled to last until 2029, are estimated at 4 billion US dollars.[770]

In France, ANDRA has estimated that the total cost of the disposal project for HLW Cigéo (including construction, operation and closure of the repository) over the facility's lifetime, i.e., more than 150 years, is between 26.1 and 37.5 billion euros (in 2012 prices), depending on the assumptions made.[771] The cost of initial construction (prior to commissioning) is estimated to be approximately 7.9 to 9.6 billion euros. Once commissioned in around 2050, Cigéo is estimated to generate average annual costs in a range between 140 and 220 million euros, covering operation, phased construction, maintenance and renovation operations over a period of 95 years, followed by a decommissioning and closure phase lasting approximately 20 years, representing a total cost between 16.5 and 25.9 billion euros. R&D costs are estimated at between 1.7 and 2 billion euros.

In the United Kingdom in 2020, the Nuclear Decommissioning Authority (NDA) calculated a fixed cost of £4.401 billion for the construction of the geological disposal facility (GDF) plus a cost of £398 300 per canister of spent nuclear fuel or HLW, leading to a total undiscounted cost of £12.3 billion.[772] However, a 2023 review published by critics of the nuclear industry argued that this was a significant underestimate.[773] In August 2025, a UK Government unit which assesses the costs and risks of major infrastructure projects estimated the whole life costs at £20bn (with £54bn as a high-end assessment).[774] In this assessment, delivery of the GDF was also rated "*unachievable*".

The cost of the copper canisters is one of the key components of the cost of a nuclear waste repository built according to the Swedish concept and these costs could increase in the future. The IAEA has predicted that the demand for copper will outstrip supply within the next decade, due to its use in renewable energy technologies.[775]

6. Alternatives

According to the IAEA, planned storage durations for spent nuclear fuel (SNF) are increasing. Typically, these were 20-50 years in the 1980s, up to 100 years in the 1990s, and over 100 years in the 2000s.[776] This is partly due to the use of higher enrichment and higher burnup fuels (which take longer to cool), and partly due to delays in deep disposal programmes.

Wet storage of spent nuclear fuel is not passively safe. Major concerns have been raised about the risk of accidents because the safe storage of spent fuel in pools depends critically on the ability of nuclear plant operators to keep the stored fuel covered with water, to stop it catching fire, which would have potentially devastating consequences.[777,778,779] Similar concerns apply to high-level waste stored in liquid form in tanks, prior to vitrification, at reprocessing plants, which requires constant active cooling.[780]

Even if deep geological disposal is implemented, responsibility for handling radioactive wastes will inevitably be passed to future generations. For example, in France, the planned closure date for its proposed deep geological repository is 2170.[781] Assuming the construction license is granted in late 2027/early 2028, the first waste packages are currently expected to arrive by around 2050. Although research has been undertaken on the option of deep geological disposal for decades, this timescale is short compared to the period of time over which the wastes will remain extremely dangerous and, as the complexity of computer models of coupled process increases, there remains a lack of scientific consensus on many aspects of the safety case.

This section describes two alternatives to deep geological disposal. The first is dry storage of spent nuclear fuel and the second is disposal in very deep boreholes. Neither can be described as a 'solution' to the problem: dry storage facilities will inevitably have limited design lives and thus pass the problem on to future generations, whereas the concept of disposal in very deep boreholes is as yet unproven. However, these examples illustrate how implementing dry storage for existing spent nuclear fuel and other nuclear wastes could allow more time for a more thorough study of alternatives.

For example, according to current policy in the Netherlands, radioactive waste is stored above ground for a period of at least a hundred years at the Central Organization for Radioactive Waste (COVRA) in Zeeland.[782] The government wants to make a decision about long-term RWM in the Netherlands around the year 2100. The success of such an approach of course depends on the period to 2100 being used wisely.

6.1 Dry storage

Dry storage casks were originally developed to transport spent nuclear fuel, but some designs are now used for longer-term storage.[783] The term canister refers to the metal container (usually steel) containing the spent nuclear fuel, whereas the cask is a package with a thick wall surrounding the container in order to provide radiation shielding. Dry storage systems are being improved, with increasing attention being paid to resilience against extreme events such as tsunamis, tornados, flooding, earthquakes and terrorist acts. The design of casks must consider the need for radiation shielding, the prevention of leaks and 'criticality' (a spontaneous nuclear fission reaction), and the dissipation of heat. A key advantage over wet storage is that the latter is achieved through passive means (i.e., canister design and ventilation, including the use of an inert gas such as helium in the void volume of the cask or cylinder, and fins on the surface to dissipate heat) and thus does not require an uninterrupted power or water supply.

However, the exposure of workers to radiation doses during emplacement into storage and ongoing monitoring and maintenance must be considered.

Over time, cracks can appear in concrete structures.[784] Thus, there has been an ongoing need to improve dry storage designs and also to recognise that all nuclear waste storage facilities will require monitoring, maintenance and (at the end of their design life) renewal by future generations. One possible future option is the use of ultra high performance concrete (UHPC), although the effects or radiation on such concrete need to be better understood.[785]

Dry storage designs have improved considerably with time, partly driven by concerns about the risks of prolonged wet storage and the failure of some deep geological repository programmes (e.g., in the USA).[786] They may be above or below ground, at reactor sites or elsewhere and based on different arrangements of casks, vaults or modules. Some recent designs may be regarded as 'highly-secured' (i.e., they are intended to withstand extreme events and/or terrorism) and are more easily inspected. Many countries already use some form of dry storage for at least some of their spent nuclear fuel, e.g., the Netherlands has a central dry storage facility, whereas Germany has dry storage facilities at reactor sites. Dry storage has been chosen as an interim storage method for some spent nuclear fuel in many countries including Canada, Germany, Switzerland and the U.S., and there is increasing interest in other countries. Current trends are to extend the interim storage period to around 100 years or even beyond.[787]

6.2 Deep boreholes

Deep boreholes (at depths of more than 1.5km) have been discussed as an alternative to deep geological repositories (at around 500m depth) since the 1950s.[788] More recently, new drilling technologies have made the idea more feasible and extended the depths considered to around 5km, deep into the earth's continental crust. Proponents of deep boreholes highlight potential advantages such as:[789,790,791]

- Expanding access to stable geological zones that have remained isolated from flowing groundwater and surface processes, such as climate change and erosion, for millions of years;
- Wide availability of relevant geologies;
- A significant (orders of magnitude) decrease in the permeability of rocks at these depths;
- The vertical nature of boreholes will limit the effects of heat in the upward direction (initial heat flow will be radial rather than vertical);
- Boreholes can be separated by 200m or more, minimizing thermal interactions between them;
- Site characterization costs, upfront capital investments, and overall construction costs are likely to be lower;
- Deep boreholes can make waste disposal more localised (e.g., to existing reactor sites), reducing decision-thresholds (compared to a large-scale repository) and transportation from reactor sites, and thus perhaps shorten the timeframe from decision-to-implementation;
- There is less risk of future human intrusion, either inadvertent or intentional (e.g., access by terrorists or governments to obtain fissile material for nuclear weapons).

The SITEX Network, based in France, notes that an additional advantage of very deep boreholes is their modularity (i.e., the possibility to drill a single borehole or a few boreholes, without the commitment to a large infrastructure project required for a deep geological repository).[792] However, they also note several important obstacles, including the difficulties in verifying geological conditions at depth, and the need to develop drilling technologies and the means to plug the boreholes after emplacement of the wastes. Thus, a lot more work is needed, including a demonstration borehole as a first step to assessing feasibility.

Russian scientists have suggested that deep horizontal boreholes, which involve drilling boreholes that branch from the deep borehole at depth, may provide additional advantages.[793] Thermal convection from deep horizontal boreholes is predicted to be much weaker than for vertical boreholes, reducing potential migration of radionuclides.[794] However, others argue that drilling horizontal boreholes poses much greater technical difficulties than drilling vertical ones.[795]

A 2022 report published in the USA advocates an international research and development programme to investigate the potential use of deep boreholes for nuclear waste disposal.[796] This report notes that, by relying primarily on strong natural barriers, particularly if situated in very low-permeability rock, deep borehole disposal depends less on long-lived waste forms and robust waste canisters (i.e., engineered barriers) compared to other disposal concepts. The report also highlights the potential benefits in terms of reduced proliferation risks and reduced upfront costs. However, it argues that, for two reasons, deep boreholes will mainly be useful for specific types of waste or countries with smaller nuclear programmes. Firstly, a large surface area would be required for a single site of deep boreholes to accommodate wastes from a large nuclear programme (estimated as more than 40 square kilometres for the USA). Secondly, many (but not all) existing spent nuclear fuel types have diameters larger than existing deep borehole technology could accommodate. However, these problems may not be insurmountable, as: (i) deep boreholes might be utilized at or near existing nuclear sites, rather than at a single central site[797], and (ii) technological capabilities might improve (e.g., leading to the possibility of using larger diameter boreholes[798]).

Other reviews have focused on the need for larger diameter boreholes to accommodate spent nuclear fuel or vitrified high level waste and also noted the potential to accommodate more difficult waste forms, such as spent MOX fuel or separated plutonium.[799] Sandia National Laboratories in the USA have concluded that there are several advantages to using large diameter deep boreholes for vitrified high level waste in overpacks.[800] However, they also note that, whilst such drilling is theoretically possible, it has not been done before. Researchers in Germany argue that the technical equipment for very deep boreholes of the required size will only be developed if there is funding and a feasibility test.[801] Large diameter boreholes, drilled to a depth of 1 000-2 000 m, are currently being investigated in Australia as a potential option for long-lived intermediate-level radioactive waste (ILW).[802] A proposal for a deep borehole disposal demonstration project located in Western Australia also highlights the potential for future disposal of spent nuclear fuel.[803]

A detailed cost analysis for drilling larger diameter very deep boreholes, suitable for spent nuclear fuel or high level waste, highlights significant uncertainties in costs due to the limited number of such boreholes that have been drilled.[804] However, proponents argue that costs are likely to be lower than for a deep geological repository.[805]

In the UK, a 2023 report from US company Deep Isolation Ltd., argued that all the UK's heat-generating nuclear wastes (but not all its intermediate-level waste, ILW) could be disposed of in deep, horizontal boreholes.[806,807] Deep Isolation has established the Deep Borehole Demonstration Center, with a mission to advance Deep Borehole Disposal (DBD) through demonstration of the technology and continued development of the supporting safety case.[808]

In August 2023, the IAEA announced a new Co-Ordinated Research Project (CRP): Enhancing Global Knowledge on Deep Borehole Disposal for Nuclear Waste in response to interest expressed by several countries (e.g., Australia, Croatia, Denmark, Norway and Slovenia).[809,810] As part of a pilot study, the IAEA has provided technological and engineering support for the construction and implementation of borehole disposal facilities in Malaysia and Ghana.[811]

A preliminary generic deep borehole disposal safety case has been developed for certain military nuclear wastes in the USA.[812]

7. Conclusions

The present report's updated review of papers published in peer-reviewed scientific journals has identified a number of scenarios in which a significant release of radioactivity could occur from a deep geological disposal facility, with serious implications for the health and safety of future generations.

This literature review has highlighted concerns regarding both repository concepts (in clay rocks, or hard crystalline rocks), casting significant doubt on the wisdom of making a commitment to a costly major infrastructure project at a particular site at the current time. For example:

- In clay rocks, the design-life of steel canisters is too short to outlast the long period of time during which intense heat from the radioactive wastes would affect the physical and chemical processes occurring in the repository. Clay repositories require significant quantities of steel and/or concrete to prevent galleries from collapsing, however cement water (together with heat, radioactivity and microbes) will damage the ability of clay to swell, and thus its abilities to protect nuclear waste containers from rock stresses and to delay the release of radionuclides. In addition, it remains unclear if large quantities of gas produced due to corrosion of the steel would be released without damaging the backfill and surrounding rock.
- In hard (crystalline) rocks, disputes regarding the corrosion rate of copper have not been resolved, bentonite can also be damaged, and groundwater and gas flow through complex networks of fractures is still not fully understood. Claims that repositories in Sweden and Finland would withstand expected future earthquakes and glaciations are also highly speculative.

The following processes could compromise containment in a deep repository:

- Copper or steel canisters and overpacks containing spent nuclear fuel or high-level radioactive wastes could corrode more quickly than expected.

- The effects of intense heat generated by radioactive decay, and of chemical and physical disturbance due to corrosion, gas generation, cement water, and resulting changes in mineral content, could impair the ability of backfill materials to protect the canisters from stresses in the rock and to trap some radionuclides.
- Build-up of gas pressure in the repository, as a result of the corrosion of metals and/or the degradation of organic material, could damage the barriers and force fast routes for radionuclide escape through crystalline rock fractures or clay rock pores.
- Poorly understood chemical effects, such as the formation of colloids, could speed up the transport of some of the more radiotoxic elements such as plutonium.
- Unidentified fractures and faults, or poor understanding of how water and gas will open up and flow through fractures and faults, could lead to the release of radionuclides in groundwater much faster than expected.
- Excavation of the repository will damage adjacent zones of rock and could thereby create fast routes for radionuclide escape.
- Future generations, seeking underground resources or storage facilities, might accidentally dig a shaft into the rock around the repository or a well into contaminated groundwater above it; or deliberately seek to extract canister metals or nuclear materials for military use.
- Future glaciation could cause faulting of the rock, rupture of containers and penetration of surface waters or permafrost to the repository depth, leading to failure of the barriers and faster dissolution of the waste.
- Faults could be re-activated, creating fast routes for radionuclides to escape or leading to earthquakes which could damage containers, backfill and the rock.

Although computer models of some of these processes have undoubtedly become more sophisticated, fundamental difficulties remain in predicting the relevant chemical and geochemical reactions and complex coupled processes (including the effects of heat, mechanical deformation, microbes, changing chemistry, and coupled gas and water flow through fractured crystalline rocks or clay) over the long timescales necessary.
This introduces considerable complexity. The existence of multiple interacting processes at different scales also undermines the ‘multi-barrier concept’ in which each barrier (waste containers, backfill and rock) is presumed to act independently to contain the wastes.

In contrast to the simple picture often presented publicly, of stable, unchanging rock formations containing wastes over geological timescales, the scientific literature highlights the significant disturbance to the rock caused by excavation of the tunnels and the extreme heat and radioactivity emitted by the wastes. Repository conditions will evolve over time over the order of 100 000 years before returning to the steady state of the undisturbed geology (assuming no major disturbances, such as earthquakes, glaciation or human intrusion in that time). Even then, excavation damage will remain and could provide fast routes for radioactive water or gas to leak from the repository.

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