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Oral intervention from

Greenpeace

In the Matter of

Ontario Power Generation Inc.

Proposed Environmental Impact Statement for OPG's Deep Geological Repository (DGR) Project for Low and Intermediate Level Waste

Joint Review Panel

September 16 to October 12, 2013

Intervention orale par

Greenpeace

À l'égard de

Ontario Power Generation Inc.

Étude proposée pour l'énoncé des incidences environnementales pour l'Installation de stockage de déchets radioactifs à faible et moyenne activité dans des couches géologiques profondes

Commission d'examen conjoint

16 septembre au 12 octobre 2013

Canada

GREENPEACE

August 13, 2013

Re: Greenpeace's Written Submission in Support of its Oral Intervention

Dear Panel Members,

Thank you for allowing Greenpeace to provide its views and recommendations on Ontario Power Generation's (OPG) proposal to build a Deep Geological Repository (DGR) for Low- and so-called Intermediate-Level Radioactive Wastes.

The attached report, *Rock Solid: A Scientific review of geological disposal of high-level radioactive waste*, was commissioned and published by Greenpeace in 2010. Based on a review of the academic literature, the report provides an overview of the status of research and scientific evidence regarding the long-term underground disposal of radioactive wastes.

This review identifies a number of significant uncertainties contained in the safety cases used to promote deep geological repositories. These uncertainties could lead to radioactive releases to the environment.

Greenpeace submits that the Panel must use precaution in examining and ruling on OPG's proposal.

The precautionary principle is a central concept in environmental law and policy that Requires decision makers to "look before they leap" when making decisions that could have adverse impacts on the environment, future generations or where the environmental impacts of a decision are not known.

The principle has been adopted and applied by courts across Canada. The Supreme Court of Canada states:

> In order to achieve sustainable development, policies must be based on the precautionary principle. Environmental measures must anticipate, prevent and attack the causes of environmental degradation. Where there are threats of serious or irreversible damage, lack of scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation.

As noted, the attached report highlights significant uncertainties in the safety case presented by OPG. The risks of this project will be foisted on future generations. Greenpeace thus recommends the Panel use a precautionary approach in making its decision.

Based on our analysis, Greenpeace makes the following recommendations:

The Panel should reject OPG's Environmental Assessment and its applications for licenses to prepare the site and construct the DGR due to the significant uncertainties contained in the safety case.

In the event that the Panel accepts the environmental assessment, Greenpeace requests Panel separate the Licence to Prepare a Site from the Licence to Construct. This would allow more time for uncertainties in the safety case and the design of the DGR to be addressed and publicly examined before the DGR can proceed. This is a reasonable request given the thousands of years the DGR is expected to operate.

Thank you for your attention to this matter.

Shawn-Patrick Stensil
Nuclear Analyst, Greenpeace Canada

Rock Solid?

A GeneWatch UK consultancy report

Rock Solid?

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

Written by Helen Wallace for Greenpeace International

September 2010

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Cover

The cover photograph by Eric Shmuttenmaer is licensed under a Creative Commons Attribution-Share Alike 2.0 Generic license. 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

Worldwide, thirteen countries are actively pursuing long-term waste management programmes for high-level radioactive wastes resulting from nuclear electricity generation, but no country has yet completed an operational geological disposal facility for such wastes.

The European Commission Joint Research Centre's 2009 conclusion that the technology of geological disposal has developed well enough to proceed with stepwise implementation is based largely on a description of ongoing research projects and nuclear agency reports, and references only three papers published in scientific journals. Further, the Centre's report falsely claims that it is mainly due to a lack of public acceptance that repository programmes in Germany and the UK have (temporarily) foundered, rather than because of safety issues. Similarly, the statement of the Organisation for Economic Co-operation and Development's (OECD's) Nuclear Energy Agency (NEA) 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"* is based on the collective views of its Radioactive Waste Management Committee, not on an analysis of the existing scientific evidence.

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.

This review identifies a number of phenomena 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 and biomineralisation, could impair the ability of backfill material 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 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.
- Future glaciations 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.
- Earthquakes could damage containers, backfill and the rock.

Although computer models of such phenomena have undoubtedly become more sophisticated, fundamental difficulties remain in predicting the relevant complex, coupled

processes (including the effects of heat, mechanical deformation, microbes and coupled gas and water flow through fractured crystalline rocks or clay) over the long timescales necessary. In particular, more advanced understanding and modelling of chemical reactions is essential in order to evaluate the geochemical suitability of repository designs and sites. The suitability of copper, steel and bentonite as materials for canisters, overpacks and backfill also needs to be reassessed in the light of developing understanding of corrosion mechanisms and the effects of heat and radiation.

Unless and until such difficulties can be resolved, a number of scenarios exist in which a significant release of radioactivity from a deep repository could occur, with serious implications for the health and safety of future generations. In this light, the existence in a number of countries of 'road maps' for the implementation of deep disposal, and the rejection of other options, do not automatically mean that deep disposal of highly radioactive wastes is safe.

At present, the following issues remain unresolved and have implications for policy development:

- the high likelihood of interpretative bias in the safety assessment process because of the lack of validation of 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, 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 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 or far-field 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.

The European Atomic Energy Community (Euratom), which was founded in 1957 to promote the use of nuclear power in Europe, has been financing research in the area of geological disposal of high-level radioactive waste for more than three decades and has provided considerable support to national research and development programmes.[1]

Worldwide, thirteen countries are actively pursuing long-term waste management programmes for high-level radioactive wastes resulting from nuclear electricity generation, but no country has yet completed an operational geological disposal facility for such wastes.[2]

The 2009 Euratom-funded Vision Document of the European Implementing Geological Disposal of Radioactive Waste Technology Platform (IGD-TP) states that *"a growing consensus exists"* that deep disposal is the most appropriate solution to disposing of spent nuclear fuel, high-level waste and other long-lived radioactive wastes, and that it is time to proceed to licensing the construction and operation of deep geological repositories for radioactive waste disposal.[3] This conclusion is supported by the 2009 report of the European Commission's (EC's) Joint Research Centre (JRC), which states that *"our scientific understanding of the processes relevant for geological disposal has developed well enough to proceed with step-wise implementation".*[4]

The IGD-TP Vision Document has been prepared by an Interim Executive Group with members from the nuclear waste management organisations SKB (Sweden), Posiva (Finland) and Andra (France) and the German Federal Ministry of Economics and Technology (BMWi). It adopts the vision that by 2025 the first geological disposal facilities for spent nuclear fuel, high-level waste and other long-lived radioactive waste will be operating safely in Europe. The Director of Energy (Euratom) for the European Commission's Directorate-General for Research states in the Foreword:

> *These will not only be the first such facilities in Europe but also the first in the world. I am convinced that through this initiative, safe and responsible practices for the long-term management of hazardous radioactive waste can be disseminated to other Member States and even 3rd countries, thereby ensuring the greatest possible protection of all citizens and the environment both now and in the future.*[5]

The IGD-TP states that inherent in *"all the successful outcomes to date in European nuclear waste management programmes"* are judgements that safe geological disposal of spent nuclear fuel, high-level waste, and other long-lived radioactive waste is achievable: *"In this context, the future RD&D* [Research, Development and Demonstration] *issues to be pursued, including their associated uncertainties, are not judged to bring the feasibility of disposal into question."* This statement reflects the view expressed by the Radioactive Waste Management Committee (RWMC) of the OECD's Nuclear Energy Agency (NEA)[6] 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".*

However, the OECD/NEA position is merely a collective statement, based on the views of the RWMC, not an analysis of the existing scientific evidence. Similarly, the IGD-TP report relies on a road map towards radioactive waste management developed by the European Nuclear Energy Forum[7], and includes no references to papers in scientific journals. The EC's JRC report is largely a description of ongoing research projects; it cites only three papers published in academic journals (one of which dates from 1999) plus lists of background reports, largely published by the NEA and International Atomic Energy Agency (IAEA), and a few conference papers. The report makes no obvious links between these summaries of research activity and its conclusion that Europe is ready to proceed to implementation of deep geological disposal.[8] In a rare example of a referenced claim, the JRC's statement that corrosion of steel (and the generation of hydrogen gas by this process) will not compromise the safety of a repository is based solely on an unpublished note of a panel discussion held in Brussels in 2007. Further, the report falsely claims that repository programmes in

Germany and the UK have *"(temporarily) foundered mainly for reasons of public acceptance"*, rather than because of safety issues.

In contrast, the present 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. It finds that significant scientific uncertainties remain and it accordingly questions whether strong conclusions in favour of deep disposal can be drawn until all the relevant issues have been addressed.

2. Nuclear power and radioactive waste

Nuclear reactors are used to generate electricity in 31 countries in the world.[9] Currently, there are 438 operational nuclear power plants in the world, with a total net installed capacity of 372.038 GW(e).[10]

The IAEA lists 61 nuclear power reactors as currently under construction, mainly in China, Russia, South Korea and India.[11] In Europe, new reactors are being built at Olkiluoto in Finland, Flamanville in France and Mochovce in the Slovak Republic. Globally, China is expected to be the fourth largest generator of nuclear power by 2025, behind the USA, France and Japan.[12]

Nuclear electricity generation creates large quantities of radioactive wastes, not only in nuclear power plants themselves, but at all stages of the nuclear chain, from uranium mining to decommissioning of nuclear facilities. 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:*** this 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 repository.

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 1GW of power typically results in spent fuel assemblies containing a total of 30 to 50 metric tonnes of heavy metal , with an initial activity of around 5 to 8.3 million TBq of radioactivity.[13] 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.[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 up to 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 as liquids into the sea or other water courses and as gases to 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]

Four countries (France, India, Russia and the UK) currently have reprocessing plants which take spent nuclear fuel from non-military reactors on a commercial scale, while Japan and China have pilot plants and aim to reprocess commercially in the future.[18] Reprocessing facilities were originally developed to extract plutonium from spent nuclear fuel in order to make nuclear weapons. The separated plutonium from commercial reprocessing is now mainly added to existing stockpiles, although small quantities are used in the production of mixed-oxide (MOX) nuclear 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).

France, the UK, Russia and China are nuclear weapons states with a significant legacy of wastes from nuclear reprocessing for weapons production, as well as from their ongoing civil nuclear programmes. Reprocessing in these countries continues to generate large amounts of liquid high-level wastes.[19] Japan has sent large quantities of spent fuel to the UK and France but is now planning to reprocess its own fuel. 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.[20]

In Europe, the Sellafield site in England and La Hague in France are the main reprocessing plants. Significant radioactive discharges to sea and air have been made from both sites over the past 60 years.[21] 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.[22] With the exception of UK and France, OSPAR member states interpreted the Strategy to mean that reprocessing should cease and be replaced with storage of spent nuclear fuel (the non-reprocessing option).[23] The UK and France have disputed the implications for reprocessing, but the UK has accepted that operational discharges from Sellafield from reprocessing should have fallen to zero by 2020.[24]

A number of other European countries have sent their spent nuclear fuel for reprocessing abroad. 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.[25] Vitrified high-level wastes and plutonium from past reprocessing are intended to be returned from the UK and France to the countries of origin. However, the return of intermediate-level wastes will be limited.

In total, over 10,000 metric tonnes of spent nuclear fuel are being produced globally each year. The global inventory of spent nuclear fuel is expected to more than double to over 445,000 metric tonnes by 2020,[26] with the highest percentage increases in developing countries. Yet, to date, no country has achieved an effective solution for the long-term management of spent nuclear fuel.[27]

According to 2004 statistics cited by the IGD-TP,[28] the annual production in the EU Member States of radioactive waste and spent fuel considered suitable for deep geological disposal is 5,100m^3 of long-lived low- and intermediate-level waste (excluding that produced in Germany which is to be disposed of in the Konrad mine), 280m^3 of high-level waste and 3,600 tonnes heavy metal of spent fuel. At the end of 2004, an estimated 220,000m^3 of long-lived low- and intermediate level waste, 7,000m^3 of high-level radioactive waste and 38,000 tonnes of heavy metal of spent fuel were stored in Europe. However, there are considerable uncertainties in these figures.

In reprocessing countries such as the UK and 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. 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 in these countries.[29] Plutonium (which is a nuclear weapons material) has no currently licensed disposal route and in practice most separated uranium is not reused.

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. Interim storage in Europe is normally at the reactor sites or at centralised interim storage facilities; concerns about the safety of such facilities are beyond the scope of this report.[30] In countries with reprocessing plants, spent nuclear fuel, liquid and vitrified high-level wastes and other radioactive wastes are stored at the reprocessing plant before and after reprocessing. Even if repositories are established by the projected dates in Sweden and Finland (the only countries which have so far selected sites), the amount of waste generated annually will account for much of the quantity scheduled to be transferred annually to the repository: hence it will take decades to reduce the amount of on-site radioactive waste significantly even once repositories are constructed.[31]

The focus of this report is on deep geological disposal of spent nuclear fuel and high-level nuclear wastes from reprocessing, i.e. heat-generating wastes. Long-lived intermediate-level wastes from reprocessing are also considered, but in less detail.

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; the higher the dose the greater the risk. If radioactive wastes leak from an underground repository they will expose people to low levels of radiation which can harm health and the environment; 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.[32]

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.[33] The estimates of harm are 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).

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***: i.e. they build up in the food chain, reaching higher concentrations in fish or seafood than in the surrounding water, and thereby posing a risk of increased radiation dose to anyone eating the contaminated food.

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.

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 ***absorbed dose*** (measured in ***grays*** or Gy) is defined as the average amount of energy (in joules or J) that is deposited per unit mass (in kilograms or kg) of tissue from an exposure to radiation. The ***effective dose*** (measured in ***sieverts*** or Sv) is calculated by weighting for how harmful the type of radiation is thought to be (its estimated Relative Biological Effectiveness, RBE) and the relative sensitivity to radiation of the organs in the body which are expected to be exposed (e.g. lungs, liver, etc.). A sievert is the dose of a given type of radiation in grays that is expected to cause equivalent damage in humans to 1 Gy of X-rays or gamma radiation: but this is not known exactly.

The International Commission on Radiological Protection (ICRP) is an advisory body which sets international standards on the calculation of doses and radiological protection.[34]

High-level radioactive wastes 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. 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 these chemicals may dissolve easily and leak out of the repository in groundwater, while others may attach to the backfill or the surrounding rock and thus be contained more easily. Some can also

bioaccumulate 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.

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. 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. These are mainly negatively charged (anionic) species (forms in which chemicals exist), which are not expected to be significantly retarded in the backfill or the rock. The main radionuclides of concern are iodine-129 (^{129}I, half-life 15.7 million years), chlorine-36 (^{36}Cl, half-life 300,000 years), selenium-79 (^{79}Se, half-life 295,000 years) and technetium-99 (^{99}Tc, half-life 212,000 years).[35] 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.[36] Selenium is an essential micronutrient for many organisms and selenium-79 can also bioaccumulate in the food chain.

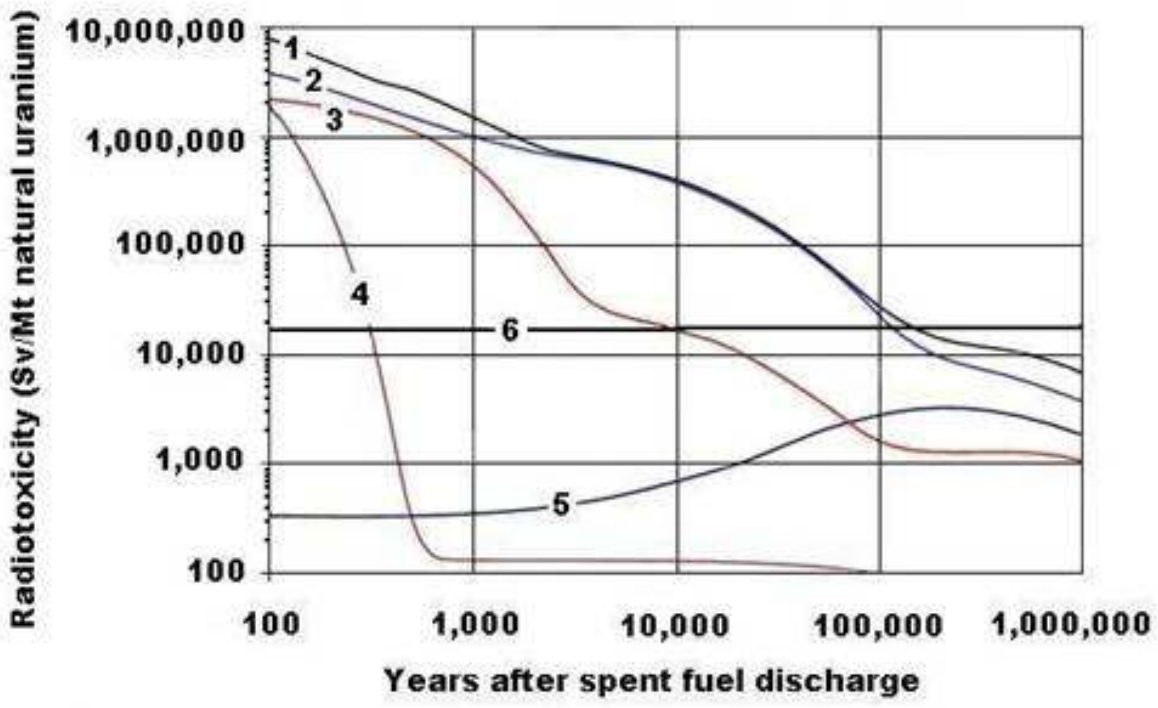
Carbon-14 (^{14}C) has a half-life of 5,715 years and undergoes beta-decay into nitrogen-14. It is relevant to radioactive waste disposal because it is the main radionuclide that might escape from a repository as gas, in the form of carbon dioxide (CO_2) or methane (CH_4). In nuclear wastes, carbon-14 exists mainly in irradiated metals (especially steels). Smaller quantities in irradiated uranium can also impact on safety if the corrosion rate is high. There are particular problems with carbon-14 in the UK inventory of intermediate-level waste from nuclear reprocessing.[37]

Figure 1 shows how the radiotoxicity of spent fuel decays with time, on the basis of published calculations for spent fuel from an LWR with a burn-up of 33 GWd per tonne of heavy metal, initial enrichment 3.2% of uranium-235, and five years' cooling.[38] The radionuclide content and hence the decay curve will differ for higher burn-up spent fuels and those from different reactor types.

Figure 1: Decay in radiotoxicity of spent nuclear fuel

Adapted from Bombini et al. (2009).[39]

1 – total radiotoxicity of spent nuclear fuel; 2 – plutonium and decay products; 3 – minor actinides and decay products; 4 – fission products; 5 – uranium and decay products. 6 – (for comparison) radiotoxicity of uranium ore. Units are Sieverts per million metric tonnes (Sv/Mt).



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 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."*[40] 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.[41]

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 over 30 years.[42]

The option of deep geological disposal would involve excavating a repository in rock, hundreds of metres underground. The radioactive waste would then be put in containers which would in turn be placed in deposition holes in tunnels in the rock. Tunnels would be backfilled to keep the containers in place and to slow the release of radionuclides from the waste once the containers had corroded. 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. However, some designs would also allow retrieval of wastes should future generations decide to undertake this. The geological disposal concept involves multiple barriers in an attempt to ensure the long-term protection of the living environment.

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 a repository may take several decades and construction is expected to take another decade. Final closure is expected to be at least several decades more after the start of the operational phase.

As well as the repository itself, encapsulation facilities would also be needed: here spent fuel or the vitrified waste from reprocessing 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.

A transportation system would also be necessary to transport the highly radioactive wastes from the interim storage facilities to the encapsulation plant and on to the geological disposal facility.

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 IAEA manages the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management.[43] It has published guidance documents on the siting of geological repositories[44] and safety standards for their operation.[45] The NEA has also developed guidelines for the post-closure safety case.[46]

The ICRP bases its recommendations on three fundamental principles – justification of exposures, dose optimisation, and dose limits (which are not to be exceeded).[47]

The principle of justification requires that nuclear activities must be justified in the sense of doing more good than harm. The ICRP states that *"no practice involving exposures to radiation should be adopted unless it produces sufficient benefit to the exposed individual or to society to offset the detriment it causes".* This principle also requires the ***collective dose*** (the average dose for a group exposed multiplied by the number of people in the group) to be weighed against the benefits of the practice (such as the generation of electricity). The collective dose gives an indication of the number of cancers and other adverse health effects that can be expected. Such cost-benefit analyses are inevitably subjective but, importantly, the requirement to consider the collective dose is intended to prevent the safety case being overly dependent on dilution and dispersion of radionuclides in the environment.[48] There is no known safe dose of radiation, and a high collective dose can arise if a large number of people are collectively exposed to very low individual doses over time.

The ICRP has set a dose limit of 1 milli-Sievert (mSv) per year for exposure situations where individuals received planned exposures from activities which are of no direct benefit to them (unplanned activities – such as major nuclear accidents – might sometimes exceed such limits).[49] A lower 'dose constraint' is set as an upper bound on the predicted dose that is allowed from planned future exposures such as that caused by waste leaking from an underground repository. For prolonged exposure to gradually accumulating long-lived radionuclides from a deep underground repository, the ICRP dose constraint is 0.1mSv per year (equating to a risk of death of one in a million per year).[50] However, the ICRP is an advisory body and in practice different countries have taken different approaches to regulatory requirements. A 2007 review by the NEA found that dose constraints set by individual countries span a range of 0.1–0.3mSv per year, while risk constraints are set at one in 100,000 or one in a million per year.[51] A major issue in the case of deep underground repositories is whether these limits can be met in practice, due to the difficulties of predicting the radiation exposures that will actually be experienced by future generations. Nevertheless the regulatory system is intended to reflect key principles, including the concept of 'inter-generational equity' or the idea that there should be no undue burden on future generations as a result of producing nuclear electricity today.[52]

The dose constraint is always lower than the dose limit and represents a basic level of protection which sets an upper bound for a process known as ***dose optimisation***. Optimisation is an iterative process that involves the identification of possible protection options and the selection and implementation of the best option under the prevailing circumstances. It is intended to ensure that doses are 'as low as reasonably achievable' (ALARA), economic and social factors being taken into account.[53]

The most recent (2007) ICRP recommendations also expand the concept of radiological protection to protection of the environment, including the maintenance of biological diversity, the conservation of species and the health and status of natural habitats. However, the environmental impact of radionuclides has only recently begun to be considered and the main focus of safety assessments remains human exposures.

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 among the key issues for safety assessment.[54,55] Computer models of the evolution of the engineered barriers and interaction between the multiple barriers have to be developed, to include all the complex thermal, mechanical, hydrogeological, chemical, and microbiological processes which will affect migration of the wastes as they are released from the containers.[56,57] The release of radioactive water and gas through the rock also calls for complex computer models, taking account of chemical interactions with the rock, the transport of water and gas through cracks and fissures, and any potential fast routes for escape, such as via the backfilled tunnels and shafts of the repository or fractures and faults in the host rock.[58,59,60] The effects of earthquakes (which can affect underground water flow or damage packaging, even when they are not major events), long-term climate change (which can alter sea level and underground hydrology) and the behaviour of future generations (who might for example dig a well above the repository at some point in the future) also need to be considered. Because many of the complex processes involved are poorly understood and many model assumptions impossible to verify, the question of whether computer predictions are sufficiently reliable to underpin a repository safety case is a matter of considerable debate.

The 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. For example, corrosion of metals involves both oxidation and reduction.[61] Relevant chemical properties in a repository will include how acidic or alkaline the groundwater becomes (its pH) during the lifetime of the repository and its redox (reduction-oxidation) potential. 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. Eh-pH diagrams are commonly used in geology for assessment of the stability fields of different minerals and dissolved substances: they show under which conditions a mineral or chemical species is the most stable form.[62] 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.

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.[63] There are obviously considerable uncertainties in defining these habits, as well as disagreements regarding the impacts of radiation on vulnerable groups such as children, babies and developing embryos.[64]

Because of the role that the geological surroundings are expected to play in containment of the wastes, site selection is a key part of the safety case.[65]

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. Because high burn-up fuel contains increased amounts of long-lived hazardous radionuclides in the spent fuel, 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.[66]

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.[67]

To date, major problems with repository programmes have been encountered in several countries, for example the UK, Germany and the USA (Box 6).

Box 6: Existing difficulties with geological repository programmes

United Kingdom: A planning inquiry into a proposal to build the first stage (known as a 'Rock Characterisation Facility') of a deep repository for long-lived intermediate-level wastes led to the rejection of the plans in 1997. The planning inspector concluded that the site near Sellafield was unsuitable for a repository for safety reasons.[68,69,70] Various generic problems with deep disposal and the site selection process were also highlighted in the rejection of the plans. Although the proposal did not explicitly include high-level wastes, it was expected that the repository, if approved, would have been expanded to include these in the future. Following the advice of the House of Lords Science and Technology Committee[71] (which reportedly advocated returning to the site[72]), the UK Government subsequently changed planning law so that in future the scientific evidence concerning safety at a site would not be cross-examined.[73] It is now seeking volunteer communities for a repository close to the original Sellafield site, with the intention of starting a new programme to develop a repository which would accommodate high-level wastes and spent nuclear fuel as well as intermediate-level wastes. A recent change in government may mean that the planning process is revised again.

Germany: In Germany, the deep disposal concept has been 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 needs to be retrieved and repackaged due to safety problems, including the leaking of saline water into the chambers.[74] It has not yet been decided where the waste will be stored. The costs of this expensive operation will fall largely on German taxpayers. 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.[75] However, 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.[76] The target date for commencing operation of a repository for spent nuclear fuel and high-level waste in Germany is still 2035, but this does not appear to be in any way realistic.

United States: Yucca Mountain, Nevada was identified in 1987 as the sole US site to be investigated for a high-level waste repository.[77] 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, 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.[78]

Currently active programmes are mainly limited to two different approaches: the first developed by the Swedish Nuclear Fuel and Waste Management Company (SKB), and the second largely by the French nuclear waste management company ANDRA. The Swedish approach involves the disposal of spent nuclear fuel in copper canisters in crystalline rock (Box 7). The French approach involves the disposal of vitrified high-level waste in steel overpacks in clay rock formations (Box 8).

Finland and Sweden plan to start operating deep geological repositories for direct disposal of spent nuclear fuel in 2020 and 2023 respectively, following the Swedish deep repository concept. Canada and South Korea intend to follow a similar approach, as does the UK for disposal of unreprocessed spent nuclear fuel from new nuclear reactors.

France plans to start operating a deep geological repository for vitrified high-level waste from reprocessing in 2025. Belgium and Switzerland are also investigating a similar approach using clay host rocks.

Box 7: The Swedish concept[79]

In the Swedish concept for a deep geological repository, spent nuclear fuel will be placed in cast iron frames surrounded by 5cm thick copper canisters. The canisters will be deposited in granite bedrock at a depth of 500m and surrounded by highly compacted bentonite clay.

Once the repository is closed, groundwater will come into contact with the canisters containing the wastes. The copper canisters are expected to corrode very slowly in the absence of oxygen: 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 chemical buffer, slowing the movement of some radionuclides, particularly the highly radiotoxic actinides (see Box 5). It also gives the canisters mechanical support, as it swells in water.

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.

Once radionuclides are close to the surface, the safety case relies on their dilution and dispersion in the aquifer above the repository and in the biosphere to limit the doses that humans receive through drinking or eating contaminated water or food.

Box 8: The French concept[80]

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 will be more reliant on the surrounding bentonite and clay rock.

Russia has been investigating the feasibility of salt, granite, clay and basalt as possible host rocks for geological repositories, but has no projected date for completion of a repository. China is investigating five potential repository sites, including a proposed underground research laboratory site in the Gobi desert, but is not expected to have an operational disposal facility until 2040 at the earliest.[81]

In Finland a disposal site has already been selected at Olkiluoto. In Sweden a site has been selected at Forsmark, on the east coast. In France the zone for disposal – the village of Bure in Lorraine – has been selected and the final site is to be specified by 2013. The Swedish, Finnish and French proposals are therefore the main focus of the remainder of this report.

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,[82] the Centre de Stockage de la Manche storage site in France, where water supplies in the aquifer have become contaminated,[83] and the Asse II salt mine in Germany[84] (see Box 6). 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.[85] 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.[86]

However, the emplacement of high-level waste in an underground repository would entail a major perturbation of the geological system, involving:[87]

(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 quantifies of highly toxic radionuclides, each with its own complex chemistry.

Nuclear Waste Advisory Associates, a UK-based consultancy, has 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.[88] Significant releases of radioactivity from an underground repository could occur if the near-field or far-field barriers were breached in ways that allowed radioactive groundwater or gas to escape faster than expected.

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

4. Literature review of post-closure issues

4.1. 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 focus of this report is on the Swedish and French designs in which the waste is below the water table and the backfill is expected to become saturated with water soon after the repository is closed. In the USA, the Yucca Mountain proposed site (now abandoned) was above the water table. However, rainwater was still expected to enter the repository and to cause corrosion.[89,90]

The Swedish safety case assumes that copper canisters 5cm thick will contain the wastes for 100,000 years, but there are serious question marks about the assumptions that have been made regarding the low corrosion rate of copper[91] (discussed further below). 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 is of the order of 10,000 years.[92] However, the safety case for the French approach remains much more dependent than its Swedish counterpart on the performance of the clay backfill and bedrock, due to the faster corrosion of steel.

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 a criticality (nuclear chain reaction) from occurring. 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.[93]

Corrosion of steel, and perhaps of copper, will release hydrogen gas into the repository. 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.[94]

These issues are discussed in more detail below.

4.1.1. Corrosion of copper

The Swedish concept for deep disposal uses copper canisters because the corrosion rates are expected to be extremely slow. 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 in the long term.[95] 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.

Nevertheless, there remains concern about the rate of corrosion of copper during the first 100 years or so, when oxygen and heat are both likely to be present. In Canada, coating copper canisters with a polymer is being considered as an option to provide protection during this early emplacement phase.[96]

After all the oxygen has been consumed, it is assumed that sulphide 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.[97,98,99]

In general, it is presumed that the canisters will corrode in a uniform way, rather than through localised corrosion such as pitting.[100,101] However, in reality, pitting may also occur and one of the scenarios that may result in early release of radioactivity is water flow into a defective canister.[102]

4.1.2. Corrosion of copper by water

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.[103] The results of his experiments are open to question due to problems with the probe used to measure hydrogen pressures. Nevertheless, an additional experiment published in 1989 supported the initial findings.[104] These experiments have now been repeated: the researchers conclude that the results show that copper corrodes in water free of dissolved oxygen, forming a hydrogen-containing corrosion product.[105] The hydrogen produced by corrosion in pure water is apparently found in the metal, the corrosion product and the water as well as in the gas phase.[106] If this conclusion is correct, it has serious consequences for the repository safety case: calculations based largely on observations of corroded copper coins recovered from the Swedish Vasa warship, which sank in 1628, suggest that the copper canisters would need to be more than 1m thick, rather than 5cm, in order to last 100,000 years.[107]

One response to the experiments suggests that corrosion of copper by pure water alone cannot occur and that there is an alternative explanation for the measurements: namely that the hydrogen evolution observed was caused, not by the reaction of liquid water with copper but by the reaction of adsorbed water with the stainless steel walls of the vacuum container in which the experiment was conducted.[108] Further, supporters of the Swedish safety case argue that the coins from the Vasa ship may have corroded because the water was polluted by sewage and contains hydrogen sulphide.[109] However, the original authors disagree and have defended their findings.[110,111] Other authors have suggested that the Eh-pH diagram for copper may differ from that currently assumed in the safety case, adding weight to the experimental evidence of Hultquist and colleagues that the corrosion of copper in water is not fully understood.[112]

In 2009, the Swedish National Council for Nuclear Waste (*Kärnavfallsrådet*) held a seminar to discuss this dispute. The report of the seminar includes the views of experts on the findings to date and on additional research that should be conducted. [113]

4.1.3. Role of microbes

It has been known since the 1980s that microbes might survive in a deep geological repository and that the effects of microbial activity could have profound impacts on waste containment.[114] In 1987, microbiology became a part of the Swedish scientific programme for deep disposal.[115] Microbes could have a number of adverse effects on the safety of a nuclear waste repository, including causing corrosion of metal waste containers.

There is now little doubt that life could survive in a repository in the form of microbes, despite the heat and radioactivity generated by the wastes. 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.[116] The microbes included heterotrophic aerobes, anaerobes and sulphate-reducing bacteria (SRB). (A heterotroph is an organism that cannot synthesise its own food and is dependent on complex organic substances for nutrition.) The microbes identified were more abundant at interface locations and absent only in those samples affected by heat and extreme drying (desiccation). Aerobic populations (those requiring oxygen) were significantly higher in the interface environments, especially at the rock–bentonite interface. Conditions in the backfill region also appeared to be conducive to microbial activity, causing a reduction in oxygen, followed by a decline in aerobic populations and an increase in anaerobic populations (ie those not requiring oxygen, including SRB). The viable population was considerably larger than the culturable population, suggesting potential for future increased activity if conditions became more favourable.

Increased heat (and possibly some radiation) was found to increase nutrient availability in bentonite-based materials and to have a stimulating effect on microbial activity.[117] Migration of micro-organisms through the bulk of the buffer appeared to be slow, but migration along the metallic holder–buffer interface was rapid, suggesting that cracks or interfaces may form preferred pathways for migration.[118] The buffer used in the experiments was a mixture of sand and clay, rather than 100% bentonite. However, other 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 100ºC for 20 hours.[119] SRB are also a characteristic component of the Opalinus Clay formation, investigated as a potential repository host rock in Switzerland.[120]

SRB reduce sulphates to sulphides. Sulphides react with copper and could potentially corrode copper canisters in a repository. However, extrapolation from underground experiments suggests that the reaction rate is too low to significantly reduce the predicted lifetime of the canisters.[121]

In concepts where the repository is to be kept open for a long period of time, to allow for monitoring and possible retrieval of wastes, 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.[122]

4.1.4. Steel corrosion and hydrogen gas generation

In a deep repository, hydrogen will be produced by anaerobic corrosion of iron. In the French concept, iron will be present in the steel overpacks 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 water alone, as some evidence has suggested (see Section 4.1.2), hydrogen may also be produced by this reaction.[123]

The corrosion rate of iron and steel may be significantly increased by the presence of gamma radiation. Experiments involving the measurement of hydrogen produced by corroding steel in artificial groundwaters suggest that the corrosion rate could be increased 10- to 20-fold in bentonite-equilibrated groundwater exposed to high levels of gamma radiation.[124] The reasons for this are not fully understood.

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 (this is discussed further in Section 4.2.5). Hydrogen embrittlement of the corroding metal might also occur, with detrimental effects on the mechanical characteristics of the overpacks or canisters.[125,126]

4.1.5. Creep

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. In safety assessments calculations are necessary to show that the canisters will not rupture under the stresses to which they will be subjected. Calculations based on a creep model of the Swedish deep disposal canisters under the pressure and temperature conditions expected in the repository suggest that there will be very high stresses at the edges of the canisters, where creep rates will therefore be high, and that the cylindrical canisters will distort to an hour-glass shape in the repository due to elastic and creep deformation. However, the creep strain at the edges is still expected to be less than would be needed to rupture the canisters.[127]

4.1.6. Summary of corrosion issues

The mechanisms for corrosion – including the role of bacteria – are not fully understood. 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.

4.2. Bentonite erosion and loss of buffer capacity

The bentonite surrounding the canisters or overpacks is expected to provide physical support and to influence the chemistry of the repository, acting as a buffer and slowing the movement of some radionuclides – particularly the highly radiotoxic actinides. However, a number of physical and chemical processes can affect bentonite in ways which could compromise safety.

Groundwater transport through bentonite remains poorly understood, with diffusion probably taking place through the interlayers of clay particles.[128]

4.2.1. Effects of heat and mineral changes on bentonite

The heat from the high-level waste in the repository will heat up the buffer/backfill and the surrounding rock of the different repository tunnels over a period of several decades as they are successively filled with the waste.[129] 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. Heating could also cause significant pore pressure changes, particularly in clay rock, affecting the stress distribution, which could in turn damage the structure of the clay rock so that water flows through it more easily. 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. 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.

Experiments show that predicting the combined effect of heating and wetting on the bentonite requires coupled thermo-hydro-mechanical models.[130,131] Complex interactions need to be included in these computer models, such as the effects of the wetting and swelling of the bentonite on water, gas and thermal flows and the effect of the changing thermal gradient on the transport of water vapour in the bentonite.

Once the repository is sealed, there will be no escape of moisture and the excavated cavity will become re-saturated with groundwater, causing the bentonite to swell.[132] 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 far field. This is also the period when the hydraulic pressure will be rebuilt in the backfilled and sealed repository opening. Thermally 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.

The heat in a repository could have a significant negative impact on the properties of clay. The bentonite clay intended to be used in repositories consists mainly of montmorillonite, which is a member of the smectite group of minerals. Smectite is considered to be a good buffer 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). The swelling bentonite is expected to exert a swelling pressure on the canisters of up to 15MPa, generating considerable stresses[133] (see Section 4.1.5).

The high-level waste placed in a repository is expected to increase temperatures considerably until its radioactivity has decreased significantly. 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 clay-sized but non-expanding mineral – in a reaction which becomes faster as the temperature increases. There are two possible chemical reactions, which depend on the chemical conditions. Experiments conducted in South Korea found that smectite transforms into randomly interstratified illite–smectite layers, and eventually into illite.[134] The experiments showed that this reaction can affect the barrier properties of smectite clay which are required for a repository. When the temperature in the experiment increased (from 90ºC to 200ºC), the percentage of the expandable smectite layers in interstratified illite–smectite decreased and its sorption capacity was very significantly reduced (with a decrease in sorption distribution coefficient Kd of more than 90% for the caesium and nickel ions tested).[135]

The Swedish repository concept currently assumes that the negative effects of illite production can be limited by spacing the spent fuel canisters far enough apart to keep temperatures to less than 100ºC. However, the rate of conversion of montmorillonite to illite is in fact not yet known, and other mineralogical changes can also take place which are not yet well understood.

A geological site where bentonites occur naturally at Kinkulle in Sweden suggests that a reduction of 50–75% in the proportion of montmorillonite may have taken place over about 1,000 years, at temperatures estimated to have reached a maximum of 150ºC; this may imply much quicker changes in a repository than has been assumed, which could have serious implications for the safety case.[136] A data synthesis reports that experiments at temperatures lower than 100ºC have also identified significant changes in the buffer: these include drops in swelling pressure of more than 50% in a Czech experiment, and a hundredfold increase in hydraulic conductivity (due to changes in particle structure) found in an experiment conducted in SKB's underground laboratory.[137] The most obvious change observed in experiments is the dissolution of minerals such as calcite and feldspar, which are present in the clay, but dissolution of montmorillonite also occurs. This happens in all experiments in a large part of the buffer. Precipitation of iron and silicon then welds the stacks of clay particles together, giving rise to a permanent increase in hydraulic conductivity and a drop in sealing pressure – meaning that water flows more easily through the heat-damaged clay, which loses its important sealing properties. A more detailed analysis of the Czech experiments suggests that the typical radius of the larger pores (macropores) in a mixture of 85% bentonite, 10% sand and 5% graphite increases threefold at 85ºC. The authors suggest that the observed microstructural changes in the experiment can be explained by mineralogical transformations, which have a serious impact on the geotechnical properties of the bentonite-based mixture.[138]

Altered mineralogy may also impact on other properties of the clay. For smectites, the risk of failure due to creep (the deformation of the clay under long-term strain, such as the weight of the canisters) is believed to be very small, with canisters expected to sink only a very small distance – of the order of 10mm – over a million years.[139] The drop in sealing pressure in heat-damaged clay observed in the Czech experiments might affect this, although the author of this report is not aware of any in-depth studies of creep in heat-damaged clay.

Because of the expected adverse impacts of heat on bentonite clay, SKB has developed thermal design criteria based on an upper temperature limit of 100ºC. The maximum expected bentonite temperature is a function of the thermal properties and geometry of the bentonite barrier, the thermal properties of the surrounding rock mass and the deposition geometry, i.e. the spacing between individual canisters and between tunnels. SKB has developed a computer model to predict maximum temperature based on these parameters.[140] It has also conducted heating experiments in the Äspö Hard Rock Laboratory and used 'inverse modelling' to try to calculate the thermal conductivity of the rock, on the basis of how the temperature changes.[141] Uncertainties in the predictions appear to be dominated by spatial variability in the thermal properties of the rock. Some of the experimental measurements also appear to be influenced by groundwater movements. Allowing a margin of error, these studies can be used to determine the spacing of canisters that will be needed to meet the 100°C temperature limit.[142]

The spacing of the canisters is one of the parameters with most impact on the size and cost of a repository (see Section 5.3). If the maximum temperature limit were lowered in order to meet

concerns about the effects of temperatures below 100ºC on bentonite this could significantly increase costs and make it more difficult to dispose of a given quantity of waste in the available volume of bedrock at a potential repository site.

Heating can also release gases from clay host rocks. In a study performed in the Opalinus Clay in Switzerland, carbon dioxide and hydrogen sulphide were the most prominent gases released, both of which could interact directly with waste containers or wastes and/or change the chemical conditions in a repository.[143] In the experiment, the clay rock in the test field was found not to be gas- tight.

4.2.2. Effects of saline water

The salinity of groundwater can also affect the properties of bentonite. In experiments, mineral alteration of bentonite due to the accumulation of magnesium occurred in saline water at temperatures of 60°C and 90ºC. The cation exchange capacity (CEC) decreased as the amount of magnesium increased – presumably due to occupation of the internal surfaces – and the distribution coefficient Kd for caesium in the altered bentonite was half that in the original, suggesting that the thermal alteration of bentonite in saline water affects the caesium sorption capacity.[144] Caesium-137 was used in the experiment, as a chemical analogue for caesium-135, which has a much longer half-life and is considered to be one of the most important radionuclides in the safety assessment for a Japanese repository. The precipitated magnesium may also prevent the swelling of the bentonite. The CEC is a measure of the quantity of positively charged ions (cations) the clay can hold, so a reduced CEC combined with a higher hydraulic conductivity is likely to mean faster escape of some radionuclides.

Preliminary experiments conducted in Spain show that swelling induced by the dissolution of salt crystals in clays may be significant in saline groundwaters.[145]

4.2.3. Effects of other minerals in clay

Bentonite clay can also contain other minerals such as carbonates, quicklime, apatite and oxides. These minerals can be formed and dissolved in the matrix. For example, various sizes of carbonate nodule are found in bentonite mines, forming and dissolving as conditions change, and potentially creating large pores or gaps in the clay. Studies in Japan have shown that these minerals can be dissolved in acid, potentially opening spaces in the rock. However, this process may not be similar to what happens in nature.[146]

4.2.4. Chemical disturbance due to corrosion

Bentonite is expected to be well-buffered, leading to stable pH conditions in the repository backfill.[147] However, chemical disturbance due to corrosion could change the properties of the backfill.

In the French repository concept, steel overpacks rather than copper canisters are expected to be used. 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. Modelling of the system over 100,000 years predicts that the porosity of the bentonite will increase, due to changes in its mineralogy, and that both the Eh and pH 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.[148]

Iron frames used 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. The incorporation of corroded iron into clay can in theory act as a pump to accelerate corrosion. A UK model again shows slowing of corrosion after time due to clogging of pores in the clay, but the chemical reactions assumed to take place differ significantly from the model developed in France. The authors conclude that meaningful application of the model requires key missing data, such as solubilities and free energies at the mineral–fluid interface. In addition, the chemical reactivity of hydrogen gas (which is assumed to be

inert and diffuse away into the rock) may need to be taken into account.[149] Experiments suggest that high concentrations of iron ions can be reached in bentonite without any mineralogical transformations but that CEC and swelling pressure may be reduced and hydraulic conductivity increased.[150] As with magnesium accumulation (see Section 4.2.2), a reduced CEC combined with a higher hydraulic conductivity is likely to mean faster escape of some radionuclides.

Large quantities of cement are also expected to be used in the repository for construction and sealing. The highly alkaline cement pore fluid may have adverse effects on bentonite, significantly reducing its swelling pressure and CEC.[151] A number of minerals are expected to form as a result of cement-bentonite interactions[152] and computer models of this process have been developed.[153] 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.[154]

4.2.5. Effects of gas on the clay barrier

Corrosion of steel in the repository would lead to the generation of hydrogen gas in the backfilled tunnels, which 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.

Four principal mechanisms have been identified by which gases can pass through clay barriers:[155]

- two-phase (water plus gas) advective flow (i.e. due to bulk motion through the rock), under the control 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 breakthrough is considered to be a serious potential problem as it could permanently damage the engineered barriers and surrounding rock. Diffusion is expected to be limited through the highly compacted clay. Experiments and computer modelling have therefore focused on demonstrating that gas could escape through advective flow before the gas pressure built up sufficiently to cause fissuring. However, advective flow could also have safety consequences because water would be pushed through the clay ahead of the gas. Advective gas flow could therefore speed up the transfer of radionuclides to the surface once groundwater had become contaminated (i.e. when the canisters or overpacks had corroded sufficiently to expose the wastes): this issue is considered further in Section 4.4.3.

The mechanisms for gas breakthrough appear to be strongly dependent on the conditions of the tests.[156] Gas breakthrough in bentonite is often abrupt, perhaps indicating channelling of gas or fracturing. In illite, the gas breakthrough pressure appears to be lower and less clearly defined: breakthrough seems to develop sequentially through many flow channels. Increased resistance to breakthrough can come from either an increase in saturation or an increase in clay density: the key consideration is the openness of potential flow channels. Above a certain degree of saturation (estimated at 93% in pure bentonite), breakthrough pressure rises sharply. Breakthrough is at least partly time-dependent and can occur at low pressures after a long period of time.

Modelling has suggested that hydrogen gas breakthrough could occur in the conditions expected in a repository following the French concept (i.e. using steel overpacks or canisters) and that the gas problem is a key issue for the long-term performance of the clay barrier and hence for disposal safety.[157] Hydrogen gas will form at the interface between the steel and bentonite and this could lead to over-pressurisation (gas build-up). Preferential pathways could form through fissuring of the rock, but could be closed again by the self-healing properties of clay, leading to a cyclical process in which the gas pressure again built up.[158] However, a more recent model that includes feedback

mechanisms suggests that the degree and physical extent of gas pressure build-up may be much smaller than earlier models found.[159] In this model, the gas pressure increases initially at the canister, but later decreases and eventually returns to a stabilised pressure that is slightly higher than the background pressure.

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 4.1.2) the hydrogen generated by this reaction might also have significant implications for the safety case; however, the author of the present report is not aware of any studies that have attempted to quantify this.

Additional steel 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[160]); 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.

4.2.6. The role of microbes: gas production and biomineralisation

Microbes can corrode compacted bentonite, but current models suggest this would occur very slowly (at a rate of a few millimetres in 10,000 years).[161] Nevertheless, other 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.[162, 163] Microbes can both produce and consume gases[164] and microbial gas production could cause a build-up of gas in a repository, potentially reducing the effectiveness of the clay-based barrier. The generation of carbon dioxide and other gases could also enhance radionuclide solubility and transport.[165] Microbial processes could in addition affect adsorption/precipitation of radionuclides, chemical conditions and the creation of colloids (see Section 4.3.2).

At the Severnyi repository of intermediate-level liquid radioactive wastes in Siberia, Russia, injection of waste has been shown to stimulate methane and hydrogen sulphide production by microbes, which existed at all depths investigated (up to 405m).[166] Experiments in the Canadian Underground Rock Laboratory have shown that the production of gas (methane) in backfill is possible and could occur in the prevailing chemical conditions.[167] The 1996 FEBEX experiment found that significant amounts of hydrogen, carbon and hydrocarbons were formed due to either thermal or microbial decomposition in the bentonite.[168] More than 0.35m^3 of carbon dioxide per 100kg of bentonite was formed, which may indicate that the gas could enhance the transport of radionuclides and micro-organisms. The gas could also have a significant impact on the permeability of the buffer material by disrupting its mechanical structure, e.g. by increasing the size and frequency of the clay pores in the bentonite near the canisters, and hence its permeability.

Microbial degradation of organic material within radioactive wastes, the main component being cellulose, can lead to generation of gases: this was a particular issue for the UK Nirex safety assessment programme due to the inclusion of large quantities of cellulose in the intermediate-level wastes destined for the proposed repository at Sellafield.[169] Degradation products of cellulose can also enhance the solubility of radionuclides such as plutonium.

Bacteria often play an important role in the production of minerals in a process known as ***biomineralisation***.[170] Depending on the conditions and micro-organisms available, biomineralisation can clog pores in rock by means of precipitation or enhance permeability due to decreased solid content.[171] 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 (Section 4.2.1). Findings that micro-organisms can dissolve smectite at room temperature (by reducing Fe(III)) 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.[172]

4.2.7. Summary of bentonite erosion and loss of buffer capacity

The effects of intense heat on the bentonite backfill of a repository could seriously damage its ability to trap some radionuclides. Chemical and physical disturbance due to corrosion, gas generation and biomineralisation could also adversely affect the properties of the bentonite backfill.

4.3. Solubility, sorption and transport of radionuclides

4.3.1. Geochemistry and buffer chemistry

The longer it takes for a given radionuclide to diffuse across the clay buffer, the lower the rate of release of that radionuclide from the near-field engineered barrier system will be, thanks to radioactive decay.[173] 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 in the buffer and thus their release rates to the surrounding rock.

The chemical conditions of the buffer are expected to delay significantly the release of some radionuclides but not others. For example, in the French safety case, the mobile radionuclides chlorine-36, iodine-129 and selenium-79 are assumed to be non-sorbing in the clay rock, and are consequently expected to be the only three radionuclides that enter the biosphere during a million-year timeframe (although it is possible that the solubility of selenium may be reduced by other complex chemical mechanisms).[174]

In contrast, the release of actinides, such as plutonium, is expected to be delayed by the chemical properties of the buffer. Thus the thickness of the buffer is expected to have a major impact on the release of relatively short-lived actinides, such as plutonium-241 (formed by the decay of curium-245) and plutonium-239.[175] However, the effectiveness of the buffer will depend on the chemical conditions (such as pH and Eh) and also on the physical and chemical form of the radionuclides.

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.[176] Safety can be significantly affected by issues such as whether radionuclides exist as particles (which may be more easily trapped in the bedrock or clay) or colloids (which may be much more mobile, see Section 4.3.2). There is particular concern that actinides, such as plutonium, might be transported long distances on colloids.

Estimation of the transport of radionuclides from a repository requires careful prediction of the chemical and physical interactions of the radioactive waste with the bentonite buffers and surrounding rock over extremely long periods of time. The complex mechanisms involved include advective-diffusive transport of radionuclides in groundwater (including advection, diffusion, and osmotic and ion restriction effects) and geochemical reactions (complexation, exchange, precipitation, adsorption and desorption) under different temperatures and pressures. Preliminary safety assessments have assumed that the chemical retardation of radionuclides in the buffer can be calculated using a constant retardation factor, Kd. However, more sophisticated computer modelling of the interactions between the different chemical species and the buffer suggest that using the Kd approach does not provide a good approximation of contaminant transport and can result in significant errors.[177] In particular, temperature has a great impact on the expected concentrations of contaminants in groundwater. Coupled thermo-hydro-mechanical-chemical processes will occur, which require complex modelling.[178] The results show that there are still significant shortcomings to geochemical modelling and its applicability to real-world repository conditions.

The geochemical suitability of a repository site is determined by the composition of the host rock and groundwater, which influence radionuclide solubility, chemical buffer capacity and radionuclide retention. However, selection of suitable conditions is generally not straightforward because of the multitude and complexity of the reactions involved.[179] The chemical parameters used in reactive transport models are not known accurately due to the complex and heterogeneous conditions and there can be multiple alternative conceptual models, none of which explain the data.[180]

Hydrogen produced by the corrosion of canisters and overpacks could act as a reducing agent and change the chemical conditions in a repository. In particular, the reduction of aqueous or mineral sulphates and other oxidised species present in the site could change the original geochemical conditions. Experiments suggest that reaction rates are highly dependent upon temperature but can probably be ignored in nuclear waste performance assessment.[181] However, further investigations are needed.

4.3.2. Colloids and complexation

A ***colloidal system*** is a type of mixture in which one substance (the ***colloid***) is dispersed evenly throughout another. 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 1nm to 1µm and have a high surface area.[182] Many radionuclides easily 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.[183]

Migration on colloids is of particular concern in the case of actinides, such as plutonium, which can be transported large distances in groundwater as colloids, and as a result could potentially be washed out of the bentonite buffer of a repository, rather than being retained there.[184] There are still significant gaps in the understanding of the transport of actinides bound to minerals and colloids. However, experiments suggest that actinide speciation may be dominated by colloid forms.[185]

Humic matter is decayed organic matter, which is an important constituent of soil. Clay is an important source of humic colloids, which can have significant effects on radionuclide migration.[186] The bentonite backfill of a repository could generate colloids, which could adsorb or incorporate radionuclides and transport them over long distances, or retain them by interaction with mineral surfaces or by ***agglomeration*** (gathering together as a mass).[187,188,189] Bentonite colloids can diffuse within granite.[190]

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 disturbed zone (EDZ) in the granite around a repository.[191]

Naturally occurring rare earth elements (REEs) can be used as chemical analogues for studying the behaviour of actinides. Preliminary studies at the Swedish Forsmark site suggest a strong association of REEs with colloids in the groundwater in the overlying aquifer but limited mixing and no evidence of transport from the bedrock groundwaters to the aquifer.[192]

The presence of oxidants can also enhance actinide transport significantly, due to the formation of complex species, which may increase solubility by orders of magnitude and potentially enhance mobility.[193]

Cementitious materials are commonly used to stabilise some radioactive wastes, such as long-lived intermediate-level wastes, which may be co-disposed with high-level wastes in some countries (such as the UK). In such wastes, cellulosic materials present in the wastes (tissues, cotton or paper) can exacerbate the above difficulties by forming organic compounds, which may then form complexes with actinides.[194]

4.3.3. The role of microbes

Microbiological processes must be taken into account when modelling groundwater hydrogeochemistry: they are expected to be involved in many reactions which would not occur in a lifeless underground environment. Experiments in the Äspö Hard Rock Laboratory in Sweden confirmed the presence of SRB, which produce sulphide corrosive to copper, and autotrophic acetogens, which produce acetate from hydrogen and carbon dioxide. The analyses also showed that different rock fractures can have very different hydrogeochemical characteristics and

microbiological profiles.[195] Measurements of the redox state (Eh) and pH at Forsmark and other sites in Sweden suggest that the waters are buffered by sulphate reduction, consistent with the presence of SRB.[196] The presence of bacteria is important because microbes can affect the mobility of radionuclides in a number of ways.[197,198] They can enhance radionuclide migration by sorption, or reduce it by immobilising radionuclides in biofilms. They can also influence the release of radionuclides by altering bulk water chemistry (especially pH and redox), by producing organic complexing ligands, or by direct accumulation onto or into cells. These complex biological effects on radionuclide transport are poorly understood but must be considered in a repository safety case.

4.3.4. 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 the steel (see Section 4.1.4). The concerns relate to any damage to containment that might be caused by pressure build-up (see Section 4.2.5) and to the potential role of the gas in pushing radioactively contaminated water upwards out of the repository. However, carbon dioxide and methane are other gases that might be produced in a repository. These gases 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.[199] It has a long half-life (5,730 years) and high mobility in the environment. The majority of carbon-14 produced in reactors is either trapped in the spent nuclear fuel, structural materials or graphite moderator, or else produced in the reactor coolant. A large inventory of carbon-14 produced in nuclear power plants is captured in ion-exchange resins, which are not heat-generating and hence not classified as high-level wastes. However, carbon-14 is also contained in spent nuclear fuel, and in some countries long-lived non-heat-generating wastes may also be co-disposed with high-level wastes in a deep repository.

In the case of a repository for low-level radioactive waste, carbon-14 is the only radionuclide that is expected to contribute significantly to radiation exposure via the gas pathway, as all other gaseous radionuclides can be neglected due to their short half-lives, low inventories or low radiological relevance.[200] For example, the Asse salt mine in Germany showed a continual release of carbon-14 during its operational phases as a result of mine ventilation, providing evidence of ongoing reactions in the waste.[201] In many low-level waste facilities, the carbon-14 inventory is the limiting factor in meeting regulatory requirements. Carbon-14 can be released in groundwater or as carbon dioxide or methane gas. It is taken up by food crops and vegetables through photosynthesis and by root uptake from soils, and can then be ingested by humans. For the proposed US deep repository at Yucca Mountain, the collective dose due to carbon-14 was predicted to exceed the Environmental Protection Agency's limit, although the dose per person was low.[202]

4.3.5. Summary of solubility, sorption and transport of 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. Build-up of gas pressure in a repository could damage the barriers and force fast routes for radionuclide escape through crystalline rock fractures or clay rock pores. Radioactive carbon dioxide and methane could also be released.

4.4. Bedrock properties and hydrogeology

4.4.1. Groundwater flow in the bedrock and fractures

Crystalline rocks contain fractures and faults, which are of critical importance in determining the flow of radionuclides out of a repository. 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.[203]

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.[204] The hydraulic conductivity can vary by one or two orders of magnitude at different points, leading to very different thermo-hydro-mechanical properties at different points in space.

Despite the progress that has been made in scaling up the measured properties of fractured rock to try to predict overall flows, the problem is so complex that it has yet to be resolved. 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 describe correctly 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.[205] An attempt to characterise a three-dimensional fracture network in a $1m^3$ block of granite has recently been published: however this is the first data-set of its kind.[206]

At the Forsmark repository site in Sweden, three major sets of deformation zones have been identified, plus a fourth subvertical zone. Two gently dipping brittle deformation zones seem to play an important role in determining the properties of the site, such as the distribution of stress, fracturing and transmissivity within fractures. Four main groundwater types are present.[207] The complex groundwater evolution and patterns are a result of many factors, including present-day topography and proximity to the Baltic Sea; past changes in hydrogeology related to glaciation/deglaciation, land uplift and repeated marine/lake water regressions/transgressions; and organic or inorganic alteration of the groundwater composition caused by microbial processes or rock/water interactions. A major conclusion from site investigations is that changes from glacial rebound and hence hydrology seem to have a major influence on groundwater chemistry.[208] Currently, the confidence concerning spatial variation is low due to relatively few observations having been made at depth, and there are significant uncertainties and discrepancies between models of the site as a result of the different assumptions made.[209] Pore water in the rock has exchanged with water circulating in fracture networks over extremely long periods of time.[210]

Mixing models have been used in an attempt to understand how groundwater chemistry has developed at Forsmark and the alternative Swedish repository site Simpevarp/Laxemar through mixing of the main groundwater types along with water/rock interactions and biological reactions.[211,212] However, the robustness of the model outputs is quite sensitive to the variables included. In addition, similar mixing proportions and mass transfers can be obtained using different reactions. Further, when chemical reactions produce an important compositional change the model may not correctly reproduce the mixing proportions.[213]

A coupled model of regional groundwater flow and solute transport, applied to the Simpevarp area, suggests that the main sensitivities are to the top surface flow boundary condition, the influence of variations in fracture transmissivity in different orientations (anisotropy), spatial heterogeneity in the regional deformation zones and the spacing between water-bearing fractures (in terms of its effect on diffusion through the rock matrix). Again, the best match to the observations may not be unique, introducing additional uncertainty.[214]

The large volume of accessible pores in fractured granitic rock may retard the migration of radionuclides through sorption onto the rock.[215] However, the effects depend on the radionuclide, with experiments in Sweden suggesting that some actinides are retarded in the rock, while others (e.g. neptunium) may break through with hardly any retardation.[216]

Data from the Callovo-Oxfordian clay formation at Bure in the eastern Paris basin – the proposed French repository zone – suggests that groundwater residence times may be very long, although significant uncertainties remain due to the complexity of the hydrogeological system.[217] The conductive layers in the clay are heterogeneous and there are several such layers identified as

'porous zones'.[218] There is also an overpressure – a pressure difference compared to the surrounding rock – of 20–60m within the Callovo-Oxfordian argillite, which has not yet been explained. The current preferred hypothesis is that this is due to chemical processes (chemical osmosis in which the rock behaves as a semi-permeable membrane).[219,220] Osmotic flow of water has been shown to occur in samples of Opalinus Clay from Switzerland.[221]

4.4.2. Excavation damage

Excavation causes significant stresses in rock and can change the apertures of fractures, which are important for determining the future groundwater flow through the wastes in a repository and the surrounding rock.[222] 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, it is greater in the case of drill and blast excavation than with mechanical excavation. 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.[223]

When the stresses on the boundary of an underground excavation reach the rock mass strength, failure occurs. In good-quality hard rock, the failure process involves splitting and cracking, known as ***spalling***. Calculations in Sweden suggest that the probability of spalling is low down to a depth of about 550m but that the probability increases below this.[224] Explosive spalling (rock bursts) can occur in hard, brittle rock at these depths.

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. These stresses could affect the stability of the rock mass pillars that surround the canisters and must be taken into account in the design.[225]

Repository construction will require the excavation of many underground openings. In the Swedish concept these range in size from the 1.8m diameter emplacement holes for the spent fuel, of which about 4,500 are needed, to an 8m wide x 15m high cavern required for the underground operations needed to transship spent fuel to different locations in the repository. The excavation-induced stresses form an EDZ in which hydromechanical and geochemical modifications induce significant changes in flow and transport properties.[226] Strength degradation of the rock may occur over time due to micro-cracking or micro-fracturing.[227]

In clay rocks such as those in France, methods are being developed to limit the flow of groundwater through the EDZ by creating radial slots filled with bentonite to interrupt the flow.[228] Clay-based seals may be key components in repository designs.[229,230,231]

In clay rocks studied in France and Belgium, an unpredicted hydraulic perturbation was found at a large distance (greater than 30m) from excavation in both clays. Herringbone fractures were observed ahead of the gallery excavation front and boreholes, and eye-shaped fracture patterns were also observed around boreholes.[232]

In the Opalinus Clay in Switzerland it has been found that the possibility of temperature-induced deformation of clay rocks due to the emplacement of high-level wastes cannot be neglected.[233] At the surface, an uplift of up to 1m has been predicted. 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.

4.4.3. 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. However, computer models of combined water and gas migration (known as two-phase flow) in an underground nuclear waste repository are still at an early stage of development.[234,235,236,237,238] Considerable complexity exists due to the highly different porous media that may surround the gas-generating waste packages: concrete buffers or plugs, bentonite backfill, and damaged or fractured zones in different host rocks. Heat-damaged (cracked) bentonite backfill or clay rock and excavation-damaged or fractured rock may provide fast routes for gas escape.

4.4.4. Summary of bedrock properties and hydrogeology

Unidentified fractures and faults, or poor understanding of how water and gas will flow through 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.

4.5. Human intrusion and human error

Other scenarios which should be considered include human intrusion.[239] 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 for energy in salt caverns, or potentially storage of hydrogen or of CO_2 as part of planned carbon capture and storage systems.[240] 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 used for geothermal energy production.[241] However, in practice it may be impossible to anticipate how future generations will wish to use underground space and resources. 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.[242]

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 for thousands of years and the sites will also contain very substantial amounts of precious raw materials.

Human error during the process of disposal is one of the hardest scenarios to identify and 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.[243]

4.6. Ice ages and glaciation

One of the greatest long-term threats to the integrity of deep repositories is likely to be the effects of future glaciation. 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.[244] 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 are likely to be affected by future glaciations because future ice sheets are likely to extend over similar regions to those in the past.[245] Direct erosion of glacial

troughs and fjords by ice in Europe was confined to Scandinavia, Scotland and the Alps, but more minor incisions and meltwater channels extended over a much larger area. Major fault displacements (scarps) occurred in northern Sweden and smaller ones in Finland and Canada. Sites near the margins of future ice sheets will be subject to repeated glacial advances and retreats and will thus undergo repeated rock stresses and hydrological changes. The greatest problems are likely in lowland regions exposed by the rapid retreat of thick ice fronts, where large lakes on or under thick warm-based ice are dammed by more distant cold-based ice. Groundwater in fractures dilated (opened up) by glacial unloading may reach over-pressures capable of hydraulically lifting blocks of bedrock or eroding more permeable rocks to depths of about 360m. When the load of grounded ice is lifted, deep accumulations of hydrocarbon gases may be capable of blowing craters or caves in bedrock. Rapid retreats of future ice sheets may therefore represent the horizon to practical safety assessments for nuclear waste repositories.

Ice meltwater, which is alkaline, could significantly change the composition of the pore water around a repository and the chemistry of the bentonite buffer.[246] An oxidising environment at depth would increase the solubility and mobility of many radionuclides and the corrosion of the canisters. Melting of glaciers is likely to be accompanied by oxidation and the formation of iron oxides, although studies in Sweden suggest that oxygenated waters do not readily penetrate beyond a depth of 100m, so a deep repository may be well-protected.[247] However, modelling suggests that oxygen could reach long distances downwards during the lifetime of a repository and penetration will depend on hydraulic properties that may vary significantly with location, with, for example, oxidising conditions occurring after a relatively short time if a fracture connects the repository with a highly conductive fracture zone.[248] The presumed depth of dissolved oxygen migration is greatly influenced by the assumptions that are made in the conceptual models.[249]

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.[250] The researchers calculate that these brines were formed relatively recently (within a few hundred thousand years during the Pleistocene period, which began more than 2 million years ago and ended around 10,000 years ago) and that the consequent dynamic behaviour of the cryogenic fluids is in disaccord with the established consensus that the hydrological system in deep crystalline basement rocks is stagnant. They state that this finding should raise concern about the planning and construction of high-level nuclear waste repositories in such rocks.

Measurements of minerals deposited in fractures at Forsmark show that different generations of fracture minerals are common, which implies that the fractures have been conductive several times and probably for long periods. Waters of quite different chemistry have been present at different times over the past million years as a result of repeated glaciation/deglaciation and transgression/regression of the Baltic Sea[251]. There are also many older fracture-filling events involving the migration of fluids many millions of years ago.[252,253,254]

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.[255] At the UK Sellafield site, borehole measurements suggest that cold climate recharge occurred at depths of about 700m, probably during the Pleistocene glacial periods between 2 million and 10,000 years ago.[256]

Modelling of the effects of a future glaciation on a hypothetical repository in the Canadian Shield, based on the last glacial cycle between about 60,000 and 11,000 years ago, suggests that under extreme conditions permafrost is able to develop down to the assumed 500m repository depth or lower. During ice sheet advance, there is a rapid rise in hydraulic head (pressure due to the ice sheet), high groundwater velocities (two to three orders of magnitude higher than under non-glacial conditions) and deeper recharge from surface water. During ice sheet retreat, the gradients reverse. In the fracture zones, the upward hydraulic gradient lasts for about 100 years, whereas in the rock matrix at depth it can last for tens of thousands of years.[257] The effects of temperature, salinity, stress-dependent permeability, permafrost and large-scale isostasy (i.e. the effects of the weight of the ice on the rock) were omitted from the coupled hydro-mechanical computer model of water flow in the rock underneath the ice, although the formation of permafrost may have significant effects on groundwater flow and chemistry.[258] The modelled head distribution is 3D, reflecting the 3D nature of

the geometry of the fracture zones in the rock and the subglacial drainage channels.[259] The details of the fracture network modelled significantly affect the response.

A model of the effects of glacial cycles on the Bure potential repository site in France has identified a memory effect of the last glaciation at depth, where as much as 80% of the last glacial maximum head disturbance may remain.[260]

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.

4.7. Earthquakes

Inactive faults may be reactivated during the lifetime of a repository and earthquakes could severely damage the containment system, including the canisters, backfill and the rock.

Networks of monitoring stations in north-west Europe have identified the positions of seismic events since the 1970s. In Britain, there are two regional-scale clusters of seismicity, one occupying the length of onshore western Britain and the southern North Sea, the other in the northern North Sea. However, this seismicity data only represents a few decades of observations and it could be argued that this length of historical record is not very relevant to earthquake hazard assessment over periods of tens of thousands of years. Seismic reflection data indicate that the fault density is as great in the areas of the UK that have been seismically quiet in the historical period as it is anywhere else; given the difficulty in declaring a fault extinct, such faults could become seismic hazards during the lifetime of a repository.[261]

The Pärvie Fault system in northern Sweden contains faults that have been reactivated since the Precambrian and which are strong candidates for future movement under suitable stress conditions.[262] In Finland and Sweden, changes in the mass of glacial ice sheets associated with periodic advances and retreats of ice are associated with very strong earthquakes. It is difficult to predict the extent to which faults may be reactivated by glaciations.

4.8. Transport of radionuclides in the biosphere

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.[263]

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.[264] However, different radionuclides move in different ways in the near-surface environment, including in soils, lakes and streams.[265] There may be multiple migration mechanisms involved, including transport by air, water, particulate matter and biota, which further complicate dose estimates.[266] Estimates of the effects of radionuclide exposure on health may also be revised in future as scientific understanding improves.[267]

The speciation of radionuclides is of great importance for biological uptake, accumulation and biomagnification.[268] 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.[269] 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.[270] 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.[271]

Until recently, it was assumed that plants did not play an important role in the transport of actinides such as plutonium in the biosphere. However, studies of the US plutonium-contaminated site at Savannah River have shown that a large proportion of the buried plutonium has 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.[272] 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 4.3.2).

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. Investigation of possible colloid-mediated transport is planned. The presence of tritium and carbon-14 in groundwater at the Maišiagala site (which operated from 1963 to 1989) also suggests possible uptake of these radionuclides in plants, with measurements confirming the transfer of tritium to plants.[273]

Other mechanisms of radionuclide transport and accumulation, as well as impacts, may be missed because the current approach to radiological protection is based on simplification of systems, rather than acknowledging and addressing complexity.[274] 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.[275] One example of an area that is only just beginning to be studied is the accumulation of radionuclides in invertebrates, including beetles, ants, spiders and millipedes, which are a major dietary component of many animals and therefore one potential route into the human food chain.[276]

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.[277] 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.[278] Processes at the biosphere/geosphere transition zone (such as groundwater recharge rates) are also neglected, although they may be essential for modelling radionuclide mobility during climate transition phases.

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; and also 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.[279] 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.[280]

5. Overarching unresolved issues

5.1. Safety assessment: the evidence base, the methodology and its 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 and biomineralisation, could impair the ability of backfill material 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 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.
- Future glaciations 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.
- Earthquakes 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 and coupled gas and water flow through fractured crystalline rocks or clay) over the long timescales necessary.

To date, preliminary safety assessments have been produced for the selected sites in Forsmark, Sweden[281] and Olkiluoto, Finland[282] and the selected region of Bure, France.[283] All these assessments have been produced by the nuclear waste management organisations SKB (Sweden), Posiva (Finland) and Andra (France) themselves. Safety assessments have also been produced in the past for the Yucca Mountain site (now abandoned) and for the failed plan to bury long-lived radioactive wastes near Sellafield in the UK.[284]

According to the Finnish nuclear waste disposal company, Posiva, the following issues are still pending final resolution and will be addressed in future updates:[285]

- the initial state of the site (e.g., in situ stresses, the fracture network, hydrogeochemical conditions at repository depth)
- the impact of the EDZ and thermal spalling on the hydraulic evolution
- the evolution of buffer/backfill saturation (e.g. time to reach full swelling pressure) and its consequences for the performance of the engineered barrier system

- flow paths to and from the repository (e.g. groundwater flows at canister scale, release paths for radionuclides)
- reaction rates and (experimental) evidence of the sequence of hydrogeochemical reactions in the near field, especially with respect to the reactions leading to the production of sulphide
- the impact on the engineered barrier system of cementitious materials and other stray materials used in repository construction
- the long-term performance of repository closing and sealing materials and the consequences for safety
- the impact of external conditions related to glaciations – e.g. taliks (unfrozen layers of ground in regions of permafrost) and glacial meltwater intrusion – on the long-term performance of the engineered barrier system.

However, there remain fundamental difficulties in resolving these issues, as 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.[286] 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.

The objective of site investigations for a nuclear waste repository is not primarily to produce a geoscientifically 'true' model, but rather to provide a basis for good decisions. Results are subject to uncertainty not only due to inherent variability but also due to 'lack of knowledge' (epistemic) uncertainties, including systematic bias, which can have a large influence on the results. It is usually assumed that the underlying physics or chemistry of the problem being modelled is fairly well understood and that there is no fundamental misunderstanding of the problem prior to investigation. However, there are situations where an investigation may provide surprising information, calling for a revised conceptual model of the problem.[287] Historic examples include collapses in fish stocks, the effects of CFCs on the ozone layer, and the harm to health caused by X-rays and asbestos.[288]

One problem is that many different models may be consistent with the available data.[289]

Therefore even perfectly calibrated models (e.g. those that fit the data at a particular site) may have limited or no predictive value (i.e. they may not adequately represent the necessary processes as conditions change with time).[290] 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 steams and groundwaters with pesticides and other contaminants.[291]

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.[292] 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 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 those models that breach safety requirements.[293] However, most safety assessment programmes remain wedded to the idea that there is a single 'best fit' model, rather than focusing on exploring possible alternative models of the site, some of which may show the proposed repository to breach safety requirements. Further, 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.

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:[294]

- ***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 determinate 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 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.[295] 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.[296] Environmental models are therefore mathematically ill-posed or ill-conditioned, meaning that the information content available to define a modelling problem does not allow a single mathematical solution.[297]

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 – a recent example being the credit crunch of 2007 – that highly expert regulators and private risk modellers sometimes exhibit 'herd behaviour' and may fail to anticipate rare and unexpected events. Such dangers are greatest when the discussion of the issues and computer model-building are 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.[298]

Numerous articles in the medical literature have also found that bias is strongly influenced by commercial interests.[299,300,301,302,303,304] 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.

Availability of alternative expertise and funding can therefore strongly 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 planning inquiry, the objecting groups had a total budget one hundredth that of Nirex but nevertheless succeeded in demonstrating significant problems with the safety case by involving sufficient alternative expertise. Nirex produced seven expert witnesses to discuss the technical, geoscience and engineering issues: all except one were directly employed by Nirex.[305] For the objectors, Cumbria County Council produced five experts (one employed by it), focusing on site selection, hydrogeology and overall risk. Greenpeace presented five experts (one employed by it) to discuss site selection, geology, hydrogeology, flow modelling, geochemistry, and comparable investigations worldwide. Friends of the Earth fielded nine experts (two employed by it) to tackle government policy, geology, site 3-D structure, hydrogeology, fluid flow in fractures, engineering and geochemistry. In one example of the expert evidence presented, alternative groundwater flow modelling by researchers at the University of Glasgow, funded by the Greenpeace Environmental

Trust, suggested that much faster groundwater return flow times than those calculated by Nirex were more consistent with its borehole measurements,[306] implying that Nirex's risk calculations might be two orders of magnitude in error.[307]

Similarly, much of the work highlighting concerns about the potential for copper to corrode in water (see Section 4.1.2) has been unfunded. The official research programme did not identify this problem.

These examples suggest that other problems may remain unidentified due to lack of sufficient independent scrutiny.

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.[308,309]

In Finland, a Posiva researcher speaking anonymously to the Finnish Broadcasting Company in May 2010 expressed concerns about pressure on scientists to meet the schedule for approval of the Olkiluoto repository despite doubts about the reliability of the copper canisters, bentonite backfill and tunnel backfill. The researcher reportedly said: *"The results of research are decided beforehand. Then we find data that gives the desired result. If there is information that does not back up the result, it is ignored".*[310]

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.[311] 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.

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.[312] Reliance on industry-funded research, although consistent with the principle that the polluter pays, is likely to introduce interpretative bias in repository safety assessments. On the other hand, significant sums of public money invested via Euratom are not being used to fund independent scrutiny. It is of particular concern that Europe's IGD-TP states that it is open only to stakeholders *"endorsing the vision and willing to contribute positively and constructively to the objectives and goals of the platform"* – in other words, critics of deep disposal are supposed to be excluded from the research programme and hence from Euratom funding.[313] Greenpeace has now joined the IGD-TP but only on condition that it is not required to subscribe to the vision. Members of the Executive Group consist of organisations either responsible for implementing a waste management programme or formally responsible for the RD&D programme needed for implementation.

It is difficult to see how adequate independent scrutiny of data and assumptions can take place in such circumstances.

5.2. Site selection, public opinion and radioactive waste inventories

Sweden has involved local communities in the decision-making process and given them a veto at each stage of the site selection process for a deep repository. Following the example set by Sweden and the past failures of site selection processes in many countries, there has been a shift in most countries since the 1980s away from finding 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.[314]

The UK and Canada have been particularly active in attempting to be seen to follow the Swedish approach by introducing new public participation and consultation programmes for nuclear waste disposal decisions.[315]

The Canadian nuclear waste management programme settled on deep disposal as a solution by the mid-1970s, initially projecting site selection by the mid-1980s, construction of a repository by the late 1980s, and an operating repository by 2000. Intense public opposition thwarted this programme, which failed to gain popular acceptance at a public inquiry, but a new process of site selection is currently under way.[316] It remains to be seen whether technical problems and scientific uncertainties are truly open to public scrutiny, or whether official claims that deep disposal has been *"found to be safe from a technical perspective"* will remain unchallenged.

In the UK, proximity to existing nuclear facilities previously led to a focus of investigations on the suitability of Sellafield as a site for the planned Nirex intermediate-level waste repository, which was rejected in 1997. The new approach therefore differs little on one level in that the same area has now been shortlisted again; however, this time people living near the final site are expected to be offered compensation. On the other hand, planning law has been changed so that the scientific evidence cannot be cross-examined (see Box 6).

Site selection processes based on 'volunteerism' typically now involve some form of financial compensation for the local population and perhaps other benefits, such as employment and new roads or other infrastructure. For example, in Slovenia two communities close to the country's only nuclear power plant competed for the financial compensation available for hosting a repository for low- and intermediate-level waste.[317]

However, 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 risks 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 JRC acknowledges, a suitable site might simply not exist in a given country seeking to implement the deep disposal option.[318]

A study of the siting of a low-level waste repository in South Korea identified four factors that influenced local acceptance: perceived economic benefit, risk perception (which has strong negative effects), trust and perceived competition for the facility.[319] In Sweden, one study has suggested that people in the two municipalities shortlisted for a spent nuclear fuel repository have less precautionary attitudes to risk than the general population.[320] There is thus a danger that concerns about repository safety and impacts on future generations may be sidelined in communities which volunteer to host a repository, especially if they are economically dependent on the compensation, infrastructure or jobs offered to them.

A recent survey of public attitudes in Finland provides strong evidence that residents in the municipality of Eurajoki, where the Olkiluoto disposal site is to be situated, perceive a threat to the safety, health and well-being of future generations from the planned repository.[321] The site was shortlisted when the use of purely geological criteria had been abandoned, and was inserted onto a list of 101 potential sites as an 'exception', based on the short transport distance that would be required for the wastes already stored at the nearby nuclear reactors. The survey, based on 606 responses which qualified for analysis, found that 63% expected a positive effect on employment and economic development in the area, but that the facility was widely expected to have a harmful impact on rural non-farm livelihoods (fishing, hunting, forest product gathering etc.), the state of the environment near the facility and the image of the area (to outsiders). Nearly 60% of respondents agreed with the statement *"Nuclear waste poses a continuous threat to the lives of future generations"* and only 23% disagreed with it. A majority felt that the repository posed a threat to the safety of future generations (55%), the health of future generations (55%) and the well-being of future generations (52%).

The information provided by the survey is important because this is the first municipality in the world where the views of local residents have been able to be studied following a site selection decision for a deep underground repository for spent nuclear fuel. The survey suggests that, far from being convinced about the long-term safety of the proposed facility, residents have reservations and a high level of concern about future generations. However, these reservations have not led to the community vetoing the site, thanks to a package of economic benefits negotiated between the municipality and the nuclear industry in 1999–2000.[322]

This tension between long-term safety and short-term economic incentives has also been seen in the UK, where compensation is now being offered to communities that volunteer to host a repository. Selection of the Sellafield site in 1991 for a repository for long-lived intermediate-level waste involved a process which gave zero weighting to safety criteria on the grounds that all short-listed sites could meet regulatory requirements. However, the chosen site met none of the geological criteria or guidelines that had ever been developed to identify appropriate sites.[323] The rejection of planning permission for a Rock Characterisation Facility (the first phase of the planned repository) at this site in 1997 was the third time the then UK disposal company Nirex had its plans rejected.[324] A key issue at the inquiry was the site selection process and Nirex's failure to optimise radiological protection using best available techniques. The site was chosen for non-scientific reasons, in a decision-making process which concealed its true geological problems, leading geologists who gave evidence against the plans to conclude that the planning inspector's comprehensive dismissal of the site would make it hard to return to it.[325,326] Over a decade later, a new planning system has now been adopted to facilitate the construction of new nuclear reactors and the associated nuclear waste repositories.[327] New geological criteria which do not exclude the Sellafield area have been developed, despite continued concerns that the area is geologically unsuitable.[328,329] Volunteer communities are being sought for a repository, to receive high-level as well as intermediate-level wastes from past and current reprocessing, plus spent nuclear fuel from new nuclear reactors, and three communities near Sellafield have expressed an interest.[330,331] The new planning system thus appears designed to allow construction of a repository to proceed at or near the previously rejected site. It remains to be seen whether this process is successful at building public confidence.

In several countries, including Canada, the UK, Sweden and Finland, the difficulties of implementing deep disposal have been exacerbated by government decisions to build new nuclear reactors, threatening to create new wastes before a solution has been agreed or implemented for existing wastes. Rather than reiterating the conclusion of the 1976 Flowers report that new reactors should not be constructed in the absence of a safe means of containing the wastes, the UK Government has adopted an active programme of new reactor construction, claiming that there is now a consensus that deep geological disposal is safe. In a sign of tension, the UK Committee on Radioactive Waste Management has clearly stated that its conclusions and recommendations regarding deep disposal are intended to apply only to committed wastes, not to wastes generated by new nuclear power stations.[332] Issues include the ethical concerns associated with producing new wastes before a solution has been demonstrated, and the increased difficulty of finding a suitable volume of rock.

In Finland, where a new reactor is currently under construction, the nuclear waste company Posiva has rejected the proposal that it dispose of waste from the new reactor, which is owned and managed by a different company.[333] 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.[334]

Thus, in addition to the tension between the economic benefits being offered to host communities and long-term repository safety, there is a tension between endorsement of deep disposal as a potentially 'least bad' option for existing wastes, if the scientific and technical difficulties can be resolved at some point in the future, and nuclear industry claims that deep repositories provide a safe solution which will allow the 'sustainable' expansion of the industry.

Yet there is little public support for the idea that the problem of high-level nuclear waste has been dealt with in the sense that it can now be 'got rid of' safely. 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.[335] Of EU residents as a whole, 41% totally agreed that there is no safe way of getting rid of such waste, while under a third (31%) tended to agree. Only 14% disagreed and a similar percentage did not know or had no opinion on the issue. The idea that there is no safe way of getting rid of high-level waste had slightly more support in Finland in 2008 than in 2005, while Cypriot, Lithuanian, Hungarian, Latvian and Dutch respondents seemed to have become more convinced by the opposite statement, i.e. that there is a safe way of getting rid of it.

The 2008 Eurobarometer survey also found that public opinion was rather divided across the EU over deep underground disposal of high-level waste. In Finland, Sweden and Hungary this idea received more support than anywhere else in the 27-member EU. Majorities in Luxembourg and Belgium did not agree that deep underground disposal represents the most appropriate solution and the largest single response in France, Poland, Italy and Latvia was also disagreement. In some countries very high proportions of citizens answered that they did not know whether deep underground disposal is the best solution.

The respondents were asked which things would worry them the most if a disposal site for radioactive waste was built in the area where they live. The main issues of concern were the possible effects on the environment and health (51%) and the risk of radioactive leaks (30%). Of all those surveyed, eight out of ten responded that one of these two issues would worry them the most. EU residents would clearly want to be directly consulted and would like to participate in the decision-making process, should this hypothetical situation take place – well over half of respondents (56%) indicated that they would want to be personally involved. Just over one in five (22%) indicated that they would prefer local non-governmental organisations to participate in the decision-making process, while 15% felt that they would rather let the responsible authorities decide.

The IGDTP Vision Document states that it is essential to develop dialogue with the general public so as to share the extensive scientific and engineering work underpinning the conclusions made by the OECD NEA that geological disposal is technically feasible and *"provides a unique level and duration of protection"*. This issue is being dealt with in the Forum on Stakeholder Confidence in the Radioactive Waste Management Committee of the NEA[336].

This suggests that, rather than genuinely seeking to address scientific and technical concerns, the nuclear industry and advocates of new nuclear reactors, such as Euratom and the NEA, are actively engaged in a public relations exercise focused on the claim that no major issues remain to be resolved. One example of such advocacy is a web-based communication system funded by the Japan Nuclear Safety Organisation to seek 'social consensus' on high-level waste disposal.[337]

5.3. Costs

The global market for nuclear decommissioning and clean-up is estimated at £300 billion (€360 billion) over the next 30 years.[338] The costs of deep geological disposal are significant: for example, South Korea has estimated the cost of its proposed spent fuel repository as 2.6 billion euros.[339]

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. In South Korea, 14,210 canisters will be needed to dispose of spent fuel consisting of 36,000 tonnes of uranium from the two existing reactor types (11,375 pressurised water reactor (PWR) canisters and 2,835 CANDU canisters). As part of a cost-estimation exercise in Korea, the cost of a CANDU canister consisting of a 5cm copper outer shell with a cast iron insert was calculated at €171,415 and the cost of a PWR copper canister produced using the cheapest method at €156,776 (2006 prices). In these calculations, the material cost was about 43% of a canister's total manufacturing cost (the rest being mainly labour costs), and the manufacturing cost of the canisters represented about 32% of the total disposal costs.[340] South Korea accordingly plans to use a thinner (1cm rather than 5cm) copper canister to reduce costs;[341] however, this will impact on containment and hence on safety. There is uncertainty regarding the future costs of both the main materials needed to implement the Swedish deep disposal concept: copper powder for the canisters and bentonite for the backfill.[342]

The repository layout will also influence costs due to the cost of constructing and backfilling the tunnels and the costs of the bentonite needed for the disposal holes.[343] For example, placing several spent fuel canisters in long horizontal disposal drifts is cheaper than excavating individual vertical disposal holes accessed via tunnels. However, this option is more sensitive to the site geology because a single large fracture zone in a long disposal drift could destroy the whole drift.[344] The design of a repository in fractured rock may need to be optimised to minimise the number of locations where water-conducting fractures are intersected.[345]

Some of the concerns highlighted in the literature review above could be mitigated by changes to the repository design. However, major changes would have significant impacts on projected costs.

Examples of proposed changes identified in the literature search include:

- thicker copper canisters
- wider spacing between canisters (to reduce the adverse impacts of high temperatures on bentonite, or to seek to avoid water-conducting fracture zones)
- purer bentonite (to limit mineral changes with heat)
- increased excavation depth (to limit gas bubbles through higher pressure, increase groundwater flow return times, give greater protection from glaciation and reduce microbial activity).

All of the above would increase costs significantly. Increasing depth would also increase the risk of rock bursts (localised earthquakes) due to the high pressures at depth.

6. Conclusion

A scientific consensus on deep disposal?

The European Commission Joint Research Centre's report bases its claim that there is a scientific consensus on the deep disposal of high-level radioactive wastes on the existence of 'road maps' towards implementing this option in Finland and Sweden.[346]

The Implementing Geological Disposal of Radioactive Waste Technology Platform states that the recommendation of the OECD Nuclear Energy Agency's Radioactive Waste Management Committee is based on work over several decades by the international scientific and technical community in which alternatives such as launching nuclear waste into space, ocean dumping, disposal under continental glaciers, sub-seabed disposal and long-term supervised storage were carefully studied and discarded.[347]

However, the existence of road maps and the rejection of other options do not automatically mean that deep disposal of highly radioactive wastes is safe.

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

The following phenomena 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 and biomineralisation, could impair the ability of backfill material 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 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.
- Future glaciations 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.
- Earthquakes could damage containers, backfill and the rock.

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