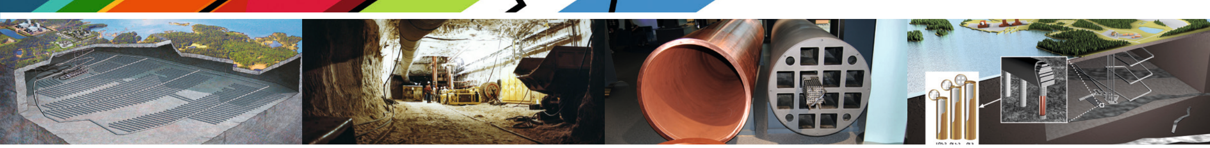
Radioactive Waste Management
2020

Management and Disposal of High-Level Radioactive Waste: Global Progress and Solutions



OECD
BETTER POLICIES FOR BETTER LIVES

NEA
NUCLEAR ENERGY AGENCY

Radioactive Waste Management
2020

Management and Disposal of High-Level Radioactive Waste: Global Progress and Solutions

© OECD 2020
NEA No. 7532

NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

The OECD is a unique forum where the governments of 37 democracies work together to address the economic, social and environmental challenges of globalisation. The OECD is also at the forefront of efforts to understand and to help governments respond to new developments and concerns, such as corporate governance, the information economy and the challenges of an ageing population. The Organisation provides a setting where governments can compare policy experiences, seek answers to common problems, identify good practice and work to co-ordinate domestic and international policies.

The OECD member countries are: Australia, Austria, Belgium, Canada, Chile, Colombia, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Latvia, Lithuania, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, Korea, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The European Commission takes part in the work of the OECD.

OECD Publishing disseminates widely the results of the Organisation's statistics gathering and research on economic, social and environmental issues, as well as the conventions, guidelines and standards agreed by its members.

This work is published on the responsibility of the Secretary-General of the OECD.

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1 February 1958. Current NEA membership consists of 33 countries: Argentina, Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Poland, Portugal, Korea, Romania, Russia, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The European Commission and the International Atomic Energy Agency also take part in the work of the Agency.

The mission of the NEA is:

– to assist its member countries in maintaining and further developing, through international cooperation, the scientific, technological and legal bases required for a safe, environmentally sound and economical use of nuclear energy for peaceful purposes;
– to provide authoritative assessments and to forge common understandings on key issues as input to government decisions on nuclear energy policy and to broader OECD analyses in areas such as energy and the sustainable development of low-carbon economies.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management and decommissioning, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

This document, as well as any [statistical] data and map included herein, are without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Corrigenda to OECD publications may be found online at: *www.oecd.org/publishing/corrigenda*.

© OECD 2020

You can copy, download or print OECD content for your own use, and you can include excerpts from OECD publications, databases and multimedia products in your own documents, presentations, blogs, websites and teaching materials, provided that suitable acknowledgement of the OECD as source and copyright owner is given. All requests for public or commercial use and translation rights should be submitted to *neapub@oecd-nea.org*. Requests for permission to photocopy portions of this material for public or commercial use shall be addressed directly to the Copyright Clearance Center (CCC) at *info@copyright.com* or the Centre français d'exploitation du droit de copie (CFC) *contact@cfcopies.com*.

Cover photos: Deep geological repository site in Oskarshamn, Sweden (Swedish Nuclear Fuel and Waste Management Company [SKB], Sweden); View of main drift looking north toward station at 2,150 foot level (Department of Energy, United States); Capsule for nuclear waste and the Onkalo spent nuclear fuel repository (Posiva, Finland).

Foreword

The Nuclear Energy Agency (NEA) assists its member countries in the development of safe, sustainable and societally acceptable strategies for the management of all types of radioactive waste. This waste includes the spent fuel considered as radioactive waste, the decommissioning of nuclear facilities and the management of legacy sites, facilities and waste. To this end, the NEA provides governments and stakeholders with authoritative, reliable information on the policy, strategic and regulatory aspects of the development of national programmes in these areas. This volume is the latest contribution to this effort.

Many NEA member countries are engaged in the development of deep geological repositories (DGRs) for the final disposal of spent nuclear fuel and high level radioactive waste. DGRs will be developed, implemented and operated over many decades and are sited and designed to isolate and contain radiological materials for hundreds of thousands of years. The scientific consensus today is that DGRs are a safe and effective approach to permanently disposing of spent nuclear fuel and high-level radioactive wastes. Such repositories are designed to be intrinsically safe and permanent and their safety does not rely on human maintenance or intervention. This document summarises the decades of worldwide analyses that confirm the challenge of high-level waste management and disposal is today well in hand.

Acknowledgments

This report was prepared by Timothy McCartin, an expert consultant to the NEA, with oversight and input provided by Rebecca Tadesse, Head of the NEA Division of Radioactive Waste Management and Decommissioning. In addition, the report was produced in co-ordination with the chair of the NEA Radioactive Waste Management Committee, Hiroyuki Umeki (NUMO, Japan), the International Atomic Energy Agency (IAEA), Sama Bilbao y León, Head of the NEA Division of Nuclear Energy Development and Economics, Jinfeng Li, NEA Radioactive Waste Management and Decommissioning Division, and Gabriella Palos, NEA Office of Policy and Co-ordination.

The NEA thanks the many individuals who contributed to the report by providing input and expert review.

Table of contents

Executive summary

Many countries around the world are currently operating or are considering building nuclear power plants. For some countries, nuclear energy is an important component of their strategies to address climate change while assuring access to cost-effective and reliable energy to support economic growth and human development. However, in some parts of the world there has been a debate about the "sustainability" of nuclear energy, and the long term management of spent nuclear fuel and high level waste (SNF/HLW) is a of particular importance in this context.

From the early days of commercial nuclear power some 70 years ago, the nuclear sector has responsibly addressed the entire life cycle of its materials and their impacts. This includes the use of advanced technology for waste management, operating under strict legislative frameworks. Some countries have applied, for several decades, the principle of a circular economy by recycling spent nuclear fuel (SNF) and minimising ultimate waste volumes. But in all cases, the final disposal of the high-level radioactive waste (HLW) has been a matter requiring attention.

Policy makers and scientists at the national and international level have fulfilled their responsibilities towards present and future generations by proposing, studying and implementing the safe disposal of SNF/HLW. Effective implementation of safe interim storage has granted experts the time necessary to develop robust technical solutions within a democratic and transparent decision-making process for the final management of SNF/HLW.

The scientific consensus today is that deep geological repositories (DGRs) are a safe and effective approach to permanently dispose of SNF/HLW. Independent national regulators, applying globally-accepted radiation protection standards, have endorsed their effectiveness to isolate SNF/HLW from humans and the environment.

The safety principles and technological solutions for the long-term management of SNF/HLW are now well established, and their requirements have been independently reviewed and determined acceptable by qualified international organisations. This has included consideration of a variety of options and the feasibility of their implementation.

The scientific and technological consensus on the safety of the deep geological disposal of SNF/HLW has been developed over more than half a century. The technologies involved have been carefully analysed thanks to one of the largest mobilisations of scientific and engineering communities worldwide ever undertaken. Underground research laboratories (URL) have been constructed and operated and in situ experiments performed and replicated in many locations. As a result, there is now a robust basis for the design and constructability of safe DGRs. The accumulated scientific results, technological evidence and safety demonstrations have been presented openly and critically reviewed by internationally recognised experts to reach the current level of maturity.

As a result, there is a science-based confidence today that removing SNF/HLW from the human environment through disposal in deep geological repositories is both safe and environmentally sound, and that the science and technology is well developed. But given that decisions concerning a deep geological repository are made today while engaging society for centuries, extensive dialogue with all stakeholders are indispensable.

Many countries are presently safely managing and storing SNF/HLW resulting from the generation of low-carbon nuclear electricity. Current disposal solutions for this waste are compliant with an extensive and strict set of laws and regulations overseen by independent authorities. Some countries are now moving forward towards the industrial deployment of final disposal. For example, in Finland after the 2016 decision to construct a deep geological repository, a DGR is now under construction with a 2023 expected commissioning date. In Sweden, the licence application for the construction of a deep geological repository was submitted in 2011 and a government decision is expected soon. In France, the choice of the deep geological repository as the reference solution for the long-term management of HLW was taken in 2006. DGRs are no longer a theory, they are a demonstrated, safe solution, now applied at an industrial scale in several countries. This experience paves the way for others to follow, benefitting from established experience.

The present report is a policy-level compendium of the current status of knowledge, technological developments, safety standards, rules and requirements applicable to evaluating the feasibility of DGRs. It summarises how the international scientific community has intensively collaborated to bring sound arguments and evidence into the debate that SNF/HLW will not cause harm to either humans or the environment. It also documents how deep geological repositories are moving forward in several countries after the case for their feasibility was accepted by scientific and regulatory authorities and other stakeholders -- including through public consultations. There is now confidence, based on science, in humankind's ability to safely manage and dispose of SNF/HLW. This confidence can only contribute to the overall sustainability of nuclear energy.

1. Introduction

Many countries are currently operating nuclear power plants or are considering using nuclear energy. For some stakeholders, nuclear energy is an important component to strategies to address climate change since it provides large amounts of dispatchable, affordable and carbon free energy. For others, nuclear technology raises questions, inter alia, related to the management of the high-level radioactive waste (HLW) and spent nuclear fuel (SNF) arising from the generation of electricity. To the degree that these questions appear unresolved, it generates debate about the long-term sustainability of nuclear energy as a contribution to a low carbon energy supply in numerous countries, while reducing greenhouse gas emissions is a worldwide priority.

The purpose of this document is to provide factual information regarding the long-term management of HLW and SNF. It is not written with a view as to what strategies countries should use to fulfil their future energy policies, but to show that long-term safe solutions are at hand and are being deployed on an industrial scale.

Nuclear energy leads to the production of small quantities of radioactive waste materials that require strict controls to safely manage their hazard to humans and the environment. These radioactive wastes are classified according to their level of radioactivity and their decay time or half-life. These two factors are used to determine the "level" of hazard from very low-level waste, through low-level waste, intermediate-level waste and on to high-level waste. In commercial nuclear energy, all SNF/HLW arises from the use of metal-clad ceramic fuel that is used in the reactor core of nuclear power plants. This fuel maintains its essential physical configuration, but once used in a reactor, becomes highly radioactive. While most of the radioactivity decays away after a few hundreds of years certain long-lived radionuclides will persist for thousands of years. SNF/HLW are safely managed in different nuclear facilities such as nuclear power plants, interim storage facilities, and reprocessing plants. For the longer term, final disposal in deep geological repositories (DGRs) is today recognised, after decades of research and demonstration in underground research laboratories (URLs), as the best solution.

The international scientific consensus that DGRs are the best technology for the disposal of these materials is based on a safety approach that differs from the safety approaches for other nuclear facilities. The difference in approach is due to the need to provide safety long after operations have ceased after all the waste has been emplaced and the facility closed (often referred to as the post-closure period). The post-closure period of DGR considers the hazards associated with the long-lived radionuclides that will persist for thousands of years. A DGR is designed to contain nuclear waste several hundred metres or more below the surface, in a stable geological site (such as granite clay or salt formations) that isolates the waste from the biosphere, thus preventing contact with humans and the environment. These facilities rely upon well-known natural laws and layers of defence-in-depth to maintain safety.

The document describes the worldwide consensus approach for the safe disposal of SNF and HLW in a DGR that has been cautiously developed and guided by decades of scientific investigation and analysis. As described herein, the robust safety approach for the DGR ensures that the risk to humans and the environment is extremely low.

2. Radiation protection and safety strategy

Storage and disposal facilities for SNF/HLW are designed and operated to: (1) comply with internationally approved and accepted radiation standards for the protection of humans and the environment and (2) implement safety strategies that utilise multiple safety functions or barriers as part of a defence-in-depth approach to ensure safety is maintained for expected and unexpected conditions for both the present and future times.

2.1 Radiation protection standards

The International Commission on Radiological Protection (ICRP), an independent non-governmental organisation created in 1928 to advance the science of radiological protection, is an advisory body that offers its recommendations to regulatory and advisory agencies, mainly by providing guidance on the fundamental principles on which appropriate radiological protection should be based.

The ICRP has issued recommendations specific to geological disposal. The most recent guidance with respect to geological disposal was provided in Publication 122 (ICRP, 2013, "Radiological Protection in Geological Disposal of Long-Lived Solid Radioactive Waste"). ICRP Publication 122 includes recommendations to address the long-term hazard such as:

- Continuing to rely on the basic principle that "individuals and populations in the future should be afforded at least the same level of protection as the current generation" (ICRP, 1998). In application of the optimisation principle, the radiological criterion for the design of a waste disposal facility recommended by the ICRP is an annual dose constraint for the population of 0.3 mSv per year for potential individuals living near the DGR (for comparison, the annual global average dose from natural background radiation is 2.4 mSv per year [UNSCEAR 2010]).
- Optimising protection (i.e. doing all that is reasonable to reduce radiation doses) has to be understood in the broadest sense as an iterative, systematic, and transparent evaluation of protective options, including best available techniques for engineering designs, for enhancing the safety functions of a DGR.
- Considering three main time frames: time of direct oversight, when the disposal facility is being operated and is under active supervision; time of indirect oversight, when the disposal facility is partly or fully sealed where indirect regulatory, administrative or societal oversight might continue; and even for times in the far future when the memory of the disposal facility might have been lost.

International organisations such as the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the World Health Organization (WHO), the International Atomic Energy Agency (IAEA), the OECD Nuclear Energy Agency (NEA) and the European Union (EU), as well as national authorities responsible for radiological protection, recognise and use the recommendations and principles issued by the ICRP as a key basis for the protection of individuals and the environment. All DGR programmes are consistent with the voluntary recommendations and principles of the independent ICRP.

For example, at EU level, the Euratom Waste Directive (Council Directive 2011/70/EURATOM of 19 July 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste) refers explicitly to the Euratom Basic Safety Standards for Radiation Protection (Council Directive 2013/59/EURATOM of 5 December 2013, which lays down basic safety standards for protection against the dangers arising from exposure to ionising radiation). The first Basic Safety Standard (BSS) Directive was adopted in 1959 to ensure the highest possible protection of workers and members of the public from exposure to ionising radiation. The Directive has subsequently been amended regularly, taking account of the latest scientific findings and recommendations. The most recent BSS Directive was adopted in 2014 and was transposed into EU member state national legislation by February 2018. The new Directive modernises and consolidates the European radiation protection legislation into one instrument, legally binding for all EU member states.

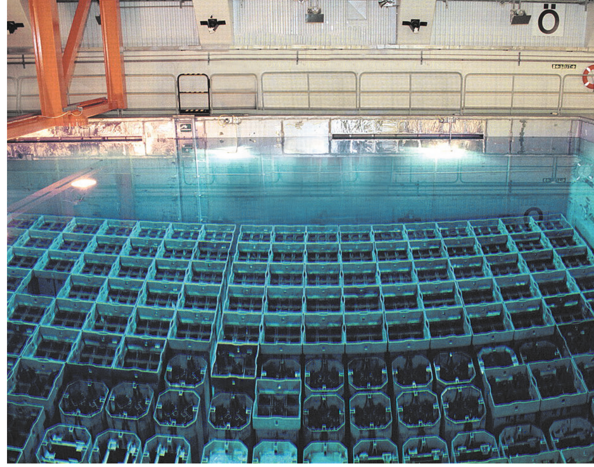
2.2 Safety strategy

The responsibility for safely managing the radioactive waste arising from the generation of electricity with nuclear energy is a key policy challenge for developers, industry, regulators, governments and international organisations, and governments. Scientific investigations and critical discussion regarding radioactive waste disposal have gone on for decades. Numerous studies and international meetings have occurred since the 1970s that have examined and evaluated approaches for the disposal of SNF/HLW. Although DGRs are being considered in different host rocks around the world, the overall strategy for safe disposal of SNF/HLW in a DGR is universally accepted for both the operational or pre-closure period (e.g. time of when waste is handled and emplaced in the DGR) and the post-closure period (i.e. time after all waste is emplaced and the DGR is sealed and closed). In 1995, the NEA Radioactive Waste Management Committee published its collective opinion entitled *The Environmental and Ethical Basis of Geological Disposal of Long-Lived Radioactive Wastes* (NEA, 1995).

At the EU level, the Euratom Waste Directive notes that:

> […] it is broadly accepted at the technical level that, at this time, deep geological disposal represents the safest and most sustainable option as the end point of the management of SNF/HLW considered as waste. Member States, while retaining responsibility for their respective policies in respect of the management of their spent fuel and low, intermediate or high-level radioactive waste, should include planning and implementation of disposal options in their national policies (EU, 2011).

Dry storage of spent fuel.
Nuclear Energy Institute (NEI), United States



Pool storage containers.
Swedish Nuclear Fuel (SKB), Sweden

2.2.1 Operational safety strategy

The operational period (sometimes referred to as the pre-closure period) begins when radioactive waste is received at the DGR and the potential for radiation exposures is present from operations (e.g. handling and emplacement activities). Operations at a DGR rely on many of the same well-established engineering designs and operating procedures used for ensuring safety at many other nuclear facilities in operation today that utilise a defence-in-depth approach that make use primarily of active safety systems (e.g. use of electrically powered filtration systems, operational procedures). Thus, handling and use radioactive materials at nuclear facilities minimise the time individuals are exposed to radioactive material, limit the release of radioactive materials, and use radiation monitors and alarms to prevent exposures. Nuclear facilities also prevent release of radioactive material to protect humans and the environment from radiation at operating facilities with engineering design and procedures such as maintenance programmes, monitoring and surveillance plans all subject to inspection and oversight by independent regulators.

Storage facilities for HLW involve activities and equipment that are similar and, in some cases, the same as is planned for a DGR (e.g. cranes for handling similar sized waste packages). Operational safety at a DGR can rely on the proven technology and procedures currently to maintain safety at storage facilities. IAEA estimates that there is an estimated 250 000 tons of spent fuel in storage worldwide and 120,000 tons of SNF has been reprocessed (IAEA, 2018). This number may sound imposing, but by industrial standards, it is actually quite small. For example, the United States has produced roughly 83 000 metrics tons of used fuel since the 1950s — all of which could fit on a single football field at a depth of less than 10 yards (DOE, 2020).

The storage options include wet storage in storage pools and dry storage in casks. The IAEA has characterised storage pools as a mature technology based on over 50 years of operating experience and dry cask storage systems as passive systems with over 30 years of operating experience (IAEA, 2013). The dry casks include specially designed canisters that are resistant to degradation mechanisms (such as exposure to heat and radiation). Storage facilities are designed to maintain safety in the event of a wide range of accident scenarios and handling activities for bare fuel (during loading of canisters). They utilise filtration systems to prevent any significant release of radioactive materials to protect humans and the environment from radiation. The decades long record for safely storing SNF has provided the time that has allowed the development of DGR programmes to proceed at a deliberative pace guided by the scientific information without the need rush to disposal.

The operational activities at a DGR present some specific concerns at an underground facility relative to surface-based facilities, as mining technologies and regulations must also be observed. Nevertheless, the operational phase of a DGR is fully adaptable within the current capabilities and practices of other nuclear facilities (especially storage facilities). These approaches ensure that safe distances are maintained between workers and radioactive materials; that release of radioactive materials to the environment are prevented; and that inspection, maintenance, and monitoring programmes are implemented throughout the operational period. Countries with large nuclear programmes have already accumulated a large experience base with operating facilities. Multinational co-operation and possible alliances with peer countries enables others to draw upon this experience.

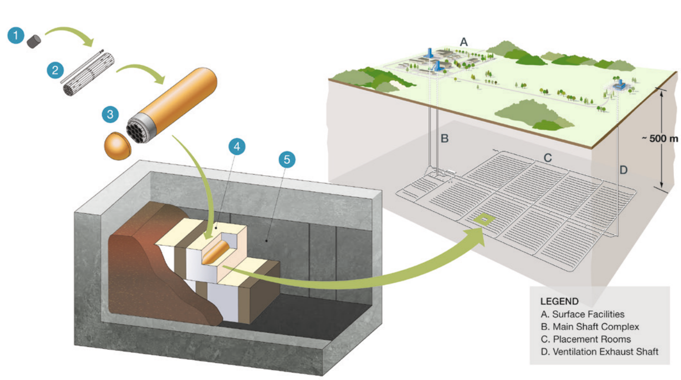
2.2.2 Post-closure safety strategy

The safety strategy for a DGR after closure offers different challenges from an operating facility. Operational safety strategies mainly rely on active safety systems (e.g. operating procedures, filtrations systems that rely on electrical power, inspection and maintenance programmes) that are based on a facility work force present during the tens of years to a century during the pre-closure period of the DGR. Post-closure safety considers very long time periods due to the persistence of high concentrations of long-lived radionuclides present in SNF/HLW. Thus, DGRs are designed to be passively safe – not reliant on active safety systems that would necessitate support from future generations (NEA, 2013a; IAEA, 2011).

The post-closure safety strategy for passive safety is one of "isolation and containment" of the waste. The DGR is located deep underground (e.g. hundreds of metres below the surface) to isolate waste far away from the environment and human activity. The DGR contains SNF/HLW in the repository with specifically designed engineered barriers (e.g. waste packages and engineered backfill materials) and siting the repository in a host rock with properties that inhibit and reduce the movement of radioactive

The five barriers to used nuclear fuel.

Nuclear Waste Management Organization (NWMO), Canada



materials and thus limit releases to the biosphere. The combination of characteristics of a good site and engineering design provides a DGR with properties such that the radioactivity decays away within the DGR underground environment. The DGR contains the SNF/HLW within the repository over a long time period through the properties of the host rock that provides a stable environment and which follows an evolution driven by well-known natural laws. This "passive safety" of the DGR make it possible to protect humans and environment in the very long term without requiring any maintenance or remedial action of future generations. Additionally, the presence of multiple safety functions increases the robustness of the DGR, its safety is not dependent on a single safety barrier (as prescribed by the principle of defence-in-depth).

Timeframes into the distant future cause all stakeholders to question the confidence in the safety case for a DGR. While it is difficult to guarantee the performance of a human construction for several hundred years, scientists agree that DGRs developed in suitable geological formations provide a stable and predictable environment over the very long timeframes associated with these geological formations that already span millions of years. The stability of geological formations for siting a DGR is based on a global geological understanding from active research in the earth sciences that supports stability for geological formations far beyond the time periods required for the long-term containment and isolation of SNF/HLW. The scientific evidence of the selected host rock makes it possible to demonstrate the post-closure safety of a DGR as the proven stability of the geological characteristics and environment provide the multiple safety functions of the DGR in a fully passive way, even should memory of the DGR be lost. Of course, this requires a cautious selection process for the DGR site.

2.3 Concluding statement on radiation protection and safety strategy

Recommendations and approaches for the protection against radiation, endorsed by the ICRP, have been developed over many decades making use of the evolving scientific knowledge. They are endorsed and applied by the EU, the IAEA, the NEA and in national nuclear programmes. As the concept of DGRs and temporary storage facilities have developed, these radiation protection standards have been used for their design, ensuring the protection of workers and populations. The safety strategy for DGRs has been developed over the past many decades both for the operational activities (e.g. storage and handling) and for the thousands of years in the post-closure period. A DGR isolates and contains the SNF/HLW over very long time periods through the combination of robust engineered barriers and properties of the host rock that provides a stable safe environment. The "passive safety features" of the DGR make it possible to protect humans and environment in the very long term without requiring any maintenance or remedial action of future generations. A DGR is comprised of multiple safety functions or barriers that increases the robustness of the facility such that safety is not dependent on a single barrier, which is consistent with a defence-in-depth safety principle, a usual practice in the nuclear field for ensuring safety.

3. Scientific consensus for DGR safety strategies

Decades of significant investigation and research have been dedicated to proving the viability of a DGR to isolate and contain SNF/HLW. The sustained and deliberative effort worldwide investigating the safety of DGRs has involved detailed national efforts as well as international collaborative initiatives. Today there is scientific consensus for the safety of a DGR designed and optimised with the characteristics of a well-chosen site. The results of the decades of investigation have come to fruition with suitable sites being identified in different rock types capable for demonstrating the safety of a DGR (e.g. granite, salt and clay).

3.1 Scientific collaboration and investigation

The safety strategy for a DGR relies on the performance of multiple safety functions or barriers to ensure the DGR provides long-term isolation and containment of SNF/HLW. In the 1980s, significant geological disposal field investigations began on the characteristics of host rock to act as a safety barrier and how engineered materials can provide additional safety benefits. The International Stripa project (1980-1992), carried out under the auspices of the NEA, focused on key aspects of a DGR, examining a variety of topics including natural barriers (e.g. flow and transport of radioactive materials in fractured rock, rock characterisation methods) and engineered barriers (e.g. buffer materials and grouts). The Stripa project was established in recognition of the need for a more comprehensive in situ research programme and because several countries were considering the possibility of crystalline rock for waste repositories an international effort was appropriate at the Stripa granite mine (NEA, 1993; page 21).

Research and collaborative projects continued to expand into the late 1990s and 2000s. The NEA, in collaboration with the European Commission, established the International Project entitled GEOTRAP that was devoted to approaches for acquiring field data, and testing and modelling flow and transport of radionuclides in geological formations in support of site characterisation and safety assessment of DGRs. The project held a number of structured workshops to address specific topics such as: roles of field tracer experiments in the prediction of radionuclide migration (NEA/EC, 1997); modelling the effects of spatial variability (NEA/EC, 1998); characterisation and representation of water-conducting features (NEA/EC, 1999); and confidence in the models of radionuclide transport for site-specific performance assessments (NEA/EC, 2001). Over 40 organisations including implementing waste management agencies (developers), nuclear regulatory authorities (regulators), nuclear research institutes, universities, scientific consulting companies, and the European Commission have been represented in the GEOTRAP Project.

Today URLs are utilised worldwide to test and evaluate a variety of aspects of a DGR, including both the safety functions and barriers of the DGR and approaches for the engineering design and operations of a DGR. Such facilities support detailed investigations of characteristics of host rocks being considered for DGRs as well as the potential in-drift processes that could impact waste package performance and radionuclide release (e.g. evaluation of thermal effects on coupled processes leading to geochemical-driven reactions, emplacement and performance of backfill materials). For example, URL investigations and studies include: radionuclide and gas migration experiments at HADES (Belgium) URL; studies of the self-sealing behaviour of a clay host rock in the excavation disturbed zone at HADES; changes in geochemical conditions in tunnel near-field environments at Mizunami and Horonobe URLs (Japan); comparison of tunnel mechanical excavation and blast excavation techniques at Äspö (Sweden), Tono (Japan) and Grimsel (Switzerland) URLs; development of geophysical methods for fracture detection at Tournemire (France) URL; heater tests at Stripa (Sweden), Yucca Mountain (United States), Waste Isolation Pilot Plant (WIPP) (United States), Asse (Germany), Mont Terri (Switzerland) and Grimsel URLs; thermal-mechanical-hydraulic tests at AECL (Canada) and Bure (France) URLs; full-scale engineered barriers experiments at Grimsel URL; materials interface interaction tests at the WIPP and Bure URLs; and radionuclide retardation and migration projects at Grimsel URL (NEA 2013b). URLs provide the required information at the depth of the DGR that supports the feasibility of the design and performance of the DGR. Additionally, the NEA has organised and continues to support multi-national collaborative groups for sharing and advancing understanding of technical topics of high interest to countries investigating specific geologic media. Examples include the Clay Club, Salt Club, and Crystalline Club.

Research continues in both generic materials processes and site-specific investigations relevant specific materials, designs, and host rock conditions. There exist a variety of waste forms (e.g. borosilicate glass, cement grout), waste package materials (carbon steel, stainless steel and cooper) and backfill materials (e.g. bentonite, bentonite and sand mixture) being considered for different host rocks (e.g. clay, granite, salt) (NEA, 2003). The extensive scientific information provides a wide range of options that are available for development of DGRs to enhance the compatibility of engineered barrier components and the host rock to optimise the safety functions (NDA, 2016). For example, the waste package and bentonite buffer design in the DGR in Finland results in minimal corrosion of the waste package over a one million year time frame in a granite host rock (Posiva 2018) and the waste package, backfill and the disposal cell design in the host clay rock in the French DGR results in minimal releases from the repository over a million year period (Andra, 2016).

Although the post-closure time periods of DGRs constitute a source of uncertainty, research on analogues in nature provide insights with respect to long time periods associated with geological processes (e.g. behaviour of uranium ore bodies). Natural analogues have been investigated to help understand the long-term behaviour of natural systems that goes far beyond the time scales of laboratory and field experiments. Analogues have been identified for both the engineered materials used in a DGR as well as the long-term movement of radionuclides. Analogue studies began in the 1980s (Chapman, 1984) and continue to provide valuable insights today (Milowdowski et al, 2015).

Analogue information, although not conclusive proof, does provide additional information on the suitability of materials and the identification of processes important to the safety of a DGR over very long time periods, thereby providing additional credibility to the performance of a DGR. For example, the Littleham Cove Natural Analogue Study demonstrates that copper metal buried in a compacted clay environment can remain stable and resist corrosion for longer than 170 million years; natural analogue studies on brine pockets in a wide range of salt deposits suggests a high degree of host rock stability (examples from Germany indicate little disturbance for up to 250 million years, despite repeated periods of glaciation in this period), and studies of basaltic glasses provide qualitative information on glass degradation processes (Milowdowski et al, 2015).

3.2 Suitable sites available for safe disposal

Following decades of scientific investigations sites in a variety of host rocks are being recommended as suitable for DGRs. Supported by site investigations and URLs sites are moving forward, for example:

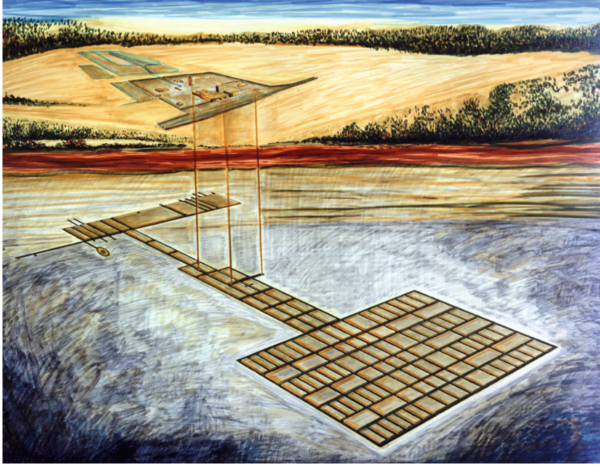
- **Granite host rock (Finland)**
  Finland's radioactive waste management organisation (Posiva) conducted an extensive site characterisation programme for over 20 years for the DGR at Olkiluoto that included an URL at Onkalo (Posiva 2012). A construction authorisation was approved for the Olkiluoto DGR on December 2015.

- **Granite host rock (Sweden)**
  Site investigations into the suitability of the bedrock in Sweden for a DGR began in the 1970s and the Swedish Nuclear Fuel and Waste Management Company (SKB) began siting investigations for priority siting alternatives in 2000. Investigations at the Äspö URL began in 1990. The site investigation of the Forsmark site commenced in 2002 and SKB submitted a licence application in 2011.

- **Clay host rock (France)**
  The French waste management organisation (Andra) has conducted extensive site investigations in the Meuse-Haute-Marne districts since the 1990s. In a first stage, a geological survey was carried out from the surface using geophysics and deep boreholes. Since 2000, Andra has constructed and operated an URL. A licence application for the DGR is expected to be submitted to the regulatory authority in 2021.

- **Clay host rock Research Facility (Belgium)**
  The HADES is the oldest URL in Europe built in a deep clay formation for the purpose of researching the possibility of geological disposal in clay. Located in the Boom Clay at a depth of 225 metres, plays a central role in research into the safety and feasibility of geological disposal of radioactive waste. Experts use it to develop and test industrial technologies for building, operating and closing a waste repository in deep clay. Scientists conduct large-scale experiments under realistic conditions in the deep clay formation over a long period of time to assess the safety of geological disposal in poorly indurated clay.

Underground shot of continuous mining machine.
Department of Energy, United States



The waste isolation pilot plant.
Department of Energy, United States

- **Salt host rock (United States)**
  The United States Department of Energy began exploratory drilling in 1975 as part of the characterisation programme for the Waste Isolation Pilot Plant (WIPP) site, which included geophysical logs, cores, geochemical sampling and testing, and hydrologic testing and analyses. The WIPP site is for deep geological disposal of transuranic radioactive waste. The WIPP was licenced for operation and received its first waste shipment in 1999.

Suitable sites are now being put forward for differing host rocks as part of a focused characterisation programme. As site selection and licensing continue to move forward it should be expected that increased information and lessons learnt obtained from these programmes will be used to inform DGR programmes that are not as far along in their process.

3.3 Management of uncertainty

The long timeframes associated with geological disposal raise questions with respect to the level of confidence and risk associated with the performance of the DGR to isolate and contain the SNF/HLW. As the 2012 NEA study *Methods for Safety Assessment of Geological Disposal Facilities for Radioactive Waste: Outcomes of the NEA MeSA Initiative* concluded:

> Uncertainties regarding a post-closure safety assessment are unavoidable due to the complexity of the phenomena of concern and the scales in time and space under consideration, and their management is central when developing a repository system and assessing its safety. These include uncertainty about whether all the relevant features, events and processes have been considered, uncertainty in their description and how they should be modelled, and uncertainty in the data that is needed in an analysis (NEA, 2012).

Significant effort has been undertaken to address and treat the uncertainties associated with DGRs. One important aspect of any assessment of the performance of a DGR is the identification of the relevant features, events and processes. The NEA developed and has maintained, since 1990, a Feature, Event, and Processes (FEP) Database that is available as an electronic tool to support national programmes for radioactive waste management in the identification, classification and screening of these elements. The FEP Database provides a comprehensive and maintained list of FEPs used to define relevant scenarios for the safety assessment of DGRs (NEA, 2000). Countries have also been evaluating uncertainties in models and parameters used to represent the behaviour of DGRs processes. For example, the international study of validation of geosphere transport models for performance assessment of nuclear waste disposal (INTRAVAL) was conducted to increase the understanding of mathematical models that describe various geophysical, hydrogeological and geochemical processes of importance in the safety assessment of nuclear waste repositories (NEA, 1997).

The scientific information developed the past five decades is used to support the consideration of uncertainty in the safety case for a DGR. The safety case provides a transparent and comprehensive evaluation of the impact of uncertainty on the performance of a DGR:

> The safety case is a basis for decision making and must be presented to the relevant decision makers for their consideration and review. The statement of confidence can make no presumptions about the confidence of the audience, which may include regulators, the general public or other stakeholders. The audience member will decide whether (s)he believes the reasoning presented is adequate and comprehensive, and whether (s)he shares the confidence of the author. The confidence of the audience in the findings of a safety case can, however, be promoted by presenting key arguments in a manner that is transparent and convincing, and by fully disclosing all relevant results, and subjecting them to QA and review procedures. At the later stages of a programme, and certainly by the time a safety case is presented as part of a licence application, uncertainties and open questions with a potential to undermine safety should have been addressed in a manner appropriate for the decision at hand, and this will be reflected in the statement of confidence. Uncertainties will inevitably remain (a host rock, for example, can never be fully characterised without, in the process, perturbing its favourable characteristics), but the safety case should indicate the reasons why these uncertainties do not undermine primary arguments for safety (NEA 2013a).

Another source of uncertainty is the possibility that far in the future there could be an inadvertent intrusion into a DGR (e.g. inadvertent drilling down to the depth of the repository). The impact of potential scenarios for an inadvertent intrusion are considered in the development of the safety case (NEA, 2004 and 2008a; ICRP, 1998). DGRs are sited in areas that lack natural resources so that exploratory drilling is unlikely and the potential for an inadvertent intrusion in minimised. Evaluation of hypothetical intrusion events in the safety case provides information that is used to evaluate the resilience of the DGR to such events and allow for the consideration of options to further reduce the probability for intrusion or to limit the potential consequences of the hypothetical intrusion.

The scientific information supporting geological disposal is available for examination and scrutiny by all stakeholders. DGR programmes have also allowed for peer reviews to be conducted to provide further assurance that uncertainty and performance of a DGR is subjected to broadest possible scrutiny (e.g. SKB, 2019; NEA, 2016; IAEA-OECD-NEA, 2002). The management of uncertainty is a key part of optimisation of the multiple safety functions that comprise the DGR design.

3.4 Concluding statement on the scientific consensus

Scientific consensus is not easily gained. Since the 1980s, scientific investigation into the feasibility of DGRs for the safe disposal of SNF/HLW has proceeded at a cautious and deliberative pace that has significantly expanded the volume (and quality) of scientific information and data regarding the safety of geological disposal. Consistent with the strategy for long-term safety research, investigations have been undertaken to evaluate the safety barriers of the DGR concept (e.g. waste package, backfill material, site characteristics). Dozens of underground research laboratories have been built to investigate and optimise the engineering of a DGR and to collect information to further advance the understanding of specific rock characteristics to isolate and contain waste and manage the uncertainties. All the scientific information has been made available to all as part of the open scientific dialogue that provides for constructive discussion and peer review to continuously advance understanding of the safety provided by a DGR. Today there is scientific consensus that DGRs provide the best solution for the disposal of HLW and SNF.

Uncertainties are associated with any complex endeavour. The possibility of finding suitable sites for a DGR is no longer a question – suitable sites have been identified in a variety of rock types. The geological stability of a good site provides the stable environment to optimise the performance of a DGR and allows for the evaluation and responsible management of the uncertainties such that safety of a DGR can be demonstrated and assured. There is scientific consensus that, based on demonstration in URLs, DGRs provide a safe disposal solution.

4. Established regulatory framework and national policy

The regulatory framework and national policies for DGRs have included commissions, public debates, citizen conferences, consultation processes, legislative frameworks, parliament sessions. It is essential to co-construct DGR projects by improving in parallel its technical design and its social acceptance alongside the strong scientific consensus. A DGR programme involves multidisciplinary scientific, technical, organisational and societal and governance issues. The strong regulatory frameworks and national policies in place worldwide ensures DGR programmes are completed within a consistent safety programme throughout their implementation.

4.1 Clear roles and responsibilities

The long time period needed to develop and operate a DGR (on the order of 100 years) requires clear roles and responsibilities be defined for all organisations and governmental bodies involved to ensure DGRs can be completed within a consistent safety programme. In particular, the European Nuclear Waste Directive 2011/70 / EURATOM establishes a community framework for the responsible and safe management of spent fuel and radioactive waste to avoid imposing undue burdens on future generations. It ensures that European Union member states make provisions for a high level of safety in spent fuel and radioactive waste management. This chain of responsibility defines and manages the requirements applicable to nuclear facilities that address all the elements important for the protection of humanity and the environment and makes clear the roles and requirements for the control procedures. The European Directive requires that member states report progress regularly (every 3 years) to the European Commission and at least every 10 years invite international peer review of their national framework, competent regulatory authority and/or national programme.

The IAEA Joint Convention on Spent Fuel and Radioactive Waste Safety and on the Safety of Radioactive Waste Management was signed by 83 countries is co-ordinated by the IAEA. This process provides for a report every three years on the implementation of each country’s obligations to safely manage radioactive waste. This reporting includes the activities and obligations of regulators and developers as required by national policies and regulations. It presents the latest developments in the fields of spent fuel management including the activities of the developer, the regulatory authority, and governments. Clear roles and responsibility are established to ensure the independence of safety decisions, monitoring and preservation of records continues during the long-term post-closure period, along with the transparency of safety decisions and stakeholder involvement.

DGR programmes are subject to an independent regulatory framework that performs independent safety reviews as well as oversight to ensure compliance with safety rules and procedures. Although individual countries use differing combinations of documents (e.g. regulations, guidance documents, government decrees and policy statements) to articulate how geological disposal of high-level radioactive waste will be developed in their country, the fundamental process for implementing DGR programmes is essentially the same (NEA, 2013a; IAEA, 2011; ANDRA, 2016; SKB, 2011b; STUK, 2013). At the EU level they are legally guided by the Euratom Waste Directive, to be enforced by all EU member states, under scrutiny by the Commission using the regular reporting obligation.

4.2 Stepwise approach that is reversible

The long development time for a DGR affords time for the collection and investigation of further information to enhance the knowledge of repository performance through a carefully planned programme of testing during the underground construction, emplacement of waste, and any subsequent observational period until the permanent closure of the repository. At each step, the information is evaluated to ensure the determination that a decision to continue to the next step is appropriately supported. Participants at an NEA workshop on the subject in 2004 concluded that:

> The uncertainties associated with the evolution of the disposal system must be appropriately considered and managed throughout a repository development programme. At each stage of a stepwise development programme, decisions should be based on appropriate levels of confidence about the achievability of long-term safety, with the current level of technical confidence established through uncertainty analysis (NEA, 2005).

The French repository programme has appropriately referred to this stepwise process as a continuous learning process that is used to continue investigations and data collection. This deliberative approach provides opportunity to increase confidence as the development of a repository proceeds that would include reversing decisions and changes to designs and plans as part of the development process (NEA, 1999; NaRC, 2003; IAEA, 2011).

Continual learning as part of a step-by-step process provides an ability to adapt the disposal process during its implementation stages such that flexibility to consider a full range of options to enhance safety, as appropriate and necessary, is considered and decisions can be reversed. The clear goal of reversibility is to ensure a full range of options are available to decision makers as information continues to be collected during the development of a geological repository.

The International Atomic Energy Agency's Specific Safety Requirements for Disposal of Radioactive Waste (IAEA No. SSR-5, 2011) states that:

> Disposal facilities for radioactive waste shall be developed, operated and closed in a series of steps. Each of these steps shall be supported, as necessary, by iterative evaluations of the site, of the options for design, construction, operation and management, and of the performance and safety of the disposal system (Requirement 11: Step-by-step development and evaluation of disposal facilities) (IAEA, 2011).

This principle of “continuous learning” is enshrined in the Euratom Waste Directive:

> Since the implementation and development of a disposal facility will take place over many decades, many programmes recognise the necessity of remaining flexible and adaptable, e.g. in order to incorporate new knowledge about site conditions or the possible evolution of the disposal system. The activities conducted under the Implementing Geological Disposal of Radioactive Waste Technology Platform (IGD-TP) could facilitate access to expertise and technology in this respect. To that end, reversibility and retrievability as operating and design criteria may be used to guide the technical development of a disposal system. However, those criteria should not be a substitute for a well-designed disposal facility that has a defensible basis for closure. A compromise is needed as the management of radioactive waste and spent fuel is based on state-of-the-art science and technology (EU, 2011).

4.3 Stakeholder confidence

Public acceptance of DGRs varies significantly around the world and among various stakeholders within individual countries. Over the past two decades, international groups have been devoted to evaluating and improving approaches for interacting with stakeholders, transparency of the safety case for DGRs, and exploring approaches for enhancing stakeholder involvement. A range of communication approaches (e.g. brochures, town hall meetings) have been utilised to improve communication of the information on DGRs to stakeholders and for stakeholders to express concerns and ask questions. The NEA Radioactive Waste Management Committee established the Forum on Stakeholder Confidence (FSC) in 2000 to foster learning about stakeholder dialogue and ways to develop shared confidence, informed consent and acceptance of radioactive waste management solutions. “The FSC experience suggests that, in addition to technical requirements, societal concerns about risk and safety need to be addressed in order for public trust and confidence to develop” (NEA 2015). In this regard the FSC has recommended that facilities should allow for community oversight and stewardship as a part of enhancing confidence in the DGR process. Countries are taking steps to enhance stakeholder involvement and participation (e.g. the Convention on Access to Information, Public Participation in Decision-Making and Access to Justice in Environmental Matters [Aarhus Convention]).

As an example, a step change was introduced in the management of the Euratom Research Programme in Radioactive Waste Management, when the European Joint Programme Project on Radioactive Waste Management (EURAD) became active in June 2019. This project involves all actors with an official role in their respective national research and development programme for radioactive waste management, along with representatives from the civil society. EURAD has developed a Strategic Research Agenda and a Roadmap to link its activities (as listed in the Strategic Research Agenda) to the typical milestones of the different phases of a radioactive waste management programme. The development of EURAD has a long history starting with the co-operation between Waste Management Organisations through the Implementing Geological Disposal –Technology Platform (IGD-TP), followed by similar co-operation between Technical Safety Organisations in the SITEX project. Both activities, which were originally supported with Euratom funding, are now continuing as self-sustained fora. Also, several research entities have set up EURADSCIENCE. IGD-TP, SITEX and developed their own strategic research agendas, all of which have been introduced into EURAD. Input has also been given by civil society groups.

Scientific openness and transparency are key for enhancing stakeholder confidence. Scientific information supporting geological disposal is openly available for examination. Decades of investigative studies and open debate into the performance of the safety functions of a DGR have led to an international consensus of the feasibility and safety for the DGR concept. At the same time, as is the case in other technological areas, consensus does not imply unanimity. The scientific community engaged in the study of DGRs is engaged in ongoing open and constructive discussions and peer reviews that challenge the status quo in an attempt to continuously advance the knowledge and understanding of the community as a whole. The transparency in the DGR programme provides for a more robust process both from the technical and societal point of view that has included commissions, public debates, citizen conferences, consultation process, legislative frameworks, parliament sessions. All these frameworks are essential to co-construct the project both by improving in parallel its design and its acceptance alongside the strong scientific consensus.

4.4 Concluding statement on the regulatory framework and national policy

Although strong scientific support for the safety of a DGR is the fundamental component absolutely necessary for moving forward in a disposal programme, it is not the only component needed for moving forward. A DGR programme involves multidisciplinary scientific, technical, organisational and societal and governance issues. To ensure development and implementation proceeds in a responsible and appropriate manner a clear regulatory framework and national policy is required. The long time period needed to develop and operate a DGR (in the order of 100 years) requires clear roles and responsibilities for all organisations and governmental bodies involved to ensure DGRs can be completed within a consistent safety programme. Decades of open investigative studies and debate regarding the safety of DGRs has served to strengthen the scientific consensus for DGRs that is transparent and available for examination by all stakeholders.

Although the different approaches are being used for implementing DGR programmes (e.g. enacting laws, regulatory requirements and guidance, recommendations), the principles and approaches to be used as part of a safe and responsible DGR programme are essentially the same in every national context. The regulatory framework and national policies, in place today, are essential to co-construct DGR projects by improving in parallel its technical design and its social acceptance in the midst of strong scientific consensus that further bolsters fulfilment for the safety of a DGR.

5. Implementation of DGRs – a long and cautious road

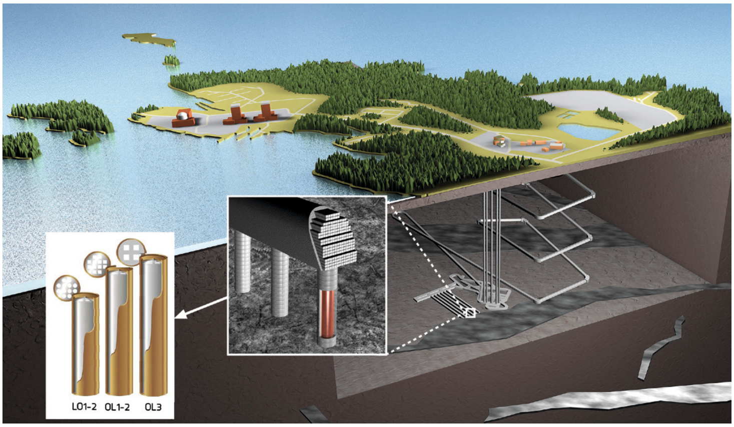
Following a long and cautious route, development of scientific consensus together with the enactment of strong regulatory framework and governmental policies has led to DGR programmes that are entering their industrial deployment, while being protective of current and future generations. Annex provides a timeline for DGR programmes in nine countries that are further along in the process of selecting a site, submitting an application, and starting the construction of a DGR.

The countries further along in the process have devoted approximately three decades for the investigation, collection and critical evaluation of the supporting information prior to the submission of an application. This time period is marked by a deliberative process that proceeded cautiously as guided by the available scientific information. Each country's process for DGRs involves an evaluation and debate of the supporting scientific information at key decisions points for moving forward. Below are descriptions of the cautious and transparent scientific processes that have been followed in Finland, France and Sweden.

5.1 Implementation in Finland (Olkiluoto)

Preparations for spent fuel disposal in Finland have progressed in accordance with the objectives set by the 1983 Government Decision. Since that time site investigations have been going on at Olkiluoto, including in situ investigations at the disposal depth at the Onkalo underground rock characterisation facility to confirm the suitability of the host rock for disposal. Knowledge of the site has increased significantly since the Decision-in-Principle stage. The current facility design (KBS-3H) has been developed jointly by SKB and Posiva since 2002. The construction of the disposal facility transportation and connecting tunnels was started in December 2016 after the Finish Nuclear Safety Regulator (STUK) had confirmed Posiva's readiness to start the construction of the underground disposal facility. The scope of the first excavation phase also includes the first central tunnel into the disposal area. The phased construction approach enables continuous improvement of the disposal technology during operation. The project aims to submit the operating licence application by the end of 2020.

STUK is committed to a transparent and open process and is responsible for communicating with the public and media on radiation and nuclear safety. STUK aims to communicate proactively, openly, promptly and clearly. A prerequisite for successful communication is that STUK is known by the media and the general public and that the information given by STUK is regarded as truthful. Communication is based on the best available information and to respond to the expectations of the public. STUK uses its website and social media platforms for two-way communication with the public.



The Onkalo spent nuclear fuel repository.

Posiva, Finland

The costs of the disposal of spent fuel are covered by funds collected in the Nuclear Waste Management Fund. In Finland, the producers of nuclear waste bear the full financial responsibility for their waste management costs. A funding system for the provisions of future costs arising from waste management and disposal as well as decommissioning exists to ensure that the costs can be covered even in case of the waste generators' inability to fulfil their obligations in the future.

Some of the key milestones in this period were:

- 1987 - Preliminary site characterisation began at five sites that included deep drilling, geological mapping, hydrogeological, hydro-geochemical and rock mechanical studies.
- 1992 - Detailed site characterisation programme began at four of the five sites and continued until 1999.
- 1999 - Posiva proposed to site a disposal facility at Olkiluoto. The application was reviewed from a safety viewpoint by STUK and accepted by the municipality of Eurajoki in January 2000.
- 2001 - A Decision-in-Principle was ratified by Parliament that authorised Posiva to continue the planned disposal project and also to construct an underground rock characterisation facility 'ONKALO' at the actual disposal depth.
- 2004 - The excavation of ONKALO began and an extensive program of site-specific characterisation, testing was launched during the construction phase, including demonstration tunnels for testing the emplacement technology.
- 2005 - Posiva developed a framework for the post-closure safety case (subsequently updated in 2008).
- 2012 - Posiva submitted the construction licence application.

- 2015 - STUK gave a positive safety statement supported with a safety evaluation concerning the construction licence application. In addition, STUK made a separate decision about the key safety documents, which were submitted to STUK for review together with the licence application. In these decisions STUK set requirements for Posiva that must be met during construction or in the operating licence application documentation. These requirements concern further work in the safety demonstration for reducing some of the uncertainties related to the project. Government granted the construction licence to Posiva in November 2015.
- 2016 - After several inspections, STUK approved Posiva's application to start the construction of the disposal facility.

5.2 Implementation in France (Cigéo)

In France, the development of the geological disposal project Cigéo has been carried out under the control of the French Parliament. It was launched by the first French radioactive waste Act in 1991 which included other options such as long-term storage and partitioning and transmutation. Scientific and technical investigations were conducted during a research phase from 1991 to 2005 including the construction of a URL. As research and development progressed in the URL towards increasingly large scales of investigation and the development of technological processes, the design of the Cigéo facility for the co-disposal of both HLW and intermediate-level wastes in the Callovo-Oxfordian clay layer has been developed since 2010. Safety options were delivered in 2016 to the French Nuclear Safety Authority (ASN) for review.

Since the 1991 Act transparency and the involvement of stakeholders in main decisions of the project has been considerably developed. A dedicated public debate took place in 2013, for which the High Committee for Transparency and Information on Nuclear Security issued a report on the transparency of the decision-making process. A set of open consultations with stakeholders have been regularly carried out to support the siting and design and will be part of the construction authorisation process. Cigéo's governance system is being developed to allow stakeholders to continue to be involved in decisions throughout the stepwise implementation and operation of Cigéo.

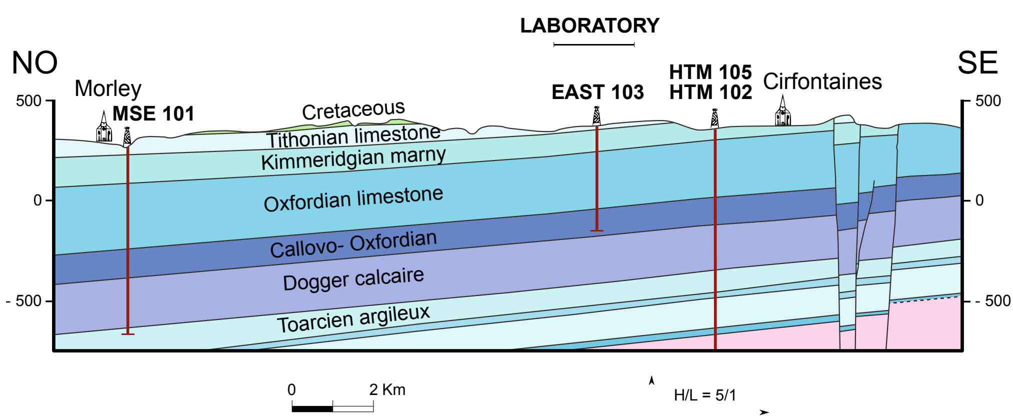
The implementation of a DGR programme requires significant resources. In France, financing of the management of radioactive materials and waste is provided by the nuclear licensees, under state oversight, in accordance with the "polluter-pays" principle (ASN 2018). A system to ring-fence the financing of long-term nuclear costs was thus set up in the 28 June 2006 Act incorporated in the Environment Code. The licensees are required to evaluate the long-term costs, including the cost of decommissioning and the cost of managing spent fuels and radioactive waste. They are required to cover these future costs as of now, by setting up dedicated assets offering a high degree of security. These operations are closely monitored by the State, through an administrative authority comprising the Ministers in charge of the economy and energy.

Some of the key milestones in this period were:

- 1993 - Geological characterisation campaign began at four sites based on voluntary applications from local authorities.

- 1998 - The government authorised the development of the Meuse/Haute-Marne Underground Research Laboratory in the Callovo-Oxfordian clay layer that provided an at-depth facility to continue to expand the ongoing scientific and engineering investigations.
- 2005 - Following 15 years of research, Andra produced the *Dossier 2005*, a feasibility study to demonstrate the existence of technical solutions for the creation of a safe reversible disposal facility – but did not commit to any particular solution as there was an acknowledgment that further optimisation could be done. The dossier went through a scientific and technical evaluation process, based on the general report of the National Assessment Board set up under the aegis of the 1991 Act, the opinion of the ASN and the report of the international expert reviews confirmed Andra's findings on the feasibility and safety of a deep geological disposal facility at the site studied in Meuse/Haute-Marne.
- 2010 - The government approved Andra's proposal for work in the host rock zone planned for the disposal facility based on the advice of the ASN, the National Review Board (CNE) and following consultation with elected officials and the Local Information and Oversight Committee (CLIS). This further geological exploration confirmed that the Callovo-Oxfordian formation in the zone exhibited characteristics favourable to the siting of a deep geological disposal facility.
- 2013 - From 15 May to 31 July 2013 and from 1 September to 15 December, a public debate on the Cigéo project was organised by the French National Public Debate Commission (CNDP). As project owner of Cigéo, Andra presented in particular the provisional inventory of waste to be disposed of, proposals for the siting of Cigéo facilities, a set of Andra proposals regarding reversibility, and the results of the conceptual design studies.

Geological section of the Bure sector.
GNU Free Documentation License



- 2014 - On 5 May, following the public debate on the Cigéo project, Andra's board decided that "Andra will submit a set of documents to the government consisting of a master plan for the operation of Cigéo, the Safety Options Report and the Retrievability Technical Options Report to prepare for the examination of the construction licence application for Cigéo".
- 2016 - Andra produced two safety option reports (Operations and Post-Closure) that presented the options for protecting human health and the environment during normal operations as well as in the event of incident or accident situations (Operations) as well as describing the post-closure objectives, principles and safety functions of Cigéo. The post-closure report highlighted how these objectives, principles and safety functions are taken into account in the project design and in the choice of site.

5.3 Implementation in Sweden (Forsmark)

The Nuclear Activities Act (1984) holds the licensee responsible for ensuring the safe management and final disposal of nuclear waste and spent nuclear fuel arising from the licenced nuclear activities. Development of the KBS-3 method for final disposal of spent nuclear fuel has been in progress since the late 1970s. The Swedish DGR programme has sustained a long and sustained effort that included extensive field investigations; development of the Äspö URL; public engagement; international co-operation (including collaborative efforts with Posiva on KBS-3H design since 2002) and development of the necessary safety case. Following an extensive research and development program SKB submitted its licence application in 2011. Sweden's Nuclear Safety Regulatory Authority (SSM) issued a positive finding for SKB's system for final disposal in 2018. The Court delivered its opinion on SKB's application in 2018 and was positive on the issues relating to the site, the rock, the buffer material and the environmental statement but called for more documentation on the copper canister. In 2019, SKB submitted further documentation on the copper canister to the government and before the government makes its decision on this matter the municipality will be consulted.

The ongoing licensing review for a spent fuel repository has benefited from the provisions for a transparent and predictable siting and licensing process, with active involvement of stakeholders since the early 1980s. Key contributing features include: (1) the nuclear industry's shared obligation for the development of waste management and disposal solutions, manifested in SKB's RD&D programmes and cost calculations, with associated regulatory reviews, public consultations and government authorisation; (2) the local communities' voluntary participation in the siting process and their right to veto a decision by the government to grant a licence; and (3) financing provided to stakeholders through the Nuclear Waste Fund, which has made it possible for local communities and environmental organisations to build their capacity to participate actively in formal consultations.

The financing system in Sweden was established in 1981 to secure financing for the nuclear licensees' future costs for the management and disposal of spent nuclear fuel and nuclear waste. The objective is to minimise the risk of the state and future generations being forced to bear costs considered to be the liability of the licensees. The licensees pay a fee to the Nuclear Waste Fund. SKB co-ordinates the nuclear power utilities' cost estimates and submits these to the Swedish National Debt Office (Riksgälden) every three years.

The National Debt Office reviews the cost estimates and calculates the fees and guarantees to be set individually for each utility. Based on the recommendations of the National Debt Office, the government sets the nuclear waste fees and guarantees for a period of up to three years.

Some of the key milestones in this period were:

- 1973 to 1985 - Studies conducted by the Geological Survey of Sweden showed that Sweden had favourable geological conditions for disposal.
- 1983 - The initial design document of the KBS-3 repository developed, the original basis for the current design. KBS (KärnBränsleSäkerhet = Nuclear Fuel Safety).
- 1985 - SKB initiated investigations for the hard rock laboratory on Äspö in Oskarshamn Municipality.
- 1993 - SKB began feasibility studies in eight municipalities concluding in 2000.
- 1995 - The government decision that the siting factors and criteria reported by SKB should serve as the point of departure for the continued siting work and that site-specific feasibility studies should be conducted on 5 to 10 sites and site investigations are to be conducted on at least two sites.
- 2001 - The government declared that the KBS-3 method would be the planning premise for the continued site investigations – based on the evaluation of alternatives presented by SKB.
- 2002 - SKB initiated consultations in the two municipalities being considered for the final repository. Approximately 60 consultations have occurred in different forms, including public meetings in each municipality and meetings with the Oskarshamn EIA Forum and the Forsmark Consultation and EIA Group. In conjunction with the public consultation meetings, written consultations have also been carried out. All consultations, whether in the form of meetings or correspondence, have been documented.
- 2006 - SR-Can, was published in preparation for SR-Site, the safety report that now serves as a basis for, and is attached to, the licence applications for licences to build and operate the final repository.
- 2009 - A systematic comparison of the conditions on the sites showed that all things considered, Forsmark is the site that offers the best prospects for achieving long-term safety. SKB therefore decided to prepare the licence application for DGR in Forsmark.
- 2011 - After 30 years of research and development SKB submitted the application for construction based on the KBS-3 design for the DGR at Forsmark.
- 2012 - A broad national consultation of SKB's licence application was conducted to offer a channel for various stakeholders and stakeholder organisations to bring forward concerns and views relevant to the licensing review. The review bodies included the concerned municipalities and county boards, environmental organisations and other non-governmental organisations, universities and other authorities. The NEA conducted a peer review at the request of the Swedish government.

5.4 Concluding statement on implementation status

Scientific information has grown significantly over the past decades as has the enactment and implementation of regulatory frameworks and national policies to ensure the development of safe DGRs. The demonstration phases in URLs bring the necessary confidence that DGRs are protective of people and the environment. The DGR is now a mature concept well endorsed by the scientific, institutional and industrial communities. Importantly, the DGR process is open and transparent to all stakeholders with resources for completion of the programme assured by governmental policies through payments by those that generate the waste. Thus, it is now the announced plan of several countries, mostly in Europe, to place DGRs into operation before the end of this decade with every expectation that these plans will be brought to realisation. Finland is anticipated to construct the first DGR. As progress continues with the successful implementation of DGRs around the world it can be expected that experience and knowledge will increase allowing development of DGRs in other countries potentially at a faster pace than experienced for these initial facilities (NEA 2019).

6. Conclusions

The nuclear industry is addressing the entire life cycle of the utilised nuclear material and governments have set precise legislative frameworks. This includes use of advanced technology for waste treatment and packaging, and minimising the amount of waste generated, which in some countries includes a circular economy by recycling spent fuel. Safety and ethical considerations for disposal of high-level waste (HLW) in a deep geological repository (DGR) have been debated in national legislatures as well as in international frameworks (EU, IAEA, NEA); at the state, provincial and local level; by individuals; in peer reviewed literature; and by scientific bodies that have resulted in the DGR now being the widely accepted approach to ensure the long-term protection of society in the future (NEA 2007). This wide acceptance has not come easily – it has evolved over decades of cautious, scientifically focused investigation that has been the subject of open debate in a process that adheres to a regulatory framework and national policy for ensuring compliance with radiation protection standards for current and future societies. In particular:

- Scientific consensus is built upon decades of dedicated and sustained investigation including significant investigation and demonstration at URLs. Throughout this time, the scientific community engaged in the study of DGRs has been engaged in ongoing, open and constructive discussions and peer reviews that challenge the status quo in an attempt to continuously advance the knowledge and understanding of the community as a whole.
- The properties of the host rock that provides a stable environment, which follows an evolution driven by well-known natural laws that ensure the “passive safety” of the DGR will be preserved over very long times such that maintenance or remedial action by future generations is not required. Natural analogues have been investigated to help understand the long-term behaviour of natural systems on geological time scales such as a million years.
- The safety strategy for a DGR includes multiple safety functions or barriers (i.e. defence-in-depth) approach for isolation and containment that ensures a more robust DGR design that is not dependent on a single barrier. Evaluation of hypothetical intrusion events in the safety case provides information that is used to evaluate the resilience of the DGR to such events and allow for the consideration of options to further reduce the probability for intrusion or to limit the potential consequences of the hypothetical intrusion.
- Continuous learning as part of a step-by-step process provides the disposal process with the ability to adapt during its implementation stages and the flexibility to consider a full range of options that optimise safety as part of an uncertainty management programme. Any decisions can be reversed within a stepwise approach that includes the ability to retrieve waste. The step-wise or phased approach has been adopted in every DGR programme.

- Transparency in the DGR programme provides for a more robust process both from the technical and societal point of view that has included commissions, public debates, citizen conferences, consultation process, legislative frameworks, and parliament sessions. All these frameworks are essential to co-construct the project both by improving in parallel its design and its acceptance alongside the strong scientific consensus.
- Clear and unambiguous regulatory frameworks and national policies, in place today, are essential to co-construct DGR projects. This includes necessary resources for completion of the programme are assured by governmental policies through payments by the waste generators.
- The countries further along in the process have devoted many decades to the investigation, collection and critical evaluation of the supporting information prior to the submission of a planning application to construct a DGR. These countries used underground research laboratories as key part of the scientific demonstration supporting DGR safety.

The long and cautious route to the submission of an application to construct a repository is proven to be a successful approach for the safe disposal of SNF/HLW. Several countries are now implementing the concept through mature projects where it is possible to demonstrate the high performance of DGRs with regards to protecting the environment and the humankind. In addition, it must be stressed that DGRs take all appropriate measures using well-established, state-of-the-art technology, as defined through international co-operation, and because assessment of the projects versus state-of-the-art is minutely carried out by the responsible regulatory authorities. It is now the announced plan of several countries, mostly in Europe, to place DGRs into operation before the end of this decade and there is every expectation that these plans will be brought to realisation. As progress continues with the successful implementation of DGRs around the world it can be expected that experience and knowledge will increase allowing development of DGRs in other countries potentially at a faster pace than experienced for these initial facilities.

7. References

Andra (2016), "Cigéo – Safety Options Report – Post-Closure Part" (DOS-AF), Andra, CG-TE-D-NTE-AMOA-SR2-0000-15-0062, Châtenay-Malabry.

Andra (2016), Cigéo – "Proposed Operations Master Plan (PDE)", Andra, CG-TE-D-NTE-AMOA-SDR-0000-15-0063, Châtenay-Malabry.

ASN (2018), "French National Plan", Autorité de sûreté nucléaire, Paris.

CEPN (2020), "Environmental Impacts Associated with Radioactive Waste Management: A Review of Standards and Practices According to the Do No Significant Harm Approach of the European Taxonomy", Report No. 326, Fontenay-Aux-Roses.

Chapman, N.A. (1984), "The Potential of Natural Analogues in Assessing Systems for Deep Disposal of High-level Radioactive Waste", KBS TR-16 (also EIR Bericht Nr. 545), Swedish Nuclear Fuel and Waste Management Company (SKB) and Swiss Cooperative for the Storage of Radioactive Waste (NAGRA), Stockholm.

DOE (2020), Five Fast Facts about Spent Nuclear Fuel, www.energy.gov/ne/articles/5-fast-factsabout-spent-nuclear-fuel (accessed 22 June, 2020).

EU (2011), Council Directive 2011/70/EURATOM, "Establishing a Community Framework for the Responsible and Safe Management of Spent Fuel and Radioactive Waste", Official Journal of the European Union. OJL 199, 2.8.2011, Brussels.

IAEA (2019), *Climate Change and the Role of Nuclear Power*, International Atomic Energy Agency, Vienna.

IAEA (2018), *Status and Trends in Spent Fuel and Radioactive Waste Management*, No. NW-T-1.14. International Atomic Energy Agency, Vienna.

IAEA (2017), *Nuclear Power for Sustainable Development*, International Atomic Energy Agency, Vienna.

IAEA (2013), *Spent Fuel Storage Operation – Lessons Learned*, IAEA TECDOC Series No. 1725, International Atomic Energy Agency, Vienna.

IAEA (2011), *Disposal of Radioactive Waste*, Specific Safety Requirements No. SSR-5. International Atomic Energy Agency, Vienna.

IAEA (2011a), *Geological Disposal Facilities for Radioactive Waste*, Specific Safety Guide No. SSG-14. International Atomic Energy Agency, Vienna.

IAEA-OECD/NEA (2002), *An International Peer Review of the Yucca Mountain Project TSPA-SR*, International Atomic Energy Agency, Vienna, and Nuclear Energy Agency, Organisation for Economic Co-operation and Development, Paris.

ICRP (2013), *Radiological Protection in Geological Disposal of Long-Lived Solid Radioactive Waste*, ICRP Publication 122. Ann. ICRP 42(3), Elsevier, Oxford.

ICRP (2007), *2007 Recommendations of the International Commission on Radiological Protection*, ICRP Publication 103, Ann. ICRP 37 (2–4), Elsevier, Oxford.

ICRP (1998), *Radiation Protection Recommendations as Applied to the Disposal of Long-lived Solid Radioactive Waste*, ICRP Publication 81. Ann. ICRP 28(4), Pergamon Press, Oxford.

ICRP (1991), *1990 Recommendations of the International Commission on Radiological Protection*, ICRP Publication 60, Ann. ICRP 21 (1–3), Pergamon Press, Oxford.

ICRP (1977), *Recommendations of the International Commission on Radiological Protection*, ICRP Publication 26, Ann. ICRP 1 (3), Pergamon Press, Oxford.

ICRP (1959), *Recommendations of the International Commission on Radiological Protection* (adopted September 9, 1958), ICRP Publication 1, Pergamon Press, London.

Milowdowski, A.E., W.R. Alexander, J.M. West et al. (2015), *A Catalogue of Analogues for Radioactive Waste Management*, Commissioned Report CR/15/106, British Geological Survey, Keyworth, Nottingham.

NaRC (2003), *One Step at a Time: The Staged Development of Geologic Repositories for High-Level Radioactive Waste*, National Research Council of the National Academies, Washington, D.C.

NaRC (1957), *Disposal of Radioactive Waste on Land*, National Research Council of the U.S. National Academy of Sciences, The National Academies Press, Washington, D.C., https://doi.org/10.17226/18527.

NDA (2016), *Geological Disposal Engineered Barrier System Status Report*, Nuclear Decommissioning Authority, NDA Report No. DSSC/452/01, Harwell.

NEA (2019), *International Roundtable on Final Disposal of High-Level Radioactive Waste and Spent Fuel: Summary Report Draft (Message for international co-operation from high-level government representatives*, NEA/RWM (2019)11/PROV, OECD Publishing, Paris.

NEA (2016), *Japan's Siting Process for the Geological Disposal of High-level Radioactive Waste, An International Peer Review*, NEA No. 7331, OECD Publishing, Paris.

NEA (2015), "The OECD Nuclear Energy Agency's Forum on Stakeholder Confidence, radioactive waste management public participation: A synthesis of its learnings and guiding principles", OECD Publishing, Paris.

NEA (2014), "Control, Oversight and Related Terms in the International Guidance on Geological Disposal of Radioactive Waste – Review of Definitions and Use", NEA/RWM/RF(2014)2, OECD Publishing, Paris.

NEA (2013a), "The Nature and Purpose of the Post-Closure Safety Cases for Geological Repositories", NEA/RWM/R(2013)1, OECD Publishing, Paris.

NEA (2013b), "Underground Research Laboratories (URL)", NEA/RWM/R(2013)2, OECD Publishing, Paris.

NEA (2012), "Methods for Safety Assessment of Geological Disposal Facilities for Radioactive Waste: Outcomes of the NEA MeSA Initiative", NEA No. 6923, OECD Publishing, Paris.

NEA (2011), "Reversibility and Retrievability (R&R) for the Deep Disposal of High-level Radioactive Waste and Spent Fuel; Final Report of the NEA R&R Project (2007-2011)", NEA/RWM/R(2011)4, OECD Publishing, Paris.

NEA (2008a), "Moving Forward with Geological Disposal of Radioactive Waste: A Collective Statement by the NEA Radioactive Waste Management Committee", OECD Publishing, Paris.

NEA (2008b), "Safety Cases for Deep Geological Disposal of Radioactive Waste: Where Do We Stand? Symposium Proceedings, 23-25 January 2007", OECD Publishing, Paris.

NEA (2007), *Regulating the Long-term Safety of Geological Disposal: Towards a Common Understanding and the Main Objectives and Bases of Safety Criteria*, OECD Publishing, Paris.

NEA (2005), "Management of Uncertainty in Safety Cases and the Role of Risk: Workshop Proceedings, Stockholm, Sweden 2-4 February 2004", OECD Publishing, Paris.

NEA (2004), *Post-Closure Safety Case for Geological Repositories, Nature and Purpose*, OECD Publishing, Paris.

NEA/EC (2003), *Engineered Barrier Systems and the Safety of Deep Geological Repositories: State-of-the Art Report*, OECD Publishing, Paris.

NEA/EC (2001), "Confidence in Models of Radionuclide Transport for Site-Specific Performance Assessment: Proceedings of the 4th GEOTRAP Workshop, Carlsbad, New Mexico, 14-18 June 1999", OECD Publishing, Paris.

NEA (2000), *Features, Events and Processes (FEPs) for Geological Disposal of Radioactive Wastes (An International Database)*, OECD Publishing, Paris.

NEA/EC (1999), "Water-Conducting Features in Radionuclide Migration: Proceedings of the 3rd GEOTRAP Workshop, Barcelona, Spain, 10-12 June 1998", OECD Publishing, Paris.

NEA (1999), "Confidence in the Long-term Safety of Deep Geological Repositories, Its Development and Communication", OECD Publishing, Paris.

NEA/EC (1998), "Modelling the Effects of Spatial Variability on Radionuclide Migration: Proceedings of the 2nd GEOTRAP Workshop", OECD Publishing, Paris.

NEA/EC (1997), "Field Tracer Experiments: Role in the Prediction of Radionuclide Migration, Proceedings of the 1st GEOTRAP Workshop, Cologne, Germany, 28-30 August 1996" , OECD Publishing, Paris.

NEA (1997), "The International INTRAVAL Project, Phase 2, Summary Report", Swedish Nuclear Power Inspectorate and OECD Nuclear Energy Agency, OECD Publishing, Paris.

NEA (1995), "The Environmental and Ethical Basis of Geological Disposal; A Collective Opinion of the NEA Radioactive Waste Management Committee", OECD Publishing, Paris.

POSIVA (2018), “Safety Evaluation for a KBS-3H Spent Nuclear Fuel Repository at Olkiluoto – Performance Assessment”, POSIVA 2016-02, Posiva Oy, Eurajoki, Finland.

POSIVA (2012), “Olkiluoto Site Description 2011”, POSIVA 2011-02, Posiva Oy, Eurajoki, Finland.

POSIVA (2007), “Safety Assessment for a KBS-3H Spent Nuclear Fuel Repository at Olkiluoto”, POSIVA 2007-09, Posiva Oy, Eurajoki, Finland.

SKB (1993), “OECD/NEA International Stripa Project 1980-1992 – Overview Volume 1 – Executive Summary”, Swedish Nuclear Fuel and Waste Management Company, Stockholm.

SKB (2019), “RD&D Programme 2019” (Programme for research, development and demonstration of methods for the management and disposal of nuclear waste), TR-19-24. Swedish Nuclear Fuel and Waste Management Company, Stockholm, Sweden.

SKB 2011(a), “Environmental Impact Statement (Interim Storage, encapsulation and final disposal of spent nuclear fuel)”, Swedish Nuclear Fuel and Waste Management Company (SKB), Stockholm, Sweden.

SKB 2011(b), “Application for Licence under the Nuclear Activities Act”, Swedish Nuclear Fuel and Waste Management Company (SKB). Stockholm, Sweden.

STUK (2013), “Disposal of Nuclear Waste: Guide YVL D.5”, Radiation and Nuclear Safety Authority (STUK), Helsinki, Finland.

UNSCEAR (2010), “Sources and Effects of Ionizing Radiation - Volume 1: Sources”, UNSCEAR Report, United Nations Scientific Committee on the Effects of Atomic Radiation, New York.

Annex

Timeline for countries further along in the DGR process

Country	Feasibility and Site Investigations Begin	Site Selected	Begin Construction of Underground Rock Laboratory	Application Submitted	Construction License Granted	Construction begin	Total years prior to application	Projected operational period
Finland	1983 [1]	2000 [1]	2004 [1]	2012 [1]	2015 [1]	2016 [1]	29	100 years [2]
France	1991 [3]	1998 [3]	2000 [3]	2021 (estimate)		2022 [3] (estimate)	30	100 years [3]
Sweden	1976 [4]	2009 [4]	1990 (Äspö) [5]	2011 [4]		Early 2020s (estimate)	34	45 years [4] (routine operation)
United States (Yucca)	1982 [6]	1987 [6]	1993 (Exploratory Studies Facility) [7]	2008 [6]		2048 [8] (estimate)	28	100 years or longer [9]
United States (WIPP)	1955 [10]	1974 [10]			1979 [10]	1981 [10]	24	35 years [10]
China	1985 [11]	2018 [11]	2020 [11]			2041 [11] (estimate)		
Canada	1978 [12]	2023 [13] (estimate)	1982 (AECL) [12]	2028 [13] (estimate)	2032 [13] (estimate)		50	40 years or more [14]
Germany	1965 [15]	2031 [16] (estimate)	1986 (Gorleben) [16]					
Switzerland	1978 [17]	2022 [18] (estimate)	1984 (Grimsel) [17] 1996 (Mont Terri) [17]	2024 [18] (estimate)	2031 [18] (estimate)		46	~30 years [18]
Japan	1976 [19]	2027 [15] (estimate)	2002 (Mizunami URL) [20] 2005 (Horonobe URL) [20]					~50 years [19]

References by Country

Finland

[1] Radiation and Nuclear Safety Authority (STUK). Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management: 6th Finnish National Report as referred to in Article 32 of the Convention (2017). https://www.iaea.org/sites/default/files/national_report_of_finland_for_the_6th_review_meeting_-_english.pdf

[2] Pirjo Hellä, Margit Snellman, Nuria Marcos, Barbara Pastina, Paul Smith, Kari Koskinen. TURVA-2012: Performance assessment. // The Safety Case for Deep Geological Disposal of Radioactive Waste: 2013 State of the Art. NEA/RWM/R(2013)9. https://www.oecd-nea.org/rwm/docs/2013/rwm-r2013-9.pdf

France

[3] French national radioactive waste management agency (Andra). Andra in Meuse & Haute-Marne. (2017). https://international.andra.fr/sites/international/files/2019-03/CMHM_2015_Version2017_EN_relu_planche_1.pdf

Sweden

[4] Svensk Kärnbränslehantering AB (SKB). Environmental Impact Statement. Interim storage, encapsulation and final disposal of spent nuclear fuel. March 2011. http://www.skb.com/wp-content/uploads/2016/03/21014-MKB-ENG-webb-150dpi.pdf

[5] Svensk Kärnbränslehantering AB (SKB). Äspö Hard Rock Laboratory Annual Report 2018. Technical Report TR-19-10. November 2019. https://www.skb.com/publication/2494274/TR-19-10.pdf

United States (Yucca Mountain)

[6] United States of America, Sixth National Report for the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, U.S. Department of Energy, In Cooperation with the U.S. Nuclear Regulatory Commission, U.S. Environmental Protection Agency, U.S. Department of State. (2017). https://www.iaea.org/sites/default/files/10-20-176thusnationalreportfinal.pdf

An application for a construction authorization for a geologic repository at Yucca Mountain, Nevada, for the disposal for spent fuel and HLW was filed before NRC by DOE in 2008; however, the adjudication on the application is suspended.

[7] Hemendra N. Kalia, James M. Replogle. Constructing the Exploratory Studies Facility at Yucca Mountain. 1996 Annual Conference of the Institute of Shaft Drilling Technology, May 1-3, 1996 in Las Vegas, NV. (1996) https://inis.iaea.org/collection/NCLCollectionStore/_Public/27/059/27059371.pdf?r=1

The underground Exploratory Studies Facility at Yucca Mountain in Nevada built by the Department of Energy to determine whether the location was suitable as a deep geological nuclear waste repository.

Courtesy of the Department of Energy, United States

[8] International Atomic Energy Agency, Status and trends in spent fuel and radioactive waste management, IAEA Nuclear Energy Series No. NW-T-1.14, IAEA, Vienna (2018). Supplementary files: National Profiles. United States of America. https://www.iaea.org/publications/11173/status-and-trends-in-spent-fuel-and-radioactive-waste-management?supplementary=44578

[9] U.S. Department of Energy. Yucca Mountain Repository License Application. General Information. DOE/RW-0573, Update No. 1 Docket No. 63–001. November 2008. https://www.nrc.gov/docs/ML0907/ML090700843.pdf

Nuclear Regulatory Commission (NRC), staff visit the proposed high-level waste repository site at Yucca Mountain, Nevada.

Creative Commons, Nuclear Regulatory Commission, United States

United States (WIPP)

[10] DGR Joint Review Panel International Visit Report Waste Isolation Pilot Plant (WIPP) – Carlsbad, New Mexico, November 14, 15, 2012. https://iaac-aeic.gc.ca/050/documents/p17520/88554E.pdf

China

[11] Ju Wang, Liang Chen, Rui Su, Xingguang Zhao. The Beishan underground research laboratory for geological disposal of high-level radioactive waste in China: Planning, site selection, site characterization and in situ tests. Journal of Rock Mechanics and Geotechnical Engineering. Journal of Rock Mechanics and Geotechnical Engineering. 10 (3): 411-435, 2018. https://doi.org/10.1016/j.jrmge.2018.03.002

Canada

[12] N.A. Chandler. Twenty years of Underground Research at Canada's URL. WM'03 Conference, February 23-27, 2003, Tucson AZ. (2003) https://xcdsystem.com/wmsym/archives//2003/pdfs/118.pdf

[13] Nuclear Waste Management Organization (NWMO). Implementing Adaptive Phased Management 2019 to 2023. March 2019. https://www.nwmo.ca/~/media/Site/Reports/2019/03/19/14/45/NWMO-201923-Implementation-Plan--EN.ashx?la=en

[14] Nuclear Waste Management Organization (NWMO). Description of a Deep Geological Repository and Centre of Expertise for Canada's Used Nuclear Fuel. (2015). https://www.nwmo.ca/~/media/Site/Files/PDFs/2015/11/12/08/10/2798_description_of_a_deep_geological_repository_and_ce.ashx?la=en

Germany

[15] Nuclear Energy Agency. Timing of High-level Waste Disposal. NEA No. 6244. (2008). https://www.oecd-nea.org/ndd/pubs/2008/6244-timing-waste-disposal.pdf

[16] Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety. Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, Report of the Federal Republic of Germany for the Sixth Review Meeting in May 2018. (2017). https://www.iaea.org/sites/default/files/jc6berichtdeutschlandenbf.pdf

Switzerland

[17] National Cooperative for the Disposal of Radioactive Waste (Nagra). Project Opalinus Clay. Safety Report. Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungsnachweis). Technical Report 02-05. December 2002. https://www.nagra.ch/data/documents/database/dokumente/$default/Default%20Folder/Publikationen/NTBs%202001-2010/e_ntb02-05.pdf

[18] National Cooperative for the Disposal of Radioactive Waste (Nagra). Annual Report 2018. (2019). https://www.nagra.ch/data/documents/database/dokumente/$default/Default%20Folder/Publikationen/Geschaeftsberichte/e_GB2018.pdf

Japan

[19] Nuclear Waste Management Organization of Japan(NUMO). Safety of the Geological Disposal Project 2010. Safe Geological Disposal Based on Reliable Technologies, English Summary. NUMO-TR-13-05. July 2013. https://www.numo.or.jp/technology/technical_report/pdf/TR-13-05.pdf

[15] Nuclear Energy Agency. Timing of High-level Waste Disposal. NEA No. 6244. (2008). https://www.oecd-nea.org/ndd/pubs/2008/6244-timing-waste-disposal.pdf

[20] Nuclear Energy Agency. Underground Research Laboratories (URL). NEA No. 78122. (2013). https://www.oecd-nea.org/rwm/reports/2013/78122-rwm-url-brochure.pdf

NEA publications and information

The full **catalogue of publications** is available online at www.oecd-nea.org/pub.

In addition to basic information on the Agency and its work programme, the **NEA website** offers free downloads of hundreds of technical and policy-oriented reports. The professional journal of the Agency, NEA News – featuring articles on the latest nuclear energy issues – is available online at www.oecd-nea.org/nea-news.

An **NEA monthly electronic bulletin** is also distributed free of charge to subscribers, providing updates of new results, events and publications. Sign up at www.oecd-nea.org/bulletin.

Visit us on **Facebook** at www.facebook.com/OECDNEA or follow us on **Twitter** @OECD_NEA.

OECD/NEA Publishing, 2 rue André-Pascal, 75775 PARIS CEDEX 16

Management and Disposal of High-Level Radioactive Waste: Global Progress and Solutions

Radioactive waste results from many different activities in health care, industry, research, and power production. All such waste must be managed safely, with the protection of human health and the environment as the highest priority. After decades of research, the international scientific community is now confident that placing high-level radioactive waste in deep geological repositories (DGRs) is both safe and effective.

The government of each country has the absolute right and responsibility to implement the energy and environmental policies it believes are best. In the case of the disposal of radioactive waste, it is paramount that these debates should be informed by objective facts. This report therefore aims to provide the general reader with the current state of knowledge with regards to the management of high-level radioactive waste in DGRs.

Nuclear Energy Agency (NEA)
46, quai Alphonse Le Gallo
92100 Boulogne-Billancourt, France
Tel.: +33 (0)1 73 21 28 19
nea@oecd-nea.org www.oecd-nea.org

NEA No. 7532