REPORT

IRSN
INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

Faire avancer la sûreté nucléaire

International panorama of research on alternatives to geological disposal of high-level waste and long-lived intermediate-level waste

IRSN Report/2019-00318

Report prepared in response to a request by the National Commission for Public Debate (CNDP)

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REPORT SUMMARY

Within the framework of the preparations for the public debate on the French National Plan for the Management of Radioactive Materials and Waste 2019-2021 (PNGMDR 2019-2021), the President of the National Commission for Public Debate (CNDP) asked the French Institute for Radiological Protection and Nuclear Safety (IRSN) to complete the project management report with an inventory, on an international level, of the research conducted on alternatives to the geological disposal of high-level (HLW) and intermediate-level long-lived waste (ILW-LL).

The literature review conducted by IRSN in response to this request was based on the use of freely available information published by international agencies (IAEA, OECD/NEA in particular) or national organizations, as well as in scientific journals. The resulting panorama identifies the main alternatives to geological disposal explored around the world, historically or currently, to ensure the long-term management of HLW and ILW-LL. It provides historical and scientific background to appreciate the context within which the various options emerged and were explored. It also identifies the concerns of technical and societal natures with which these options are associated, without however stating IRSN position with regard to their relevance or technical feasibility.

The panorama highlights the diversity of alternatives to geological disposal explored since the 1950s. These can be grouped into six major families: storage for centuries, partitioning-transmutation, borehole disposal, seabed disposal, launching into outer space, and disposal in polar ice sheets. The extent of the international work on each of these is highly variable. All of these have, however, been the subject of investigations carried out by official bodies, often involving several countries, as well as involving experimental devices and tests.

The technical difficulties of implementation, as well as the changing ethical considerations and their legal extrapolation led to the abandonment of several of the options considered historically. This was the case of seabed disposal, launching into outer space, and disposal in polar ice sheets, which are no longer the subject of studies and research.

Discussions and researches continue, however, on storage, partitioning-transmutation and borehole disposal. The status and nature of the work on these three alternatives differ greatly from one another. With regard to storage, which is generally perceived as a standby solution, the work is aimed at evaluating the possibilities of extending the lifetimes of the facilities and at reinforcing their robustness. With regard to partitioning-transmutation, the work covers a very broad field of scientific knowledge and combines developments in fundamental research and studies to establish the feasibility of deploying the technologies envisaged on an industrial scale. With regard to borehole disposal, studies are underway internationally, particularly in the United States. They deal in particular with the handling and transfer of waste from the surface to the containment area, as well as with the sealing of boreholes after the waste has been placed inside them.

Table of Contents

Table of illustrations

1 FOREWORD

This paper presents the results of the bibliographical review of the international panorama of research on alternatives to the geological disposal of high-level waste (HLW) and intermediate-level long-lived waste (ILW-LL) by the French Institute for Radiological Protection and Nuclear Safety (IRSN) in response to a request by the National Commission for Public Debate (CNDP) within the framework of the public debate organised on the occasion of the development of the 5th edition of the French National Plan for the Management of Radioactive Materials and Waste (PNGMDR 2019-2021).

In line with this request, this document is not intended to provide a critical analysis of the various technical options identified, or to provide IRSN's point of view as to their relevance or feasibility. It endeavours to report, as factually and objectively as possible, on the context and arguments that led to their study, the nature and progress of the research that has been devoted to them, and in some cases the reasons that led to their abandonment. The document thus provides keys to understand the potentialities of each of the identified alternatives.

Several of these alternatives have given rise to opinions by IRSN, which can be consulted on the institute's website (www.irsn.fr).

To complement these elements, the reader will also be able to refer to the results of the initiative "Clarification of Controversies"[1] organised by the Special Commission for Public Debate (CPDP) prior to the debate on the PNGMDR (see pngmdr.debatpublic.fr).

2 INTRODUCTION

On the occasion of the public debate organised prior to the development of the 5th edition of the French National Plan for the Management of Radioactive Materials and Waste (PNGMDR 2019-2021), the President of the CNDP asked IRSN, in a letter dated the 15th of February 2019 [1], to present two expert assessments aimed at completing the information of the project management report[2]. These expert assessments concern, on the one hand, the dry cask storage of spent uranium-oxide and plutonium-oxide (MOX) based, or enriched reprocessed uranium oxide (ERU) based, nuclear fuel and on the other hand, the state of the research on an international level on alternatives to the geological disposal of HLW/ILW-LL. This report is the response to the second part of the CNDP request. It presents an international panorama of the research on alternatives to deep geological disposal of HLW/ILW-LL.

In the request that she sent to IRSN, the President of the CNDP included the following reminder[3]:

"In the law of 2006, France decided to retain deep geological disposal as a reference solution for managing the most dangerous radioactive waste in the very long term (high-level and long-lived intermediate-level waste, or HLW/ILW-LL). This decision came after a process of evaluating several possible options. Three approaches defined by the 1991 law have been more specifically explored:

- *The search for solutions enabling the partitioning and transmutation of long-lived radioactive elements present in high-level waste;*
- *the study of the possibilities of reversible or irreversible containment in geological formations;*
- *the study of long-term packaging and surface storage processes for this waste.*

[1] The "controversy clarification" process was initiated by the CPDP before the public debate on the PNGMDR. It is aimed at providing members of the public who are not specialists, but are anxious to obtain good technical information to understand the various arguments expressed by experts or institutional bodies on issues covered by this plan. The following institutions, companies or associations took part in this process: Andra, IRSN, EDF, Orano, CEA, Wise Paris, Global Chance, France Nature Environment (FNE), and Cruas CLI.

[2] The project management comprises the French Directorate-General for Energy and Climate (DGEC), on behalf of the French Ministry for the Ecological and Solidary Transition, and the French Nuclear Safety Authority (ASN).

[3] Ed. note : non-official translation.

The results obtained for these three approaches and the criteria for selecting the choice set forth in the law of 2006 are presented in the project management report for the public debate on the French National Plan for the Management of Radioactive Materials and Waste.

The project management report also includes a reminder that deep geological disposal presents exceptional challenges due to its deployment duration, which spans more than a century, and that it must therefore be designed to integrate technological advances and to meet the expectations of civil society throughout its lifetime.

In order to meet these challenges, the legislature established a principle of containment reversibility for a period of at least one hundred years. Retrievability is one of the ways envisaged for the application of this principle. It offers future generations the opportunity to reconsider the choice of deep geological disposal as a radioactive waste management method, by making it possible to retrieve packages of waste already disposed of and to implement a possible alternative solution. "

The President of the CNDP said that the panorama of alternatives should enable the information contained in the project management report to be completed by providing a summary description of the main options that have been explored in the past on an international level, as well as the state of the research currently underway worldwide for developing alternative management solutions to deep geological disposal.

In order to respond to the CNDP's request, IRSN has carried out a thorough literature review, although it does not claim to be exhaustive. Publications produced by the International Atomic Energy Agency (IAEA) and the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (OECD/NEA) constitute one of the important sources of information used. The national reports prepared by the contracting parties of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management within the context of periodic reviews organised under the aegis of IAEA have been particularly helpful to find out the management options currently in use or envisaged. Further research was conducted to reconstruct the history of the discussions. The documents published by the national agencies of the main countries with nuclear industry have been favoured for this purpose. Scientific publications presenting academic research and publications by non-governmental organisations were also taken into account if they made it possible to complete or widen the panorama. All of the information sources used are public; most of them are available directly on the websites of the organisations that produced them.

Several major families of alternatives are presented in the document. The first, which is the subject of Chapter 3, concerns the storage of waste. Different variants are mentioned. All can be considered as standby solutions requiring human intervention. Some, however, tend to move closer to geological disposal by incorporating "passive safety" provisions (that is, not requiring human action) and seeking to enhance the level of protection against natural hazards and certain risk situations. Chapter 4 is devoted to partitioning and transmutation options. It summarises the research undertaken to modify the characteristics of waste and reduce its harmfulness or life span. Chapters 5 and 6 present, respectively, the deep borehole and sub-seabed disposal options. Chapter 7 is devoted to the two other options identified through the bibliographical study: the launching of waste into outer space or its disposal in polar ice sheets. The use of desert areas or volcanoes has also been suggested by scientists, particularly in France. In the absence of substantial documentation to support them, the corresponding solutions were however considered to be too anecdotal to merit specific development. Ceasing to produce radioactive waste, sometimes cited as an alternative, is also not covered by the panorama proposed since it does not, strictly speaking, constitute an alternative to geological disposal for waste that has already been produced.

In each of the chapters, the main principles are successively presented, together with the history of the research carried out worldwide and the current state of the art, including, where applicable, current research underway and, finally, the work and discussions more specifically conducted in France in connection with each of the options considered. Although the panorama proposed focuses on HLW/ILW-LLW and spent fuel (SF) management options, since the latter are considered as waste, the management of other types of waste is mentioned in some cases for illustration purposes.

The level of detail and the amount of information may vary significantly from one chapter to another. This disparity reflects, in part, the inhomogeneity of the documentation collected, but also and especially the very different degrees of maturity that each of the alternatives has reached.

3 STORAGE

3.1 What does it involve?

In nuclear terminology, the storage of radioactive waste means "*the operation of temporarily placing* [waste] *in a facility specially designed on the surface or near-surface for this purpose*." According to this definition included in the Environmental Code[4], storage is distinct from disposal because it constitutes a **temporary management solution** (as opposed to disposal, which is considered as a definitive solution): After a given period, the radioactive waste placed in a storage facility is intended to be removed and the facility dismantled.

The previous distinction between storage and disposal induces practical differences in the design of these two types of facilities and in defining the requirements that are applicable to them in terms of safety. Unlike other solutions discussed in this report, storage is a "conventional" nuclear facility. Its safety is based on both technical devices and organisational provisions, intended to keep the facility in a safe state, to prevent possible incidents and to control the consequences of accidents. Storage thus falls under a so-called "**active safety**" principle, that is to say, requiring human intervention (maintenance, monitoring) to ensure its proper operation, while disposal is based on a passive safety device after its closure. This notion of passive safety is also an expectation for the alternative solutions mentioned in the other chapters of this report.

Based on the above definitions, storage is not, strictly speaking, an alternative to geological disposal as a definitive management solution for HLW/ILW-LL, since it implies an intent to remove waste again. Many countries that have retained geological disposal as the reference solution for the management of their HLW/ILW-LL, thus resort to storage facilities for the duration needed to develop their disposal project. In other cases, opting for storage can be a deliberate alternative to creating a disposal solution by allowing the choice of a definitive solution to be postponed. Storage therefore responds to the desire to give future generations the time and opportunity to opt for solutions other than those currently available.

Many storage facilities already exist, or are planned, or have been studied, around the world. They are intended to accommodate radioactive waste of all categories, and are usually located on the surface but may in some cases be built underground. Some, which can be qualified as "**conventional**", are authorised to operate for periods **on the order of a few decades**. Their safety is based on maintenance and active monitoring. Their useful life and their degree of robustness[5] and passivity can, nevertheless, vary according to design choices.

The remainder of this chapter is not intended to cover the diversity of existing or studied facilities, but rather, it specifically addresses the case of those whose purpose is to extend the duration of the storage period beyond the time

[4] Article L. 542-1-1 of the Environmental Code.

[5] For a nuclear facility, robustness refers to the ability to withstand various types of aggression and events.

that would be needed to develop a geological disposal solution. Thus, so-called "**long-term storage**" (LTS) and "**permanent storage**" are distinguished.

An LTS facility refers to storage facility, either on the surface or underground, whose lifespan is longer than that of conventional storage facilities and can last up to **a few hundred years**.

The concept of "**permanent storage**" refers to storage times greater than a few hundred years. Two methods can be distinguished to try to achieve these lifetimes:

- The successive use of **conventional storage** facilities. The construction of a new facility and repackaging of the waste are then required, with a frequency on the order of a hundred years;
- The use of a **facility** likely to remain intact over very long periods, up to tens of thousands of years. This type of surface (or near-surface) structure is sometimes called a "**monolith**" or "**mausoleum**". The need for maintenance and monitoring leads to the principle of "guardianship", according to which it is up to successive generations to monitor and supervise waste.

A last variant that can be likened to an alternative to disposal consists in using an underground storage facility designed to be eventually **converted into a geological disposal solution**. Although its intention is different, this solution is similar to the principle of reversible geological disposal.

3.2 Ways explored around the world

Several countries, such as the **United Kingdom**, **Switzerland** and **Canada** studied LTS facilities as a possible long-term surface management option for high-level waste until the mid-2000s [2][3][4][5].

In the **United Kingdom**, the expert panel before the authorities, the *Committee on Radioactive Waste Management,* or CoRWM, drew up in 2004 a list of around 15 options for radioactive waste management [2]. After applying a series of criteria, including the feasibility of the solution, the impact on the environment, the burden for future generations, safety and health, the choice was restricted to various disposal options (geological or in boreholes) and LTS options (either centralised or not, and either on the surface or underground). These different options were then ranked by combining a set of additional criteria that included the expectations of civil society. At the end of this work, the CoRWM proposed that geological disposal be favoured for the long-term management of the aforementioned waste [3].

Since the 1970s, in **Switzerland**, the national program developed by the Swiss agency in charge of waste management, Nagra, was aimed at creating geological repositories for all types of waste. In 1997, following a public referendum held in the Canton of Nidwalden, it was decided to suspend the low and intermediate level waste disposal project planned for the Wellenberg area. In response to this situation, the Canton of Nidwalden and the federal government set up several work groups. In 1998, the work of these groups resulted, among other conclusions, in the recommendation to develop a management solution that would allow the geological disposal options promoted by nuclear power plant operators to be combined with the concept of active monitoring of a permanent storage facility defended by environmental protection organisations [6]. The expert group for radioactive waste management, EKRA, was set up in June 1999 to take on this task. At the end of its work, EKRA recommended that long-term storage options be excluded due to the lack of guarantee, over the periods considered, of the integrity of the facility and the uncertainties regarding social changes [4][7].

In **Canada**, the Nuclear Waste Management Organisation (NWMO) was established in 2002 to study three options for the long-term management of spent fuel and then to implement the option ultimately selected: geological disposal, storage on reactor sites, and centralised storage (deep or surface). For the last two options, the complete renovation or replacement of facilities is considered to be necessary every 100 to 300 years. Research and public consultation on these options led the NWMO to propose a fourth "Adaptive Phased Management" (APM) option. This integrates the advantages of the three initial options, while striving to avoid their drawbacks [5]. The drawbacks pointed out by the NWMO are, for the storage an indefinite monitoring, replacement and renovation activity cycle, and for the public lack of decision and transfer of responsibility to future generations. Geological disposal, for its part, requires further research and is associated in the public mind with notions of permanence and irretrievability. APM comprises three successive phases. During a first phase of approximately 30 years, the waste is stored on the reactor site and a site research program including the construction of an underground laboratory is implemented in order to decide whether or not to build a centralised underground storage facility at shallow depth. During the second phase, consisting in the centralised storage or on-site storage of spent fuel, also planned over a thirty-year period, the desirability of constructing a geological repository is planned, based on the site analysis results obtained by the underground laboratory. This APM principle, the last phase of which may consist in constructing the geological repository itself, was accepted by the Canadian safety authority CNSC in 2007 [8].

Finally, it should be mentioned that **Finland** [9] and **Sweden** [10] have examined situations (called "zero-option") that could lead to a lack of decision with regard to the creation of a geological repository. The challenge of this exercise was not to identify the causes of such situations, but rather to assess the resulting safety implications for existing spent fuel storage facilities, which would become *de facto* LTS facilities, or even permanent storage facilities. The assessments concluded that it would still be possible to operate these facilities safely provided that the storages were constantly maintained. In particular, with regard to the Oskarshamm underground underwater storage facility in Sweden (CLAB: Figure 1), the findings indicate that maintaining the structures and infrastructure for up to 200 years would require the reinforcement of the rock support. These conclusions also hold the possibility of maintaining the integrity of the spent fuel over a long period provided that it remains under water, while underlining that it does not appear possible to ensure this beyond 100 years based on the experience and R&D available to date. Lastly, the assessments established that the abandonment of the storage facility before the age of 250 years, which is a period of high heat release by the spent fuel, would notably have significant consequences for the environment due to the evaporation of the pool water [10].

The concept of monolithic or "mausoleum" storage systems was also raised in the late 1980s [12], as an alternative to the principle of definitive geological disposal (e.g., [13]). These facilities are inspired on the Egyptian pyramids. They are imagined as being massive, resistant to alterations due to natural phenomena (hydro-meteorological in particular) and to intrusion, to the point of being able to remain passively intact for tens of thousands of years. The waste would be deposited within them in a form that would limit the risk of dispersion of their contents. Marking intended to warn future generations of danger is also envisaged. The principle of such facilities was examined in the **United Kingdom.** In 2002, Nirex pointed out that the implementation of this solution would require research, particularly on packaging that would allow the waste to maintain its integrity over very long periods of time, as well as on the architecture of such facilities, in order to allow extensive package monitoring and retrievability compatible with the need to isolate waste and deter human intrusion [14]. A comparison by multi-criteria analysis of the advantages and disadvantages of different forms of storage and disposal facilities, led the group of experts advising the UK authorities, the CoRWM, to recommend the abandonment of the monolithic storage option in 2006 [3]. The documentary research carried out to produce this panorama suggests that this concept is currently not being used or studied in any country.

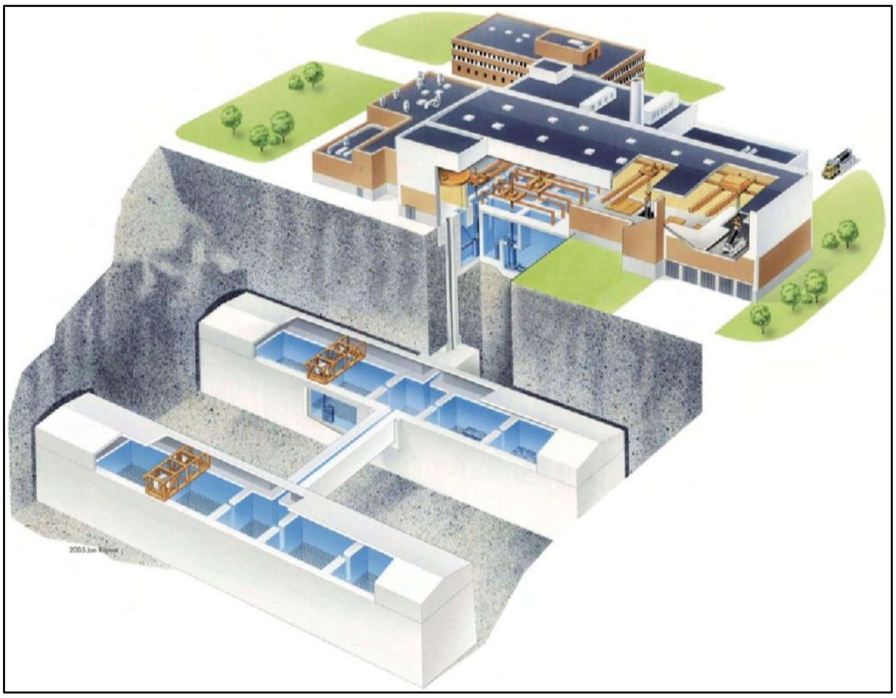

***Figure 1**: The Swedish underground storage facility CLAB (about 30 m deep) for spent fuel in water [11].*

3.3 State of the art and perspectives

Today, without excluding the option of geological disposal, several countries are planning to implement LTS, or even permanent storage, pending better visibility on the future of nuclear energy or on the development of treatment techniques to reduce the harmfulness of waste and modify the constraints associated with its long-term management:

- The **Netherlands** are not considering the commissioning of a deep geological repository before 2130 [15]. This is conditional on the emergence of a regional project associating several radioactive waste producing countries, or the cumulative production of a quantity of waste sufficient to justify, from an economic point of view, the implementation of a national geological repository. In the meantime, the Dutch waste management policy provides for the surface storage of all radioactive waste in structures designed to: i) resist the most extreme external aggression, ii) operate in the most passive way possible, and (iii) allow the retrieval of packages for a period of at least one hundred years. Long-term storage requirements were considered in the design of the facilities: the capacities of the storage sites are sized to receive the estimated waste production of the next hundred years [16];
- The **United Kingdom** relaunched in 2014 a site search process to implement one or more geological repositories. This is based on the principle of voluntary participation of potential host communities [17]. In 2015, following a public consultation, **Wales** agreed to enter this process. **Scotland,** for its part, chose to remain out of it and considers that waste should be managed in near-surface facilities, located as close as possible to the site where the waste is produced. The Scottish program, established to last beyond 2070, provides for the construction of successive generations of near-surface storage facilities [18];
- **Italy** does not envisage geological disposal for intermediate and high-level waste, but is currently seeking a site for long term storage, without specifying the duration [19];

- In the United States, the storage of spent fuel on the reactor site where they are produced is considered a standby solution until a repository is available. Since the Yucca Mountain disposal project was suspended in 2010, three scenarios are being considered by the US *Nuclear Regulatory Commission* (NRC) for the existing spent fuel storage facilities in on-site pools or off reactor sites (dry cask or underwater), depending on the date of availability of such a facility: (i) storage over a period of time exceeding the duration of the reactor operating license by 60 years, (ii) storage over a period of time exceeding the duration of the reactor operating license by 100 years, and (iii) indefinite storage, in the event that no repository is commissioned [20]. For these three scenarios, the NRC is assessing the safety of these storage facilities and the possible radiological consequences of accident situations. The NRC has concluded that it is technically feasible to ensure safety of these provided that they are continuously managed in accordance with sound regulatory requirements, in particular to ensure that maintenance and monitoring devices are maintained.

An international conference on LTS

In June 2003, IAEA organised a conference in Vienna on the sustainability and safety of the LTS of radioactive waste (IAEA, 2003). During this meeting, international experts pointed out the following:

- the longer the storage period, the greater the deterioration of structures and packages will be, and therefore the radiological risk will be high for workers having to handle the packages when they are being transferred to another storage facility or to a repository;
- storage facilities are at risk of inadvertent or malicious intrusion if they are not permanently protected. Currently, they are generally placed on nuclear sites (reactors, treatment plants, etc.) and benefit from the general security features of the site, which may no longer be the case when the other facilities are dismantled;
- the retrievability of packages is at first glance easier for surface storage (if maintenance is ensured throughout the storage period) than for deep disposal. However, a deep repository can be designed to be reversible with progressive closure in stages, corresponding to a gradual decrease in reversibility;
- LTS requires a considerable transfer of information to future generations. Long-term safety requires that future societies be able to exert active control and maintain an effective transfer of responsibilities, knowledge and information from generation to generation. The safety of LTS is only sustainable if future societies can maintain these responsibilities, which cannot be guaranteed perpetually.

3.4 And in France?

In France, the packaging and storage of HLW was one of the three approaches defined by the 1991 law on radioactive waste management research ("Bataille law", 1991 [22]). It was then a question either of refurbishing the current storage facilities at the end of their life, or deciding from the outset to develop storage facilities designed for periods of several centuries.

In 2005, the CEA, which was in charge of the implementation of this line of research, submitted a study report [23] presenting four storage concepts (Figure 2), distinguishing between a surface concept and a sub-surface concept (10 to 150 m depth, on a hillside) for ILW-LL, a concept for HLW and one for SF. These facilities, placed on a fictitious site, were assumed to be in operation for 300 years with a package receipt and storage phase estimated at 50 years for HLW and SF, and at 30 years for ILW-LL, then a long storage phase (monitoring and maintenance), and finally an unloading phase with a similar duration to that of the loading phase.

With regard to the storage of HLW and SF, the design relies essentially on a robust package (metal container), natural ventilation ensuring the durability of the package by its cooling, and a moisture control that minimises corrosion. The CEA focused on the evacuation of the heat released by relying on its Marcoule expertise centre (Southern France) with regard to the packaging and storage of radioactive materials (CECER), which studied on a mock-up the functioning of the storage galleries, air circulation and convective heat dissipation. These studies led the CEA to dismiss the pool storage concept for HLW and SF because, with reduced monitoring, the risk of loss of technical control of the pool cooling over very long durations was too important. This led to the adoption of a dry cask storage solution cooled by natural convection, in which packages would be stacked in wells and air circulation would be passively ensured by a chimney effect. The CEA concluded that it was possible to build a HLW and SF storage facility that would be safe for centuries, but that despite design efforts, safety and durability could not be achieved without a maintenance requiring human intervention.

With regard to the storage of ILW-LL, the CEA concluded that, thanks to all of the measures taken during construction and preventive maintenance during the lifetime, the facilities would have a lifespan of 300 years.

The assessments of the studies conducted by the CEA [24][25] point out that only preliminary studies have been proposed and that they are based on a fictitious site, which does not make it possible to identify any benefits conferred by the surrounding rock for the sub-surface concepts, or by the location of the site for the risks of a flood or falling aircraft, for example, for surface concepts. These assessments highlighted a number of long-term issues, such as natural ventilation, the durability of concrete, and the long-term monitoring of the facilities, which cannot be guaranteed for periods longer than a few hundred years and which postpone the burden of waste management onto future generations. In addition, the scenario of a total abandonment of the facility could lead to unacceptable radiological consequences for the population.

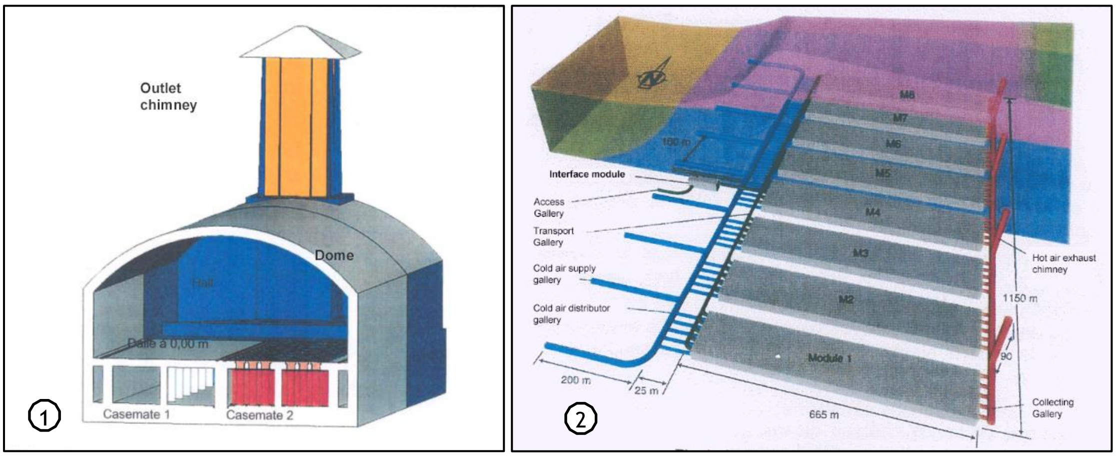

***Figure 2**: CEA Concept for HLW and SF storage facilities: (1) surface storage, (2) sub-surface storage [80].*

In 2006, G. de Marsily, then a member of the French National Evaluation Commission (CNE), published as an appendix to the CNE evaluation report on the results of the studies relating to the three approaches of the “Bataille law” [24], a personal opinion on the possible transformation of an underground LTS facility into a repository. He suggested building a LTS facility for ILW-LL directly at depth, in order to have a secular period of observation of the waste and the environment, on the order of 200 to 300 years, in order to acquire the conviction that the site is well suited for disposal. Otherwise, or if a better option was found, the waste could then be removed.

In order to maintain the possibility of eliminating waste definitively in the future, Global Chance [26] and Greenpeace [27] proposed the use of reversible disposal or dry cask storage for spent fuel in shallow galleries, for example, in the side of granite mountains, if necessary over long periods of time, considering that these solutions would facilitate the monitoring of facilities and ensure the possibility of removing these fuels in the event of a better technical solution being found.

The law of 28 June 2006 [28] entrusted Andra with the responsibility of carrying out, or having carried out, research and studies on storage in addition to deep geological disposal, in accordance with the French National Plan for the Management of Radioactive Materials and Waste (PNGMDR). These research and studies are aimed, in particular, at increasing the life of storage facilities from fifty to a hundred years and to have more modular storage facilities to anticipate the needs for waste storage prior to their disposal in deep geological layers.

4 PARTITIONING-TRANSMUTATION

4.1 What does it involve?

The insert "***Radioactivity, nuclear reactions and spent fuel***" below provides some general elements for understanding this chapter on partitioning and transmutation processes.

When developed as part of a radioactive waste management strategy, the goal of **transmutation** is to transform the very long radioactive half-life radionuclides contained in the spent fuel of nuclear reactors into stable or shorter-lived atoms. The idea of transmutation is thus to facilitate the management of the most dangerous radioactive waste in the long term and possibly not have to fall back on geological disposal.

Although other types of transmutation have been studied (see Chapter 4.5), the principle of transmutation generally consists in causing neutron absorption by the nucleus of a radionuclide (a phenomenon called **neutron capture**). This results in a change in its atomic mass and its radioactive half-life, or a **fission reaction** of the nucleus (see Figure 3). Transmutation reactions can be induced in thermal or fast neutron power reactors (see Chapter 4.3) or in systems dedicated to transmutation (see Chapter 4.4).

The transmutation of long-lived radionuclides first requires their **partitioning** from the other constituent elements of the spent fuel (see the insert "***Partitioning, recycling of recoverable materials, and transmutation modes***" and Chapter 4.2). The partitioned radionuclides are then converted to an oxide or metal element, and incorporated into fuels or "transmutation targets" for irradiation.

The interest of applying a **transmutation strategy** to all or some of the long-lived radionuclides of spent fuel depend on the type of nuclear reactors and the associated "fuel cycle", possible transmutation efficiencies according to available technologies and the physical characteristics of the radionuclides (mobility, dangerousness and life span). The expected advantages for geological disposal consist in a reduction in the inventory and the harmfulness of waste and a decrease in its thermal power, allowing its handling to be optimised. These advantages are to be considered with regard to the consequences resulting in particular from the emission of neutrons and the very high thermal emissions associated with the materials to be transmuted, when they pass through nuclear reactors, their treatment in "fuel cycle" facilities and during their transport. As such, "scenario" studies, incorporating hypothetical facility changes over time and different recycling options, are conducted to evaluate the interest of implementing transmutation.

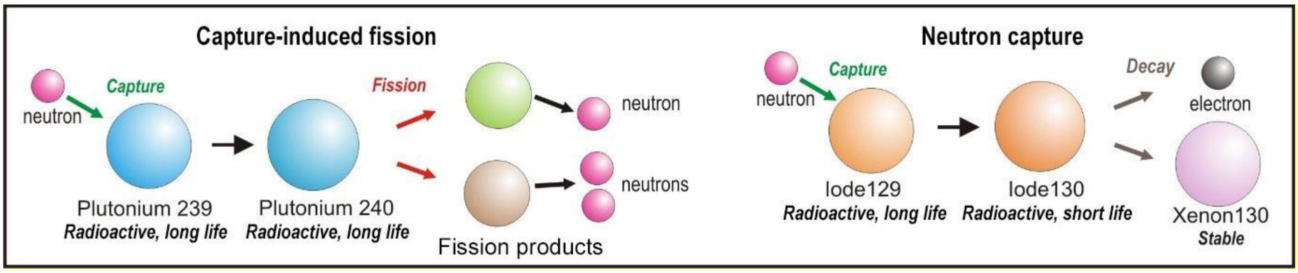

***Figure 3**: Transmutation by fission (left) or by simple capture of a neutron (right) (according to [29], modified).*

Radioactivity, nuclear reactions and spent fuel

1) Radioactivity

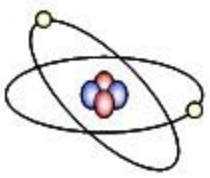

***Figure 4**: The atom.*

Every element in our Universe, from the Sun to our body, whether it is solid, liquid or gaseous, is composed of atoms. Very small in size - a tenth of a millionth of a millimetre - atoms (Figure 4) are themselves composed of three types of particles:

- Protons, which have a positive charge;
- Neutrons, which have no charge (protons and neutrons make up the nucleus);
- Electrons, which have a negative charge and orbit around the nucleus.

An atom can be stable **or** unstable. When it is unstable, it naturally tends to evolve towards a more stable state by emitting radiation (emission of energy and/or particles); the atom is then called a radionuclide. This reaction is characterised by a radioactive period (or half-life), which is the time that it takes for half of the nuclei of a radionuclide in a sample to naturally decay. The radiation may consist of:

- A helium nucleus (two protons and two neutrons), commonly called alpha radiation;
- An electron or positron, commonly known as beta minus or beta plus radiation;
- Photons (waves composing light), commonly known as X-ray and gamma radiation.

2) Nuclear reactions

Fission is the splitting of a heavy atom into lighter atoms (known as fission products) following an interaction between an atom and a neutron, for example. This reaction is accompanied by the emission of neutrons and photons, and leads to the release of energy.

Fusion consists in bringing two hydrogen atoms (deuterium[6] and tritium[7]) to temperatures of several million degrees, like in the cores of the stars. The fusion reaction between these light nuclei leads to the emission of a helium atom (alpha radiation) and a neutron, as well as to the release of energy.

Nuclear transmutation consists in the transformation of one atom into another by modifying its nucleus. The natural decay of radioactive elements, as well as nuclear fission and fusion reactions, are examples of transmutation.

[6] A deuterium atom is a hydrogen isotope with a neutron in the nucleus.
[7] A tritium atom is a hydrogen isotope with two neutrons in the nucleus.

3) Spent fuel from nuclear reactors

After being used in a reactor, spent nuclear fuel contains uranium and plutonium, which are considered to be recoverable in the nuclear power industry, as well as **fission products** and **minor actinides**[8] (essentially, americium 241 and 243, curium 244 and 245, and neptunium 237). In addition, spent fuel assembly structures contain radioactive elements **produced by the activation** of impurities (especially chlorine 36, calcium 41 and carbon 14).

Most fission products have a half-life of less than 30 years and only a small fraction corresponds to radionuclides with very long radioactive half-lives (notably technetium-99, iodine-129 and cesium-135). Minor actinides have very long radioactive periods (from several thousand to millions or even billions of years).

With regard to spent fuel management, two major strategies stand out on an international level:

- The first considers spent fuel as waste; it is called the **"open cycle" strategy**;
- The second consists in treating the spent fuel and then recycling the materials (U, Pu, Th) into new fuels; it is called **"closed cycle" strategy**. There are several types of "closed cycle", differing in particular by the type of recycled materials and the number of recycling processes carried out (mono-recycling or multi-recycling).

The "fuel cycle" management implemented in France is described as "closed cycle". The details of its implementation are presented in the report published in July 2018 by the French High Committee for Transparency and Information on Nuclear Safety (HCTISN) [30].

4.2 Partitioning processes and strategies

4.2.1 Ways explored around the world

Depending on the characteristics of the spent fuel, two main treatment routes can be used to partition the elements to be transmuted (see the insert "***Partitioning, recycling of recoverable materials and transmutation modes***): hydrometallurgical processes and pyrochemical processes.

Partitioning, recycling of recoverable materials and transmutation modes

In countries that have chosen a "cycle" of "closed" fuel, uranium and plutonium from spent fuels are **partitioned** from fission products and other actinides for **recycling**. With some adaptations, the fleet of reactors and partitioning processes that they have can then form the basis of a first transmutation strategy. This can be complemented by the development of new partitioning processes and the deployment of new reactors within a fleet specifically adapted to the purpose of waste transmutation.

Two modes of transmutation, conditioning in particular the choice of partitioning processes, are conceivable:

- A so-called "homogeneous" mode: the radionuclides to be transmuted are incorporated, up to a few percent, in all the fuel of the reactor or of the dedicated system;
- A mode known as "heterogeneous" radionuclides to be transmuted are introduced, at significant levels (on the order of 10 to 20%), in supporting elements that differ from the "standard" fuel elements of the reactor or of the dedicated system.

[8] Actinides are a family of elements of the periodic table. They are heavy metals, radioactive and fissile. Uranium and thorium are the most abundant actinides on Earth. In a nuclear reactor, other actinides are formed by neutron capture. Plutonium is the main one; the others are called "minor actinides".

Hydrometallurgical processes

The so-called hydrometallurgical processes consist in partitioning and purifying the materials of interest of the spent fuel by subjecting them to a solubilisation step and then a liquid phase extraction using a suitable "extractant" molecule (or solvent). These processes have been the subject of many international developments. For example, the PUREX process (*Plutonium and Uranium Refining by Extraction*), developed since 1947 in the **United States**, allows the recovery and purification of plutonium and uranium contained in spent fuel mainly from light water reactors.

Although the joint partitioning of uranium, plutonium and neptunium is already possible by adapting the PUREX process, the retrieval of americium and curium is almost impossible with the solvent (TBP) used in this process. Innovative processes involving selective minor actinide extractants have been developed for more than 20 years in **Europe**, **Japan** and the **United States** (TRUEX and TALSPEAK processes). They are intended to be used downstream from the PUREX process and are aimed at recovering almost all of the americium and curium. These processes have been tested at the laboratory scale. New even more selective extractants have been studied in **Japan**, **France** and, more generally, in **Europe** (ACSEPT [31], SACSESS, and GENIORS projects). **Japan** has also developed a multistage process to retrieve only americium (SELECT method).

For fission products, the main radionuclides for which a transmutation strategy has been considered are technetium, iodine and caesium isotopes. They contribute in a significant way to the estimated dosimetric impact for a geological repository, because of their very long radioactive periods, their mobility in the environment and their radiotoxicity. The research carried out has shown that the PUREX process makes it possible to partition the first two elements almost completely. Other processes have been developed and tested, particularly in France and the United States, to extract caesium [32].

Pyrochemical processes

Pyrochemistry encompasses all operations involving high-temperature chemical reactions (between 500°C and 1000°C). It is characterised by the use of non-aqueous solvents, such as gases, molten salts or liquid metals, and the use of very diverse partitioning techniques (electrochemistry, precipitation, distillation, etc.). These processes are particularly well suited to dissolving fuels that are difficult to dissolve in an aqueous medium, such as metal fuels.

Pyrochemical techniques for nuclear applications were developed in the United States in the 1930s to obtain metallic uranium and then became the subject of important studies. Thus, the application of pyrochemical processes to the treatment of spent fuels has been studied since the 1960s, mainly in the context of the development of the fast-neutron reactor sector, particularly in the **United States**, **Russia** and **France**.

Two processes, developed on a pilot scale, can be mentioned: the **electrolytic treatment** of MOX fuels[9] ("Dimitrovgrad" or DDP process) and the **electrorefining treatment** of U-Zr metal fuels (within the context of the "Integral Fast Reactor" or IFR concept).

Manufacture of targets or fuels carrying minor actinides

Once partitioned, actinides must be converted into a chemical form suitable for the production of targets or fuels (mixed oxide most often) that will be used for transmutation. For this purpose, co-precipitation and conversion of all or some of the actinides are necessary. "Oxalic" co-precipitation is currently preferentially used in studies. Other alternatives are also being studied on an international level (co-gelification, codenitration, etc.).

[9] Mixture of plutonium OXide and uranium OXide, obtained by the recycling of uranium and plutonium from spent fuel.

At the end of these steps, it is necessary to manufacture the fuel or targets for transmutation. This key step includes the operations of development and forming of the fissile compound (grinding of actinide oxide powders, pressing of the powders, and sintering of the pellets obtained) and closing of the fuel elements.

These operations are the subject of numerous studies aimed, in particular, at adapting the processes to the particular constraints of thermal powers and the high neutron emissions attributable to actinides. These constraints induce, in particular, stringent requirements in terms of radiation protection.

4.2.2 State of the art and perspectives

Hydrometallurgical processes benefit from an important industrial experience feedback, the PUREX process being the one used in all of the spent fuel treatment plants in the world. In the studies carried out, they are thus chosen as a priority to isolate minor actinides and possibly fission products for their transmutation. The purpose of ongoing research is aimed at defining new extractant molecules that are more selective, perform better with regard to charge capacity and are robust to irradiation.

Pyrochemical processes are of potential interest for the treatment of the very strongly irradiating spent fuels of future reactors (fast type). The latest US studies on the IFR concept have led many countries (Japan, South Korea, India, France, etc.) to re-evaluate the potential of these processes for the treatment of future fuels (metal, oxide, nitride or molten salt) or transmutation targets.

Manufacture of targets or fuels carrying minor actinides

Fuel pellets including minor actinides have already been manufactured in France for irradiation experiments in the PHENIX reactor (FUTURIX, EUROTRANS, COPIX programmes, etc.).

Nevertheless, the alpha and neutron emissions of minor actinides, in particular americium and curium, constitute an important constraint for the production of targets and fuels from actinide compounds. These intense alpha emissions cause, in particular, the production of helium and damage the matrix in which the actinides must be placed before they can be transmuted. A lot of research is underway to evaluate the importance of these degradations.

The intensity of the alpha radiation of the materials handled is also a major constraint in terms of radiation protection. This constraint requires that the production of contaminating and irradiating dust be limited as much as possible. It is the subject of studies currently underway, particularly in France and in Europe (ASGARD and GENIORS projects, etc.), to simplify and optimise fuel manufacturing processes. One of the main challenges faced by current research is to qualify these processes on an industrial scale, which requires the availability of pilot facilities and experimental irradiation capabilities.

4.3 Transmutation in nuclear reactors

4.3.1 Ways explored around the world

Transmutation tools

Transmutation of long-lived radionuclides (minor actinides, fission products and activation products) in thermal or fast neutron nuclear reactors has been the subject of numerous studies.

Although thermal neutron reactors constitute almost all of the reactors installed worldwide, the fast neutron reactor sector is a preferred route in studies carried out on the transmutation of minor actinides. Fast neutrons favour the fission reactions of these minor actinides, whereas thermal neutrons favour neutron capture reactions. Thus, when subjected to a thermal neutron flux, minor actinides can lead to the formation of other minor actinides of higher atomic mass, which are more radiotoxic or have a longer decay period, whose management as waste is not simpler than that of the original minor actinides.

Moreover, under the standard irradiation conditions in reactors (whether thermal-neutron or fast-neutron), all of the targeted elements are not transmuted in a single irradiation cycle. It is therefore necessary to carry out several partitioning-transmutation operations, each for a duration of at least several decades, to approach a fission rate of 100%.

The FNR fleet in the world is currently limited to 4 reactors located in **Russia** (BN600 and BN800 in Beloyarsk), **China** (CEFR experimental reactor) and **India** (FBTR in Kalpakkam). Two others are under construction in China (CDFR-600 in Xiapu [33] [34]) and India (PBFR also in Kalpakkam [35]). About 15 other FNR have been exploited in **France** (Phénix and SuperPhénix) in the **United States** (EBR-I and EBR-II, e.g., [36][37]), in the **United Kingdom** (Dounreay PFR, e.g., [38]), **Japan** (Joyo and Monju, e.g., [39][40]) and Kazakhstan (BN-350 [41]), but are currently shut down. Various FNR technologies have been studied or are under study, notably within the framework of the Generation IV International Forum (GIF [42], see [43]). These reactors are cooled by sodium but also by lead (BREST project [44]) in Russia, lead-bismuth [45], gas (see [46]), or are molten salt reactors (SAMOFAR project [47]; MOSART project [48]).

Neutron capture by fission products generally generates a stable body. They could therefore be transmuted in the installed **thermal neutron reactors**.

4.3.2 State of the art and perspectives

Transmutation tools

The potential yield of minor actinide transmutation in thermal neutron reactors in the current fleet worldwide is limited (see Chapter 4.3.1). On the other hand, significant yields can be obtained in the FNR.

For activation products (chlorine 36 and calcium 41), reducing the content of impurities in new materials is preferred. In addition, the transmutation of these radionuclides is of little interest because of their presence in limited quantities in the waste.

The transmutation of long-lived fission products (mainly iodine, technetium and caesium), if theoretically possible, raises implementation difficulties on an industrial scale that have not been resolved to date. This remains an outstanding issue on an international level [49]:

- At this stage, the known iodine-129 compounds, which are thermally and chemically unstable under irradiation, raise safety concerns for reactors, mainly because of the fuel corrosion that they cause. The transmutation speeds are also low (a few tens of years to transmute half of the initial mass). Some studies, however, continue on an international level (see the international program EFTTRA [50]);
- The transmutation of technetium 99[10] could theoretically be implemented in thermal-neutron reactors. Nevertheless, the transmutation yields remain low for this radionuclide. To achieve a significant reduction in inventories (for example, by a factor of 10), several cycles are necessary, which implies the deployment of the process over secular times. In addition, it would be necessary to improve the efficiency of the technetium partitioning process. Given these difficulties, few teams or countries are studying the transmutation of this element.
- Finally, the transmutation of caesium 135 would be difficult to implement, since it would first require a complex isotopic partitioning operation from its stable isotope, caesium 133. Very few studies are being carried out on the transmutation of this element [32].

[10] Technetium Tc-99, a long-lived fission product (210,000-year period), is transformed through neutron capture into Tc-100, which has a short radioactive half-life (15.8 seconds). Through radioactive decay, the latter is transformed into the ruthenium isotope Ru-100, which is stable.

4.4 Transmutation in dedicated systems

4.4.1 Ways explored around the world

The idea of coupling a particle accelerator with a subcritical nuclear reactor[11] dedicated to the transmutation of nuclear waste is the result of research by K. Furukawa [51], C.D. Bowman [52] and finally C. Rubbia (e.g., [53]). The corresponding system is called ADS (for Accelerator Driven System). The CERN has implemented two experiments to study this system:

- FEAT (First Energy Amplifier Test, 1995 [54]), to show that this system was able to produce more energy than it consumed;
- TARC (Transmutation by Adiabatic Resonance Crossing, 1996 [55]), to show that it was suitable for the transmutation of some nuclear waste.

On an international level, efforts have been focused on the development of an experimental reactor within the framework of the European project EUROTRANS, with the objective of demonstrating the technical feasibility of transmutation in such a system. The MYRRHA project ("Multi-Purpose Hybrid Research Reactor for High-tech Applications"), developed in Belgium, is today the most advanced in Europe (see the MYRRHA website [56] and Figure 5). The MYRRHA reactor project is based on an accelerator that, by projecting protons onto a target (lead-bismuth liquid spallation target[12]), generates fast neutrons, which will maintain the fission reactions in the reactor. The reactor, which is subcritical, is cooled by a lead-bismuth alloy.

Figure 5*: Myrrha (SCK • CEN), with its large hall for the LINAC accelerator [56].*

Other projects intended to study this transmutation system are currently underway in the world, in particular:

- In **China**, the CiADS project (China Initiative Accelerator Driven System) relates to an ADS with a FNR-Pb [34];

[11] A reactor is said to be subcritical when the fission reactions that occur in it generate neutrons in an amount that is insufficient to maintain the chain reaction by itself. It must be fed with neutrons from an external source.

[12] Spallation is a high-energy nuclear reaction in which a target nucleus, struck by an incident particle (neutron, proton, etc.) or a high-energy electromagnetic wave, emits a stream of lighter particles. A fission reaction is possible if the spallation target is surrounded by a nuclear fuel assembly, such as fissile isotopes of uranium or plutonium (see Figure 3) or thorium 232, capable of producing uranium 233.

- In **South Korea**, a minor actinide transmutation program by ADS is being developed by the Nutreck Institute (Nuclear Transmutation Energy Research Centre of Korea) and Seoul National University (SNU);
- In **India**, design studies are underway to achieve a thorium and natural uranium reactor, fed by an accelerator (ADS).

4.4.2 State of the art and perspectives

In the above studies, the benchmark technology for the accelerator part of the ADS system is a **continuous-wave superconducting linear accelerator** (LINAC). Programmes in recent decades have led to significant experimental innovations and advances; however, the feasibility of a complete system on an industrial scale remains to be established. Research is ongoing based in particular on the experiments developed for the MYRRHA demonstrator project. They concern the control of the reactivity during the operation of the system, the behaviour of materials subjected to a strong high-energy neutron flux and the development of inert fuels containing high levels of minor actinides. Moreover, scenario studies simulating the use of ADS systems in addition to a fleet of nuclear power reactors (so-called "double stratum" scenarios) show that, in order to stabilise plutonium and actinide inventories, it is necessary to multi-recycle minor actinides in ADS and plutonium in the fleet reactors. Even in this case, a significant amount of minor actinides is permanently present in the facilities necessary for the "cycle" of ADS systems.

An alternative technology to the LINAC relies on a laser-generated-plasma-based particle accelerator concept[13], called Laser Wakefield Acceleration (LWFA) [57]. This concept is based on the **laser technique called "Chirped Pulse Amplification"** or **CPA**[14], which won the 2018 Nobel Prize in Physics for Gérard Mourou and Donna Strickland [58]. The design of the LWFA, made more compact and less expensive by many international programmes (e.g., [59]), could lead to the building of extremely powerful accelerators of reduced dimensions. Recently, teams working with Gérard Mourou (e.g., [60][61]) proposed the use of this laser technology to accelerate deuterium ions intended to cause a fusion reaction (see the ***"Radioactivity, nuclear reactions and spent fuel"*** insert above). Neutrons[15] would then be used to feed a molten salt reactor containing elements to be transmuted by fission.

4.5 Other types of transmutation

4.5.1 Ways explored around the world

Biological transmutation

The theory of **biological transmutations** was in particular developed by the **Frenchman** C.L. Kervran over the 1960s-1970s (e.g., [62]). It is based on the observation, during the mineral nutrition of plants and animals, of the transformation of elements, such as potassium or magnesium, into calcium (respectively by incorporation of an oxygen nucleus and by incorporation of a proton). Such a transformation would be made possible by the presence of enzymes activated by a fossilized algae. This theory is disputed by various authors [63][64][65][66]: the "transmutations" observed result from erroneous interpretations of non-zero mineral balances or small statistically insignificant differences.

[13] Tajima & Dawson [57] had the idea that a very high-power laser could generate a plasma wave that can accelerate electrons to an energy of 1 GeV over a distance of 1 cm. Today, at the Lawrence Berkeley National Laboratory (California), a petawatt laser accelerates electrons up to 4.2 GeV over a distance of 9 cm.

[14] Proposed in 1985 as the foundation of Donna Strickland's thesis [58], CPA technology temporally lengthens (or modulates) laser pulses to reduce peak power, then amplifies them before eventually compressing them, thus increasing their intensity. It became possible to build high-power ultra-short pulse laser systems. In addition, their size is small and their use simple. This technique is applied to current high-power lasers and is used worldwide, particularly in the fields of eye surgery and micromachining.

[15] The neutrons would be generated by the laser irradiation of a sheet of deuterium of nanometric thickness; deuterium atoms would be accelerated to interact with a solid or gaseous tritium target. The fusion of a deuterium atom and a tritium atom is accompanied by the emission of a neutron.

Recently, publications have again tried to show the existence of biological transmutations, following the documentation by Kervran [67][68][69].

Cold fusion

British researchers M. Fleischmann and S. Pons announced in 1989 through the press [70] that an experiment[16] performed at ambient temperature and pressure caused a release of heat disproportionate to the amount of electrical energy received, called "**cold nuclear fusion**". Preliminary elements of this experiment were published in a "*Preliminary Note*" [71]; the full version promised by these researchers in the journal *Nature* was never published. Researchers from several laboratories, such as those of the **United States** *Department of Energy* (DOE) [72], tried to reproduce the results obtained by Pons and Fleischmann without success. The apparatus used for the purposes of their experiment also seems to not have had the expected traces of a nuclear fusion reaction. In October 1989, the DOE therefore concluded that there was no evidence of cold fusion [72]. However, this theory continued to be defended in the mid-1990s, more often under the term "*Low-Energy Nuclear Reactions*" (LENR) to refer to heat production caused by an unknown process taking place at the atomic scale and not accompanied by ionising radiation.

Direct laser transmutation

Nuclear fission by laser pulses in the visible spectrum (or photofission) directly applied to sources to be transmuted was tested on uranium with the PCA technique (Chapter 4.4.2) by the *Rutherford Appleton Laboratory* (RAL, **United Kingdom** [73][74]) using a VULCAN petawatt laser, and the *Lawrence Livermore National Laboratory* (LLNL, **USA** [75][76][77]) with the NOVA laser.

In 2003, the laser fission of uranium 238 and thorium 232 was performed by a **German** team [78], with a Jena laser. In the same year, a **British** team [79] used a VULCAN laser with a gold target to transmute long-lived radioactive iodine 129 to iodine 128 (see Figure 3).

4.5.2 State of the art and perspectives

To IRSN's knowledge, the research mentioned above is not the subject of specific developments within the context of national HLW/ILW-LL management programmes.

4.6 And in France?

France has been one of the main contributors to advances in partitioning and transmutation [80] within the framework of the application of the “Bataille law” of 1991 [22].

In particular, the CEA has developed a number of actinide partitioning processes (COEX™, DIAMEX-SANEX, GANEX or EXAm).

The research carried out by the CEA, within the framework of the waste law of 2006 [28] in particular, made it possible to validate at the laboratory scale, on real fuels, the processes developed for the retrieval of minor actinides, to prepare the experimental irradiations for the various transmutation concepts envisaged, and to specify the conditions for the industrial implementation of the various options [81]. Given the very significant difficulties associated with the recycling of curium, the research carried out since 2012 at the CEA only concerns the partitioning and transmutation of americium alone [82]; research on other actinides is nevertheless being studied in a European context.

[16] The experiment described by Pons and Fleischmann consists in producing the electrolysis of heavy water (D2O) with a palladium negative electrode, a platinum positive electrode and a lithium salt (LiOD) as electrolyte. They claim to have thus observed a heat production higher than that normally due to the electrical energy supplied to the system, which they attribute to the fusion of the deuterium nuclei (D), which according to them would have gathered on the palladium electrode (source : www.vulgarisation-scientifique.com/wiki/Pages/Que_sont_la_fusion_froide_et_les_LENR).

The FNR-Na are considered as the benchmark sector in France, in particular because of the ample feedback from the international community on this technology. Research for industrial implementation is supported by the CEA, through the Astrid project [83].

The possible industrial deployment of a transmutation option is envisaged within the framework of a future nuclear fleet comprising fast-neutron reactors suitable for the transmutation of minor actinides, or in dedicated systems.

5 BOREHOLE DISPOSAL

5.1 What does it involve?

Borehole disposal consists in placing waste in **vertical structures drilled into rock**, in order to isolate them from natural surface phenomena, to reduce the possibility of their contact with humans by reducing their accessibility and, finally, to prevent the dispersion of their contents into the environment. Through these objectives and because it involves the geological environment, this option is very similar to the deep geological disposal option. However, it differs in certain important specificities. Although geological disposal is based on the digging of an underground facility into which the waste is conveyed and then set in place inside specially designed and equipped cells, all of the borehole disposal operations are carried out **from the surface**, from the digging and the handling of the packages to the closing operations. For one same type of waste (HLW or ILW-LL), the target depth for some borehole disposal concepts can be much greater than that of a geological repository.

Three types of borehole disposal can be mentioned according to the type of waste:

- **Embedding of exothermic waste**[17] (such as vitrified waste or spent fuel) **in a vitreous gangue resulting from the melting of the host rock.** In order to trigger the melting phenomenon, the waste must be placed in a rock that dissipates little heat and whose melting temperature is sufficiently low; this is particularly the case of granitic rocks. Since temperature naturally increases with depth, the use of deep boreholes can be a favourable element;
- **Injection of liquid waste directly into the rock**. In this case, the rock, located several hundred meters deep, is chosen for its injection capability (characterised in particular by its porosity), as well as for its hydrogeological characteristics, the objective being that they make it possible to limit horizontal and vertical transfers;
- **Stacking of solid waste packages in a borehole**. In this case, the waste is placed at a depth that depends in particular on its nature, and then the borehole is sealed.

5.2 Embedding of exothermic waste in molten rock ("rock melting")

5.2.1 Ways explored around the world

The paths to achieving this option explored around the world consist in placing the waste in cavities or boreholes made in magmatic rocks[18] so that the heat that they generate leads to the melting of the materials around them. In some concepts, the waste is placed in a capsule designed to maintain its integrity while the rock that surrounds it melts and will form a protective gangue during its cooling. In other concepts, waste is intended to mix with the rock and can be injected in a liquid form. The objective is that, during cooling, the whole forms a vitreous mass that incorporates the

[17] Release of heat by waste due to its radioactivity (energy released during radioactive decays).

[18] Magmatic rocks (granite, basalt…) result from the crystallization of magma. Granite begins to melt at 900°C, and basalt begins to melt at 1200°C.

radionuclides, potentially in a larger volume than initially (thus of weaker mass activity). Most of these concepts have been explored in the United States. We can mention in particular (see [84]):

- The Deep Underground Melt Process (DUMP) concept, developed by the *Lawrence Livermore National Laboratory* in the 1970s [85][86][87]. This project consisted in introducing exothermic waste into a cavity made from a borehole, either using conventional explosives or by means of a nuclear explosion, at a depth of between 2 and 4 km. The goal is to place a large amount of waste in the same cavity;
- The Deep Self Burial (DSB) concept (Figure 6-1), originally developed by *Sandia National Laboratories* [88][89]. This concept consists in taking the waste down to a depth of 2 km, enclosed in high-density containers, possibly cooled in cased boreholes, then if necessary in disconnecting the cooling system so that the waste melts as it sinks deep into the liquefied rock, under the effect of its own weight. Renewed interest in an option derived from this concept emerged in the 1990s, particularly in Russia, China and the United Kingdom, aimed at eliminating small quantities of high-level waste [90][91]. The new option was only aimed at partial melting of the host rock, the waste itself being protected by a container[19] not intended to melt and mix with the molten rock;
- The Deep Rock Disposal (DRD) concept (Figure 6-2), also developed by *Sandia National Laboratories* [92][93]. The concept combines elements of the two previous concepts: the targeted wastes are essentially liquid effluents from spent fuel reprocessing plants. The project does not envisage them being placed in containers, but rather directly injected in liquid form into deep boreholes, where, due to their exothermicity, they would melt the surrounding rock;
- The solidified Waste *In Situ* Melting Concept [94] (Figure 6-3) consists in mixing the solid waste with rubble inside a cavity. The average thermal load of the waste-rubble unit should allow the melting of the rubble to be carried out while avoiding a thermal degradation of the rock beyond the molten rock zone. Likewise, the voids in the embankment are imagined to allow the expansion of the rock during the melting, thus reducing the risk of causing the surrounding formations to fracture.

[19] The melting temperature of steel (which begins to melt at 1400 °C) is higher than that of a basalt.

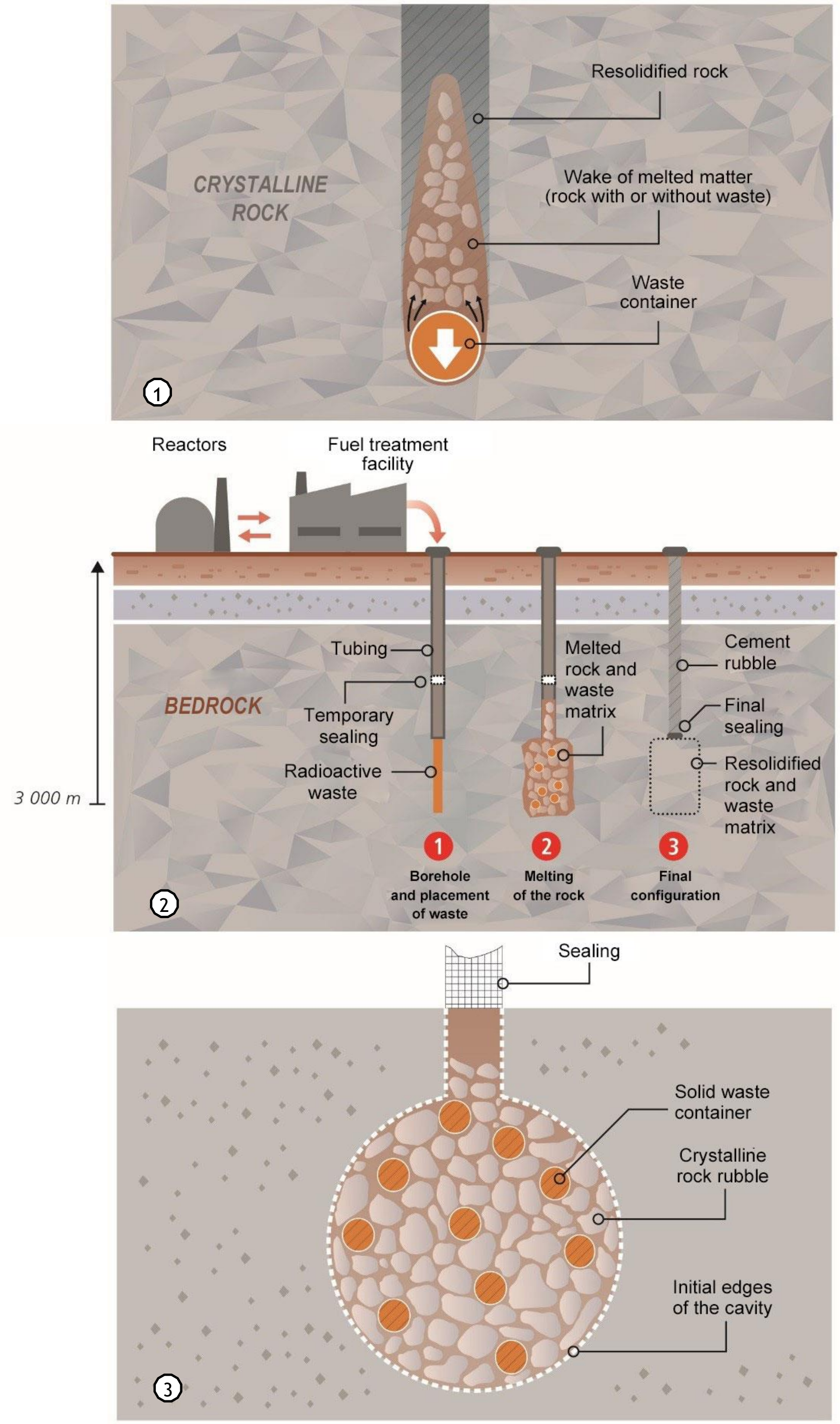

***Figure 6**: Various types of disposal by rock melting: 1) the DSB concept (according to [89], modified); 2) the DRD concept (according to [92], modified); 3) the initial device of the Solidified Waste In Situ Melting Concept (according to [94], modified).*

5.2.2 State of the art and perspectives

The various initial concepts presented in the previous chapter are currently no longer, to IRSN's knowledge, the subject of official studies. On the other hand, an option derived from DSB is still under study in the United States [95][96][97][98]. In particular, it is considered as a disposal solution for Hanford caesium and strontium sources (see Chapter 5.4.2 below). Its principle is based on the partial melting of a granite-based material ("rock welding", see Figure 7) placed around or above the waste packages. The heat released by the waste is, for this concept, high enough to cause the melting of the material that surrounds it but remains low enough not to deteriorate the containers in which it is enclosed. When cooling, it is expected that the granite-based material will naturally seal the area around the waste in the deep boreholes. Current research focuses on materials (especially crushed granite) that would allow effective recrystallisation for sealing.

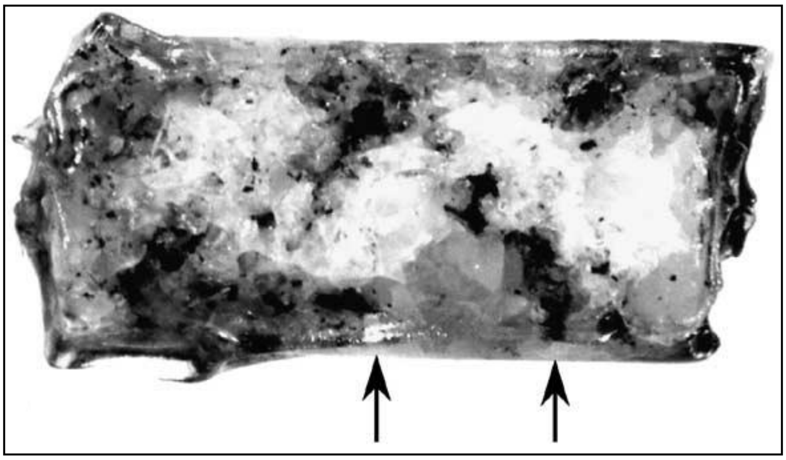

Figure 7: *Granite core (2 cm long) partially melted after 570h at 800°C (at 2.55% humidity). The arrows indicate "glass" areas (uncrystallised molten mass because rapidly cooled) [96].*

5.2.3 And in France?

The embedding of exothermic waste in molten rock has not been the subject of dedicated work of significant magnitude in France.

However, the French nuclear test programme carried out in French Polynesia in the years 1970-1990 shed some light on the mechanisms of fracturing, rock melting and the trapping of radioactive substances in molten rocks. Some experiments carried out in this context consisted in placing test devices at the bottom of vertical wells a few hundred meters deep, filled with drilling rubble and basaltic sand, and then sealed with cement. The results made it possible to study the capacity of the lava formed by the melting of the basaltic sand to trap the radioactive products contained in the device [99][100]. These experiments did not have any particular follow-up in the research programme on radioactive waste disposal.

5.3 Liquid waste injection in deep boreholes

5.3.1 Ways explored around the world

Direct injection of waste in liquid form (or incorporated in a solution after crushing in the manner of a cement grout) in a geological layer requires that the rock be sufficiently porous and permeable to allow injection. Its characteristics must also make it possible to limit the horizontal or vertical migration of radionuclides. The choice of a porous and permeable geological formation, but with weak hydraulic gradients and framed by formations of low permeability, is therefore favourable.

In the **United States**, after initial tests in 1959 and 1960, the *Oak Ridge National Laboratory* in Tennessee has regularly conducted radioactive effluent injection operations. Between 1966 and 1979, about 7,500 m^3 of waste was injected in the form of cement mortar at a depth of about 300 m [101][102], in shales previously treated to increase their porosity and permeability based on hydraulic fracturing techniques. These experiments were followed up by IAEA [103]. In 1972, high-level waste injection in crystalline rock under the Savannah River site (South Carolina) was abandoned prior to its implementation, due to public concern [104].

In **Russia**, injection operations have been carried out since 1962 in sedimentary rocks on three sites: in limestone and sandstone formations at a depth of 1400 meters in Dimitrovgrad (injections on this site have now ceased), as well as in two porous sandstone beds capped with clay at a depth of 400 meters in the Krasnoyarsk-26 ("Severny" site) and the Tomsk-7 (Sversk Sites 18 and 18a) [105]. On the Krasnoyarsk-26 site, since 1962, eight boreholes were used for the injection of intermediate and high-level liquids and four boreholes were used for the injection of low-level liquids. For all of the sites, in total a few tens of millions of m^3 of high and intermediate-level waste were injected.

5.3.2 State of the art and perspectives

In **Russia**, four of the boreholes near the reactor site and the spent fuel reprocessing plant in Krasnoyarsk are still being used to inject low-level effluents. The volumes injected have, however, considerably decreased since the shutdown in 1992 of two plutonium production reactors and the slowdown of the fuel reprocessing activities on this site [106].

In 2013, the practices of injecting waste and effluent into rocks were the subject of a technical review under the auspices of **IAEA**. This review was based on the standards laid down by the agency[20] , which require, under the principle of " in-depth defence ", that a geological disposal system be designed according to a multi-barrier device, in which the failure of one element can be compensated for by the existence of others. According to this principle, the performance of the disposal system must be based not only on the host rock but also on engineered barriers. The interpretation of these standards (e.g., [107]) was discussed during this review and the compatibility of the direct injection of liquid effluents into rocks with fundamental safety principles remains today a subject of dissent within the international community [105].

In the **United Kingdom**, the injection of liquid radioactive waste into rocks, after examination based on the work done in the United States and Russia [108][109], is now considered to be contrary to UK regulations in force, the latter requiring in particular that the waste be managed exclusively in solid form.

To IRSN's knowledge, rock injection is now not being considered by any country as a definitive management option for intermediate or high-level waste.

5.3.3 And in France?

In France, studies and research on the injection of radioactive waste and effluents performed in the 1970s were conducted in connection with similar discussions initiated by other industrial sectors. In particular, these studies contributed to the development of hydraulic fracturing techniques used by the oil and gas industries to improve reservoir productivity and to participate in the campaigns for nitrated effluent injection at a depth of 1,800 m performed by the Ile de France fertilizer company in Grandpuits [110]. These investigations were gradually abandoned in France at the end of the 1980s, with the radioactive waste management programmes revolving partly around the exploitation of surface disposal centres, and partly around research structured along three approaches defined by the “Bataille law” of 1991 [22].

[20] See Requirements 7 and 8 of the IAEA Guidelines “SSR-5” of 2011, in particular.

5.4 Solid and packaged waste disposal in boreholes

5.4.1 Ways explored around the world

The first concept of solid waste disposal in boreholes was developed by the *National Academy of Sciences* of the United States in 1957 [111]. It consisted in drilling boreholes, at sea or from the mainland, in crystalline or sedimentary rocks to a depth of up to 5,000 m and then placing packages of radioactive waste in them. Research on this option was abandoned in the 1970s in favour of that on disposal concepts in mines or underground facilities, because of the difficulties encountered in attempting to drill boreholes with sufficiently large diameters and depths using the technologies then available.

The significant technological advances of the past thirty years have recently led some countries to re-examine this option. In the United States, a benchmark concept has been proposed by *Sandia National Laboratories* at the request of the Department of Energy (DOE) [112]. This consists in placing 400 waste containers at the bottom of a deep borehole of approximately 5,000 m. Above the 2,000 m in which the waste would be deposited, Sandia proposes the construction of a seal consisting of bentonite and concrete that would occupy an uncased part of the 1500 m long borehole. The upper part, also representing a length of 1500 m, would be filled according to standard methods.

Research on disposal in deep boreholes has also been conducted in several countries such as Denmark, Switzerland, Sweden (e.g., [113]), Finland (see [114]) and the United Kingdom [115][116].

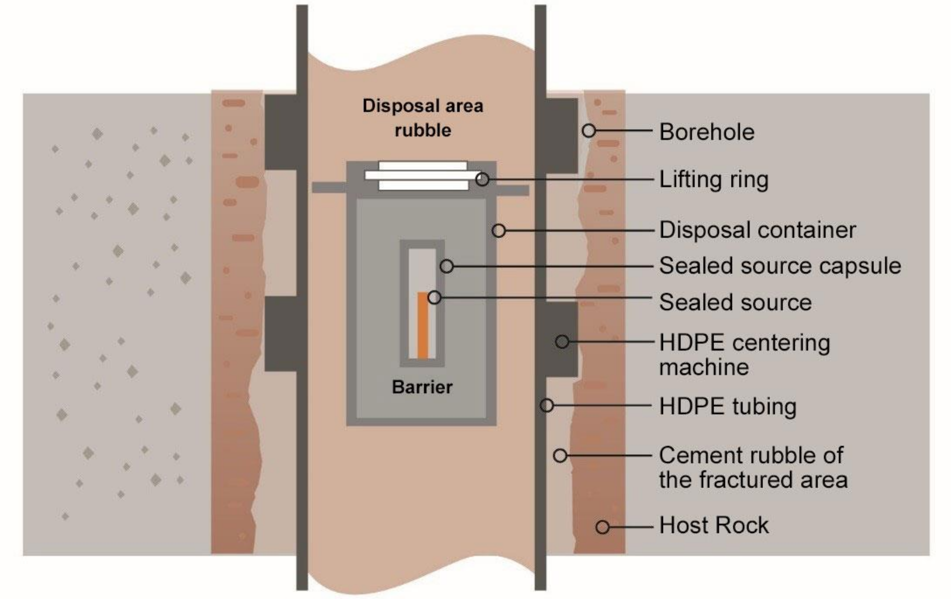

Figure 8*: The concept of multi-barrier disposal applied to borehole disposal (according to [118], modified).*

The principle of solid waste disposal in boreholes is of particular interest to countries with very limited amounts of waste consisting mainly of small objects, such as sealed radioactive sources from medical and industrial applications. In 2009, IAEA published a guide (SSG-1 [118]) specifically dedicated to the borehole disposal of sealed radioactive sources withdrawn from service and small volumes of waste. The solution described in this document (see Figure 8) consists in the drilling of boreholes with a diameter of at most a few tens of centimetres and with depths varying between a few tens and a few hundred meters, depending on the activity of the waste. It proposes a "multi-barrier concept" comprising the waste and its container, the rubble and the borehole casing, and, finally, the host rock. These successive barriers are designed as obstacles against the transfer of radionuclides to the biosphere. The guide specifies that, for waste placed in a borehole less than 30 meters deep, it is advisable to refer to the safety principles for waste placed at a depth of more than 30m and to the safety principles for disposal in deep geological layers [119][120].

5.4.2 State of the art and perspectives

Since the issuance of the IAEA Guide "SSG-1" [118] mentioned above, extensive research and development has focused on the concept of borehole disposal for implementation in a number of weakly-nuclearized or non-nuclearized countries. For the long-term management of sealed radioactive sources, countries such as **Ghana**, **Malaysia**, the **Republic of Cyprus**, **Moldova** and **Brazil** have adopted the concept proposed by IAEA as a benchmark option. For small volumes of waste (excluding high-level waste), the **United Arab Emirates** has also adopted this concept as a benchmark, while this option is under consideration in the **United States**, **Australia**, **Cuba** and **Jordan** [121]. The quantities and activities of the waste concerned by these various programmes are incommensurate with those of HLW/ILW-LL resulting from the operation of a fleet of nuclear power reactors.

In the case of nuclearized countries, some maintain a watch on the subject (e.g., **Sweden** [122]) and others consider borehole disposal as a possible option, the same as a geological repository (e.g., **Belgium** [123][124]), but only the **United States** are pursuing advanced studies:

- A report published in October 2013 by *Sandia National Laboratories* [125] indicates that preliminary deep borehole disposal assessments show significant and robust waste isolation potential, and that the concept could be a faster to implement definitive management solution for some types of waste than geological disposal in an underground facility. This position has recently been developed in several scientific articles published in leading international journals (e.g., *Nature* [126] and *Science* [127]). More specifically, studies on the disposal of civilian spent fuel estimate the number of boreholes required for the reference design described in Chapter 5.4.1 at around 800 [128]. These studies have found particular acceptance in the **United Kingdom** [117] and **Germany** [129].
- In January 2016, the company Battelle was commissioned by the DOE to drill a 4,880-meter test-borehole in a crystalline basement of North Dakota for the disposal of caesium and strontium sources that are currently stored at the Hanford site, as well as possibly high-level calcinates and salts resulting from the electrometallurgical treatment of sodium fuels [130]. The site identified in North Dakota having been abandoned as a result of protest movements, the DOE and Battelle have successively considered several other sites for this test-borehole (South Dakota, New Mexico, Texas, etc.), but have had to abandon them in turn due to local opposition [131]. The DOE announced the termination of its test-borehole project on the 23rd of May, 2017 (see [130]).

Although the studies underway in the United States cover *a priori* all types of waste, borehole disposal is currently not retained by the DOE for the long-term management of spent fuel [132][133].

In terms of research, the knowledge needs for the development of this type of solid waste disposal are quite similar to those explored in geological disposal projects in an underground facility. They include: geodynamics, the identification of potential natural resources, the characterisation of the properties of host rocks at the site-selection stage, and the criticality for the assessment of risks in operation, etc. Some specificities stand out nevertheless from the past or current discussions. They relate more particularly to package-handling techniques while they are being placed in boreholes, as well as the sealing methods, which, although they are also required for underground facilities associated with geological disposal, require specific techniques in the case of borehole disposal.

In terms of handling, the techniques explored by the DOE [132] are: i) free fall slowed down by the viscosity of the borehole fluid and the clearance between packages and casing (this solution is, however, excluded for deep boreholes, with the fall of a package having been studied only for the purpose of risk analysis), ii) the use of cables, iii) the use of drill pipes like in the oil industry.

In terms of sealing techniques, there is ongoing research on an option derived from the concept, described in Chapter 5.2.1, of rock-melting around exothermic waste. The solution explored consists in promoting the melting of a granite backfill by introducing an electric heating element [128][95][96].

5.4.3 And in France?

Like for the injection of liquid waste in deep boreholes, the option of borehole disposal of waste packages has not been considered in France.

6 SUB-SEABED DISPOSAL

6.1 What does it involve?

The disposal of radioactive waste in the **seabed** involves moving the waste away from any human presence by placing it at the bottom of the ocean. Several options have been considered for this. They consist in:

- depositing the waste in areas where water depth is great or sedimentation is rapid. These areas correspond, in particular, to the abyssal plains of the oceans, or to the "**deep seabed**". The height of the water column can reach about 5,000 to 6,000 meters. Under this option, the waste would be either placed **on the seabed** in anticipation of being covered by sedimentation, or buried **in the unconsolidated sediments** that cover the bedrock, usually comprised of basaltic formations;
- placing the waste to the right of the so-called "**subduction**" zones, where the oceanic plate sinks into the Earth's mantle (see below). This configuration has led to imagining the possibility of sending the waste to the mantle by placing it on the "treadmill" constituted by the oceanic plates.

Depending on the location of the area, the disposal operation can be carried out at sea, from a boat or an offshore structure, by means of **boreholes** or "**penetrators**" (heavy containers falling in free-fall into soft sediments, see the chapter here-after) or possibly from land, through a tunnel.

6.2 Ways explored around the world

6.2.1 Deep seabed disposal

The study of the definitive disposal of high-level waste on the seabed is a continuation of the low-level radioactive waste disposal operations at sea carried out by most nuclearised countries in the 1950s and 1970s, and in a much more limited way until the 1990s (see the insert: "***Disposal of radioactive waste at sea***"). It started in the **United States** in 1973 (e.g., [133]) and the work then focused mainly on the abyssal plains of the Pacific Ocean. At this time, the idea of disposal on the floor of the deep seabed was related to the weak interest that these areas were expected to show with regard to human activities. It was also justified by the conditions considered to be *a priori* favourable - from the point of view of dilution/dispersion and corrosion - ensured by the slow ocean currents and the expected low temperatures at the bottom of the oceans. The MPG programme (Mid Plate/Mid Gyre), which is part of this research, focused on the study of the water column properties and the evaluation of their ability to constitute a barrier preventing the transfer of radioactivity to areas in which human activities take place. The results of these investigations showed that the water column was not as stable as envisaged and that exchanges were established between the surface and the bottom.

The research then focused on the possibility of burying waste in marine sediments. In this context, sediments were considered as a barrier against the migration of radioactive substances, the ocean itself being considered as an environmental compartment in which transfers are possible but slow. One of the research challenges was to establish that dilution-diffusion kinetics were slow enough to allow radioactive decay (and therefore a significant decrease in activity) before the radionuclides reach humans. The option of burying waste in the marine sediment was considered more acceptable than disposal at sea, in that it did not consist in deliberately diluting and dispersing the radioactivity in the ocean, but rather in confining the waste in a thick layer of sediments on the seabed with the capacity to absorb the radioactive substances.

Sediment burial studies began in 1976 with the "Sub-seabed Disposal Programme". This international cooperation programme under the aegis of the NEA involved the United States, France, the United Kingdom and Japan; Canada, the Federal Republic of Germany, the Netherlands, Belgium and the Organisation of European Communities also contributed (e.g., [135][136]).

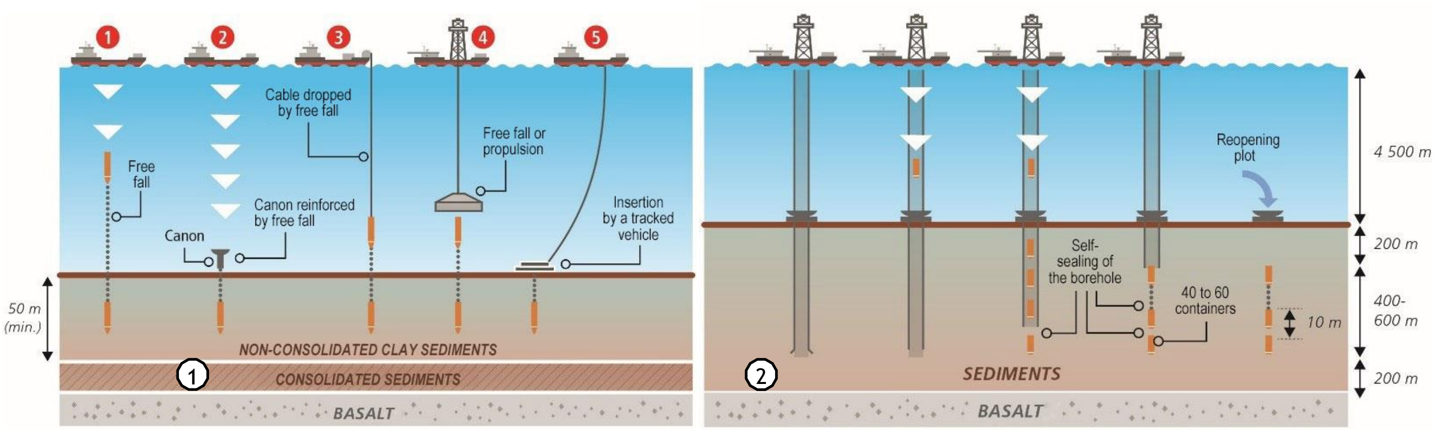

Figure 9: *The two concepts for placing the waste in seabed sediments: 1) using a penetrator; 2) by drilling ([144] according to Sandia under the Sub-seabed Disposal Program, modified).*

The work resulted in two main options:

- Insertion of waste into sediments using penetrators (see Figure 9-1). This option consisted in placing the waste in sufficiently heavy warhead-shaped containers and dropping them in free-fall at around 30 m/s. In the 1980s, the United Kingdom and the United States conducted penetration tests of mock containers in sediments, under a water-depth of a few hundred meters ([137][138]). The experiments showed that the containers sank more than 30 meters and that the holes created were ultimately filled with remediated sediments of a density equivalent to that of the sediments initially present [138];
- Drilling of boreholes, inside of which stacks of packaged waste would be placed (see Figure 9-2). A depth of 800 meters below the sea floor was targeted, with the top of the stack of containers being located 300 meters below the sea floor. The initial projects studied in the United States by the non-profit company Battelle [139] provided for the boreholes to pass through all of the loose sediments to anchor into the bedrock, generally basaltic, in which the waste containers were to be placed.

Studies carried out have focused on heat transfer [141], diffusive transport [142], and radiological impact [143]. In 1986, the United States DOE, which was the largest contributor to the *Sub-seabed Disposal Program*, decided to cease funding it in order to fully devote its attention to the "geological disposal" project, thus ending the programme (see [144]).

Disposal at sea of radioactive waste

The disposal at sea of radioactive waste consists in dropping containers filled with waste from the deck of a ship. These containers can be either designed to implode at depth under the effect of water pressure, or to flow intact to the seafloor. The principle of this management method is to choose an immersion zone characterised by sufficiently strong dispersion and dilution conditions. Disposal on the seafloor also makes it possible to consider sorption of radioactive substances into the sediments of the seabed.

Between 1946 and 1982, 14 countries regularly dumped radioactive waste into the Pacific and Atlantic Oceans. The first disposal at sea was conducted 80 km off the coast of California. The last disposal at sea by a western country took place in 1982 in the Atlantic (1993 by Russia), about 550 kilometres off the European continental shelf.

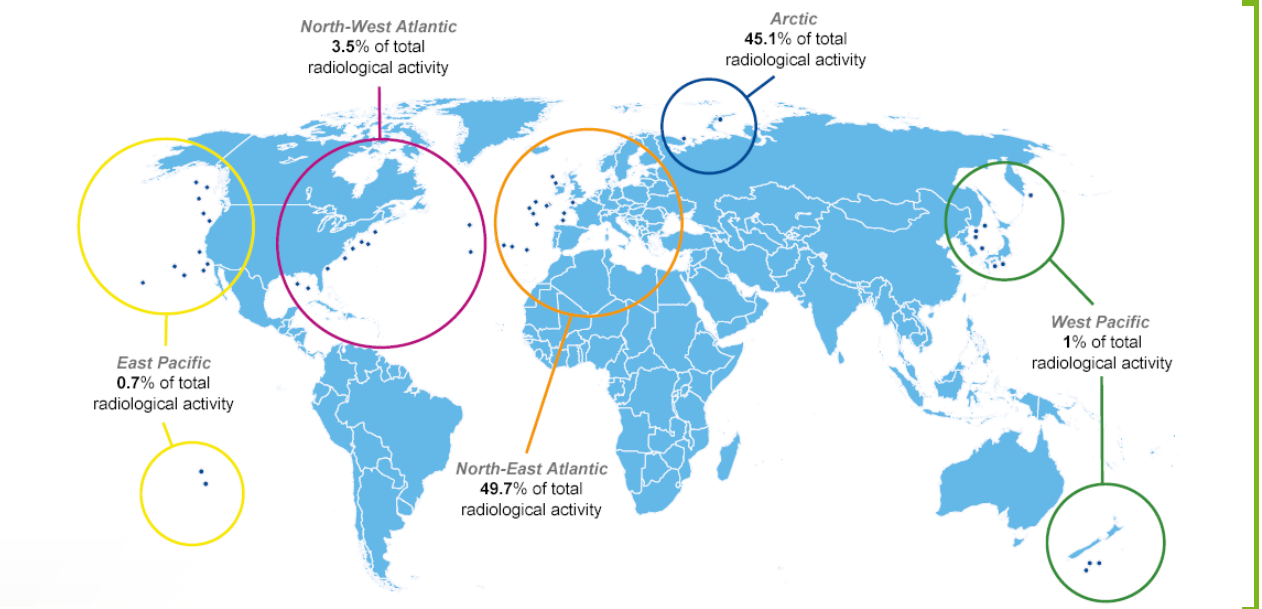

***Figure 10**: Sites of radioactive waste disposal at sea around the world and percentage of total radiological activity (85,000 TBq[21]) ([146][147]).*

Of the approximately 85,000 TBq of submerged waste (activity at the date of the operation [147]), half was carried out off the European coasts in the Atlantic and the English Channel (low-level, liquid or solid waste). It should be noted that most of the activity of submerged waste in the Arctic Ocean comes from damaged (high-level) spent fuel in the reactors of six submarines and an icebreaker belonging to the former USSR [147].

With regard to the disposal at sea in the North Atlantic, from **1949 to 1963**, the United Kingdom and, to a lesser extent, Belgium have submerged their waste at various sites. The one closest to the French coast is **Hurd's Deep** (150 m deep), 15 km northwest of Cap de la Hague (60 TBq). The following operations have been coordinated by the Nuclear Energy Agency (NEA) of the OECD (then known as the European Nuclear Energy Agency) [148][149]. **France participated in two of the campaigns organised within this context** (see Figure 11).

- Between May and August **1967**, Germany, Belgium, France, the United Kingdom and the Netherlands submerged about 11,000 tonnes of waste (about 300 TBq, including 219 TBq submerged by France) at a site 400 km **off the coast of Galicia** (Spain) to a depth of more than 4,600 meters.

[21] 1 TBq = 10^{12} Bq = 1 000 000 000 000 Bq (Becquerel)

- In July-August **1969**, a new operation, this time involving Belgium, France, the United Kingdom, Italy, the Netherlands, Sweden and Switzerland, involved submerging approximately 9,000 tonnes (on the order of 900 TBq, including 134 TBq submerged by France) at a site 900 km **west of Brittany**, to a depth of between 4,000 and 4,600 meters.

The following campaigns of disposal at sea, off the **Bay of Biscay**, were again supervised by the NEA. More important in terms of activity (36,000 TBq), they were conducted by Belgium, the United Kingdom, the Netherlands and Switzerland. France ceased to take part in these operations after the commissioning of the Centre de la Manche disposal facility in 1969. The disposal at sea of waste resulting from nuclear tests carried out in Polynesia (0.083 TBq) continued in French waters in the Pacific until 1982 [146].

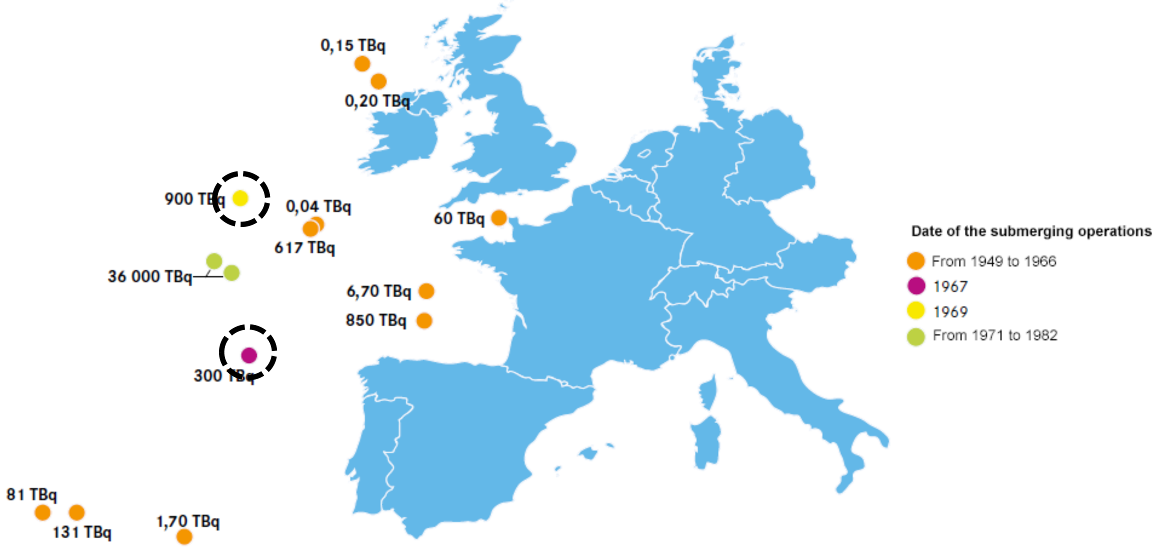

***Figure 11**: Campaigns for the disposal at sea of radioactive waste in the North-East Atlantic - Location, date and radiological activity of submerged waste ([146], source [147]). Dotted circles: sites used by France.*

Following the entry into force of the **London Convention** [150] prohibiting the dumping of radioactive waste (see the insert "***Changes in Maritime Law***"), a moratorium on dumping was adopted in 1983 [151] and in **1993** the signatories of the London Convention decided to **prohibit the disposal at sea** of any type of radioactive waste.

The changes in maritime law and the international initiatives undertaken to protect the oceans (see the insert "***Changes in Maritime Law***") have progressively led to a slowdown in research on the disposal of waste under the seabed and then to their ceasing following the moratorium on the disposal of waste at sea in 1983 [151]. This change resulted both from the development of knowledge and the possibilities of exploitation of natural resources present on the seabed (metal nodules, hydrocarbons, etc.), as well as from a growing awareness of the need to preserve the marine environment.

Changes in Maritime Law

The principle of "freedom of the sea" set forth since the 17th century, defining the sea as a territory open to all and belonging to no one, gave way in the 1970s to that of "international management of the seabed" [152]. The "1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter", the so-called **London Convention** [150], which entered into force in 1975 (see the insert "***Disposal at sea of radioactive waste*** ") associates the term pollution with a deliberate release of substances that may have adverse effects on the marine environment. This convention covers radioactive substances, regardless of their level of activity since the amended version of 1983. To date, **87 States** have ratified it.

The 1972 Treaty was supplemented and modernised in 1996 by the "1996 Protocol to the 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter", called the **1996 Protocol**. The latter prohibits the disposal at sea of any substance other than those appearing on a list of authorised substances whose radioactivity levels do not exceed the exemption thresholds defined by IAEA. This protocol, ratified in 2006, now has **48 contracting parties**.

In the case of disposal at sea, since the risk of accidental harmful effects cannot be totally ruled out, the concept of "acceptable risk" and its compatibility with international law were discussed during the negotiations leading up to the adoption of the 1996 Protocol. In particular, due to the impossibility of excluding the risk of an accident during the transport of waste at sea and its transfer into the sediments, it was considered that this concept was not in accordance with various international conventions (e.g., [153]). Ethical and political considerations, such as the notion of "common heritage of humanity" for the high seas and the finding of unequal access to the sea among countries, were added to the debates. The legal issues remain unresolved (e.g., [154]) and extend beyond the case of radioactive waste. For example, the 1982 United Nations Convention on the Rights of the Sea (UNCLOS or UNCLOS III), which came into effect in 1998, has still not been signed by some UN members, such as the United States.

After many discussions, one aspect is currently the subject of a consensus: to create a repository at sea from land (by tunnels, descendants, etc.) is compatible with international law (e.g., [155]).

6.2.2 Disposal in subduction trenches

Current knowledge of plate tectonics, including their formation in rifts and their convergence at subduction zones (see the insert "***The subduction phenomenon***") or their collision (mountain chains), only emerged in the 1960s, within the context of the first seabed exploration campaigns[22] [156]. The idea, proposed in the 1970s in the **United States**, of placing radioactive waste in subduction trenches - and thus using a natural mechanism to send them into the Earth's mantle - (e.g., [157]) results directly from this evolution of scientific knowledge. At the time when the work began, the data and the understanding of the phenomena on which they are based was limited and fragmented. In 1972, geologist E.A. Silver of the US Geological Survey emphasised in *Nature* magazine [158] the slowness of the subduction phenomenon and the even slower rate of sedimentation processes. He added that the subduction zones showed signs of strong seismic activity (deformations and faults). Finally, in slow-subduction zones, the observations suggested that sediments on the top of the subduction plate did not penetrate the mantle, but rather were levelled off during the sinking of the plate and accumulated on the surface.

[22] Seabed topography then revealed the existence of ocean ridges and rifts.

The subduction phenomenon

When an oceanic lithosphere (crust) plate meets a continental plate, it passes beneath it - this is called "**subduction**" – due to its lower density. It then sinks into the Earth's mantle, generating an **ocean trench**. Disposal in a subduction zone consists in placing the waste in the ocean trench so that it is carried away with the subducted crust.

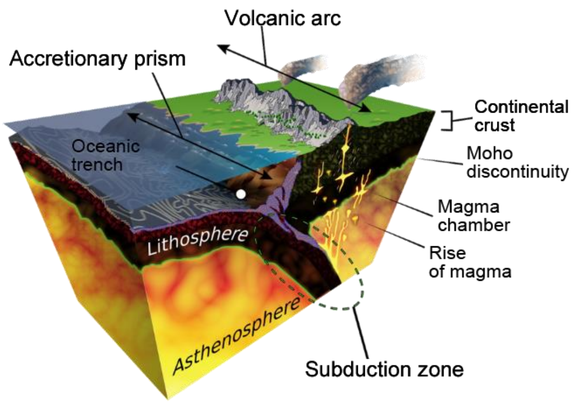

Figure 12: Diagram of a subduction zone (Wikipedia, according to K.D. *Schroeder)*.

The subduction process is slow, with the plate sinking about 1 to 10 centimetres per year (maximum speed in the western Pacific Ocean). Friction produces earthquakes and the melting of the oceanic crust from a certain depth leads to a rise of magma and therefore explosive volcanism on the surface (volcanic arc). During the subduction of the oceanic crust, its upper part, consisting of unconsolidated marine sediments, accumulates on the surface to form a mountain range (accretionary prism).

The possibility of the waste remaining on the surface with sediments has not been fully clarified to date (e.g., [159]). Finally, the conclusions by A. Alden, in 2017 [160], note the difficulty raised by the slowness of the subduction phenomenon, already mentioned by E.A. Silver [158]. He points out that in the Peru-Chile subduction zone, the Nazca plate sinks under South America at an angle of 30 degrees and at a rate of about 7-8 centimetres per year, making it the fastest subduction zone in the world. Under these favourable conditions, he deduces that it would take 10,000 years for waste to move horizontally 600-700 meters and vertically 350-400 meters.

Although the need for geological research was identified in the 1980s (e.g., [161][162]), the expert group advising the **United Kingdom** authorities, the CoRWM, noted in 2004 a lack of knowledge regarding the subduction zone disposal option [163]. In particular, very few studies were available to assess the long-term future of the waste that would be placed there. The group also highlighted the international legal obstacles against various forms of disposal in the seabed (see insert "***Changes in Maritime Law***"), which is a finding subsequently shared by the UK radioactive waste management agency [164][165].

The option for disposal in the subduction trenches was removed from the list of those to be considered by **Canada** in 2005 [5], because of: a) the distance of potential sites and therefore the great distance that the waste would be required to travel, (b) difficulty - judged to be greater than that associated with geological disposal - to maintain monitoring and ensure the retrievability of waste, (c) uncertainty as to the fate of the waste (in particular, of its potential return to the surface during volcanic eruption) and, finally, d) the probable incompatibility of this option with international conventions, since it is implemented from the sea. Some authors (e.g., [166][167]), however, consider that this option is still possible in the Juan de Fuca Trench (Figure 13) by accessing it from land from the Brooks Peninsula on Vancouver Island.

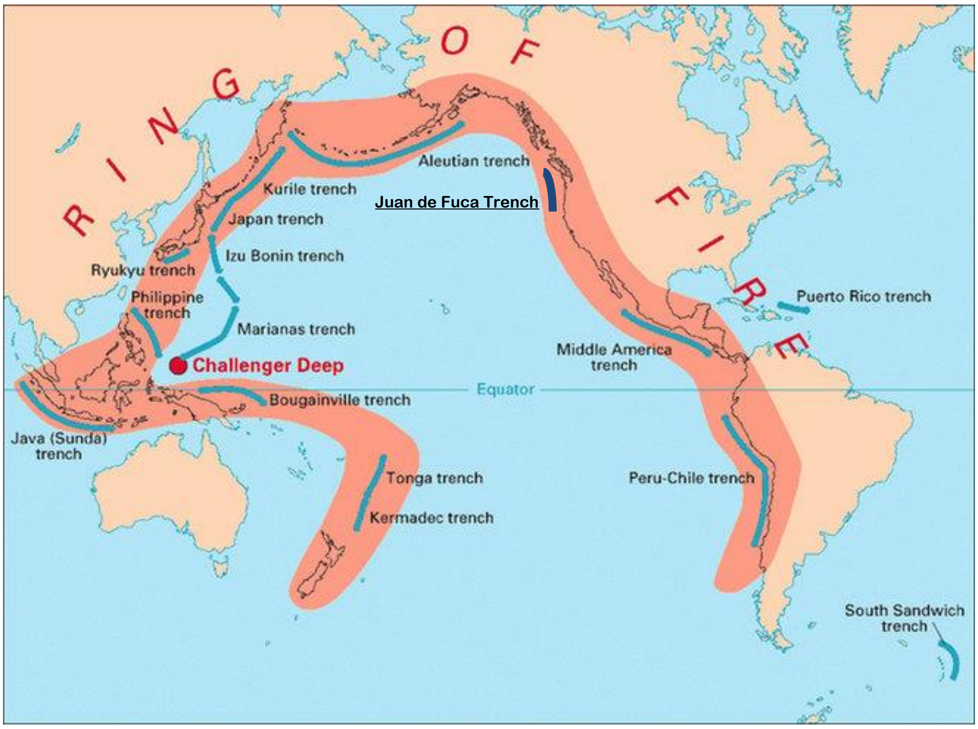

***Figure 13**: Location of the main subduction zones in the world (Live Science, according to USGS, modified).*

6.3 State of the art and perspectives

Of the two options for seabed disposal mentioned in this chapter, none are currently the subject of work within the framework of national radioactive waste management programmes.

Regardless of technical progress or difficulties, the option of deep seabed sediment disposal has been progressively abandoned as a result of changing ethical considerations and the progressive structuring of a more protective international maritime law. Only the option of disposal at sea accessible from land is considered, which in practice is very directly related to geological disposal in an underground facility, for example in the **United Kingdom** (see [168]).

Although not dedicated to high-level waste, it can also be mentioned that facilities, accessible from land but located below sea level, are currently being exploited in Finland and Sweden:

- The Loviisa repository in **Finland** (90 km east of Helsinki) houses low and intermediate level waste. It is carved out of granite about 110 m deep in the Gulf of Finland, from a peninsula of the same name. An extension of this facility is planned to place the waste produced during the dismantling of the nuclear power station located on the same site [169];
- The Forsmark "SFR" storage facility in **Sweden** (140 km north of Stockholm), commissioned in 1988 and operated by SKB, is dedicated to short-lived low-level and intermediate-level waste resulting from the operation of nuclear power plants, as well as medical, industry and research applications. It comprises four 160 m long cavities and a 50 m high silo, carved out of the crystalline rock 50-60 m below the level of the Baltic Sea. Access to the facility is from land through two parallel tunnels one kilometre long. In 2018, the Swedish safety authority [170] approved the plant operator's application for extension of the facility in 2014 [171], to carve six new cavities at a depth of 120 m.

The subduction zone disposal option is, to IRSN's knowledge, currently not being studied by any of the agencies in charge of radioactive waste management.

6.4 And in France?

The various options for disposal at sea and in subduction zones have been studied in France (e.g., [145]), particularly through participation in Sub-seabed Disposal Program until 1986.

France on particular conducted research expeditions to the Cape Verde Abyssal Plain in 1979 and 1980, and in northern Bermuda in 1978. The studies included geological investigations to define the site and studies to characterise the biology. France has also conducted engineering studies on the insertion of penetrators and biological studies on the uptake and transfer of radionuclides by organisms from samples collected during missions [172]. Since then, no technical work or discussion has been pursued.

7 OTHER ALTERNATIVES

7.1 The launching of radioactive waste into outer space

7.1.1 What does it involve?

The principle of this option is to permanently rid the Earth of the most harmful radioactive waste, by launching it into space beyond the atmosphere, using spacecraft. One of the discussions of the teams that worked on the subject relates to the packaging of the waste. This must indeed be designed to remain intact in all accident scenarios considered. Several ultimate destinations have been considered for waste, including the sun.

7.1.2 Ways explored around the world

The shipment of waste into outer space was mainly studied in the **United States** by NASA in the 1970s and early 1980s. Studies focused on long-lived high-level waste resulting from reprocessing spent fuel, this option being therefore considered by the US authorities. However, the use of this option for the management of spent fuel has never been considered, given the great mass of the fuels and the packaging in which it would be necessary to place them, and therefore the energy cost and financial cost of sending such cargoes into space. Studies published in 1974 by Battelle [140] at the request of the US Atomic Energy Commission, assume the reprocessing of the spent fuel, the partitioning of recoverable materials (uranium and plutonium), the packaging of the waste resulting from the reprocessing (mainly minor actinides and long-life fission products) - see the insert "***Radioactivity, nuclear reactions and spent fuel***", Chapter 4.1), the launching of this packaged waste into a low Earth orbit (150-500 km) on board a space shuttle, and then its transport to its final destination using a space tug.

Studies published by NASA in 1978 [173] consider five possible destinations for waste. The surface of the moon (achievable in a few days) and an orbit around the sun (in six months) are those considered to be the most interesting from the point of view of safety. The option of a storage facility on the moon was mentioned, but its cost seemed unacceptable [173].

Among the means envisaged, a space shuttle with an in-orbit transfer vehicle, or a heavy launcher[23] (a process already tested in 1978 during missions on the moon but considered as requiring a technological leap to lighten the cost), were identified as the most suitable.

In its report, NASA also discusses the study programme implemented to design waste packaging. For this design work, thermal resistance and mechanical resistance are particularly important parameters. The waste package must indeed withstand situations of atmospheric transfer and falling to the ground that could result from an accident of the

[23] A launcher is a rocket capable of placing a payload in orbit around the Earth or sending it into interplanetary space. It is called a heavy launcher when it is able to place at least 20 tons of payload in low orbit.

spacecraft, while remaining extremely light (see also [140], mentioning the need for R&D). The development of a retrievability demonstrator in space for a package that was incorrectly sent was also considered by NASA.

NASA's projects have been abandoned due to the excessively high cost and risk of launch failure. More punctual work has however been pursued by researchers from the American aerospace world. In particular, they led to a more thorough examination of launch techniques [174][175], accident risks and economic viability [176]. Raising the risk of future space exploration craft colliding with waste sent insufficiently far from the Earth and astronomical observations being disrupted by these local sources of radiation, Brookhaven National Laboratory researchers have studied the possibility of using an electrostatic gun placed on a shuttle in low orbit or on the moon to send waste containing fission products out of the solar system [177]. The use of an ion thruster as a rocket has also been considered, since this technique is considered to be less energy-consuming than a "conventional" orbit transfer vehicle [178].

Launching waste into outer space has also been studied by other countries, including the **USSR** (e.g., [179][180]) and **Kazakhstan**. Pshenin and Suimenbaev (1996 [181]) studied the shipping of high-level radioactive waste by shuttle from the Kazakhstan base to an intermediate orbit, and assessed the safety during the various stages. They suggested that, for political and economic reasons, the legal, methodological and scientific aspects should be jointly investigated by several countries under the auspices of the United Nations and IAEA.

7.1.3 State of the art and perspectives

In addition to the high costs associated with it (e.g., [163][182][183]), the option of launching radioactive waste into outer space has faced the difficulty of reliable space technology. This difficulty to control risks was highlighted by the accidents of the space shuttles Challenger in 1986 and Columbia in 2003. These accidents led to the discontinuation of the research (e.g., [5]).

7.1.4 And in France?

The option of launching radioactive waste into outer space has not been specifically developed in France.

7.2 Disposal of waste in ice sheets

7.2.1 What does it involve?

The disposal of **exothermic radioactive waste**[24] in the thick layers of **polar ice** ("ice **sheets**") of Antarctica or Greenland consists in placing the containers either on the ice or at shallow depths, so as to cause them to sink gradually by the **melting of the ice** around them. Depending on the mechanism considered, the melting would lead to the gradual descent of the waste into the core of the ice and its imprisonment due to the refreezing of the water at the end of their transit.

7.2.2 Ways explored around the world

Disposal of exothermic waste in ice sheets was investigated by the **United States** until the 1980s (e.g., [140][184][185]). Several options have been considered (Figure 14). They consist in:

- allowing the waste packages to gradually descend to the base of the ice on the bedrock;
- restraining waste packages with cables a few hundred meters long, thus preventing their descent, in order to allow their retrievability for a few hundred years, and allowing an electrical connection to monitor instruments placed at depth;

[24] Exothermic waste gives off heat because of its high radioactivity (energy released during radioactive decay).

- building a surface repository that allows the heat to dissipate and allows the waste packages to be retrievable until the snow finally buries the facility.

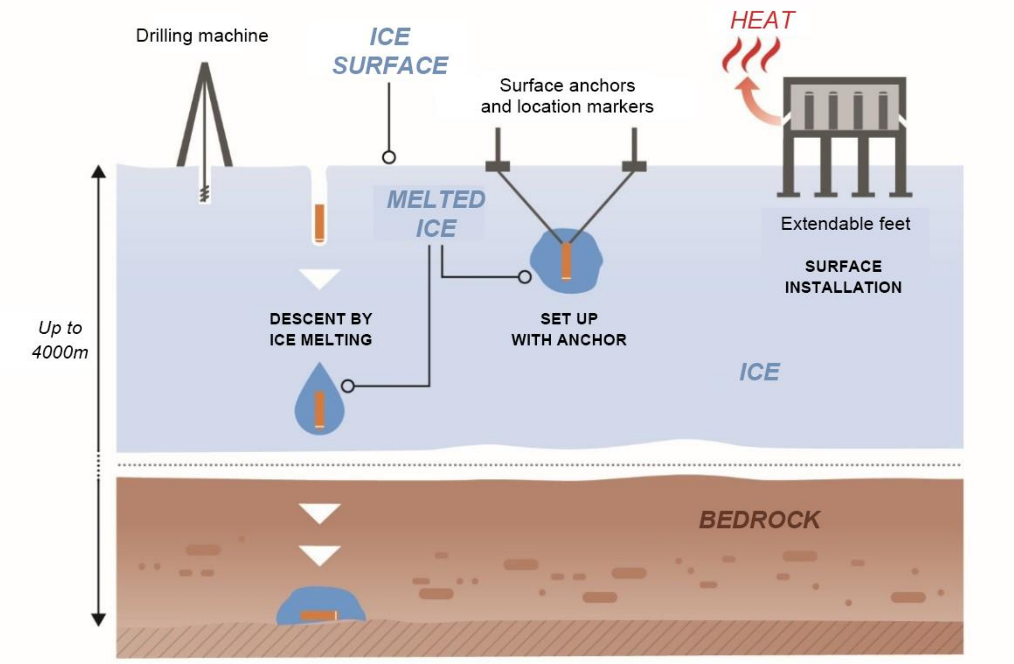

***Figure 14**: Illustration of concepts as envisaged in the United States in 1974 (from [140], modified).*

After the first investigations, the glaciologists revealed the presence of salted pockets trapped in the ice and stressed the risk of extremely rapid corrosion of steels that they could cause. Stability problems associated with the movement of ice on the bedrock and the impossibility to rest assured that the ice caps will remain for the hundreds of thousands of years necessary for the decay of the waste were also put forward [186][187].

Finally, it should be mentioned that this option raises the same concerns as disposal in a marine environment, in terms of the risks associated with the long-distance transport of radioactive waste by ship [140].

7.2.3 State of the art and perspectives

The possibility of disposal of radioactive waste in the South Pole ice sheets is formally excluded by the 1959 Antarctic Treaty. It is also unworkable for countries committed to managing their radioactive waste within their national borders.

An amendment proposal to the 1959 Treaty has, however, been submitted by some signatories (such as the United States: see [140]) who wanted to place high-level waste there. Disposal under the Greenland icecap has also been considered several times [188][140].

7.2.4 And in France?

The option of radioactive waste disposal in ice sheets has not been contemplated in France.

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