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Reversibility and Retrievability (R&R) for the Deep Disposal of High-Level Radioactive Waste and Spent Fuel

Final Report of the NEA R&R Project (2007-2011),
Nuclear Energy Agency, Organisation for Economic Co-Operation and Development (OECD –NEA), December 2011

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Radioactive Waste Management
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Radioactive Waste Management Committee

Reversibility and Retrievability (R&R) for the Deep Disposal of High-level Radioactive Waste and Spent Fuel

Final Report of the NEA R&R Project (2007-2011)
December 2011

This is the final full report of the 4-year international project on Reversibility and Retrievability (R&R) launched in 2007 by the OECD/NEA Radioactive Waste Management Committee. Major milestones in the project have been the conduct of a bibliographic survey, a survey of NEA countries' positions, and discussions within an ever-widening group of interested parties that culminated with an International Conference and Dialogue in Reims, France (December 2010). The report surveys, in an empirical manner, the statements that have been made over the decades about reversibility and retrievability, thereby documenting a history and an evolution across time. It surveys, also empirically, how R&R have been integrated (or not) in national programmes, or in various stakeholders' positions on waste disposal, giving a respectful and empowering grasp of the different conditions in which R&R may be applied. The report proposes definitions and conclusions that reflect the mutual understanding built up in the R&R working group made up of persons from many nations.

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FOREWORD

The most widely adopted policy for the definitive management of high-activity radioactive waste involves its emplacement in deep geological repositories whose safety should not depend on the active presence of man. Repositories are designed to be robust to a large spectrum of events and to prevent the release of their radioactive contents in amounts that would be harmful to man and the biosphere without the need for active control or oversight.

This broadly accepted policy of concentrating and confining the waste in a repository creates *de facto* a situation of potential availability of the waste for future retrieval. To what extent retrieval can or should be further facilitated in designing a repository, and if so over what time scales, are issues of continued interest in OECD Nuclear Energy Agency (NEA) member countries. The intention of the present report is to help national reflections by providing a neutral overview of relevant issues and viewpoints in OECD countries based on the current understanding and views of specialists from the waste management community as well as from stakeholders, opinion leaders and from researchers in the technical and social sciences.

The present document is the full report of the results of a 4-year project and study launched in 2007 by the OECD/NEA Radioactive Waste Management Committee (RWMC), which is a forum of senior national representatives of operator, regulator, policy-making, and R&D organisations in the field of radioactive waste management. The Committee promotes safety in the short- and long-term management of radioactive waste and assists the NEA countries and the wider OECD family by providing guidance on the solution of radioactive waste problems, including consideration of stakeholder confidence.

The Reversibility and Retrievability (R&R) project aimed to improve awareness amongst the RWMC constituency of the breadth of issues and positions regarding these concepts. The goal of the project studies and activities was to acknowledge the range of approaches to R&R, rather than to recommend a specific approach, and to provide a basis for reflection rather than to lead towards a particular conclusion. The study was carried out by a working group on Reversibility and Retrievability, with participation from 15 countries and 2 international organizations. Major milestones in the project have been the conduct of a bibliographic survey, a survey of NEA countries' positions, and discussions within an ever-widening group of interested parties that culminated with an International Conference and Dialogue held in Reims (France) in December 2010. The project is documented online at www.oecd-nea.org/rwm/rr/.

The point of view and intended audience for this report is that of someone planning or designing a repository for high-level wastes or spent nuclear fuel, not that of someone contemplating retrieval. Some of the discussion will also be applicable to related situations such as that of planning a repository for low- and intermediate-level wastes. Note that this is the full report of working group findings. A shorter presentation of the main messages is available in a brochure published by the NEA [Ref. 1].

The report proposes definitions that reflect a mutual understanding built up during the course of the international initiative. It surveys, in an empirical manner, the statements that have been made over the decades about reversibility and retrievability, thereby documenting a history and an evolution across time. It surveys, also empirically, how R&R have been integrated (or not) in national programmes, or in various stakeholders' positions on waste disposal, giving a respectful and empowering vision of the different conditions in which R&R may be applied. The report represents an example of memory preservation in the domain of long-term safe management of radioactive waste and constitutes a statement of knowledge at this point in time.

Acknowledgements

This report reflects the findings of the RWMC working group on Reversibility and Retrievability, which grew in number from about 15 at the start of the project to about 50 at the end the project through a process of assimilation of as many contributors and viewpoints as possible. We would like to thank the many who contributed to the working group by direct participation, or responding to project questionnaires, or commenting on previous drafts of the report.

Financial contributions towards the work on the project were provided by Belgium (ONDRAF/NIRAS), Canada (NWMO), France (Andra), Germany (GRS), Japan (NUMO), Spain (CSN and ENRESA) and Switzerland (Nagra). Participants in the project represented not only these countries, but also Austria, the Czech Republic, Finland, Hungary, the Republic of Korea, Sweden, the United Kingdom, the United States, the European Commission and the International Atomic Energy Agency.

Claudio Pescatore of the NEA was the project co-ordinator, assisted by Richard Ferch, an independent consultant.

EXECUTIVE SUMMARY

Introduction

Interest in reversibility and retrievability (R&R) in geological disposal of high-level radioactive waste and spent fuel disposal has been increasing steadily since the late 1970s. In 2008 the Radioactive Waste Management Committee (RWMC), an internationally established group of high-level experts with regulatory, industrial, R&D and policy backgrounds from the OECD Nuclear Energy Agency (NEA) countries, concluded that: "There is general recognition that it is important to clarify the meaning and role of reversibility and retrievability for each country, and that provision of reversibility and retrievability must not jeopardise long-term safety."

The present report represents another step in this evolution. It documents the results of an NEA RWMC initiative that took place in 2007-2011, with the goal of providing a neutral overview of relevant issues and viewpoints in OECD countries. The "R&R" project enjoyed intellectual contributions from 15 countries plus the International Atomic Energy Agency (IAEA) and the European Commission (EC) as well as other working parties of the RWMC: the Forum on Stakeholder Confidence (FSC), the Integration Group for the Safety Case (IGSC) and the RWMC Regulators' Forum. There were five project meetings involving about 50 persons, and one major International Conference and Dialogue involving over 180 participants. The R&R project benefitted from inputs by and exchanges among representatives of waste management organisations, regulatory agencies, policy making bodies, and civil society at large, including social scientists and community leaders.

Terminology

Terminology matters a great deal when discussing R&R and geological repository concepts. For the sake of clarity, the project produced its own definitions of key terms:

Reversibility describes the *ability in principle* to reverse or reconsider decisions taken during the progressive implementation of a disposal system; **reversal** is the concrete action of overturning a decision and moving back to a previous situation.

Retrievability is the *ability in principle* to recover waste or entire waste packages once they have been emplaced in a repository; **retrieval** is the concrete action of removal of the waste. Retrievability implies making provisions in order to allow retrieval should it be required.

Observations on reversibility

Reversibility requires conceiving and managing the implementation process and technologies in such a way as to maintain as much flexibility as possible so that, if needed, reversal or modification of one or more previous decision(s) in repository planning or development may be achievable without excessive effort. Reversibility implies a willingness to question previous decisions and a culture that encourages such a questioning attitude. Reversibility can best be accommodated within a stepwise decision-making process.

While always ensuring that safety requirements are met, such a process should also allow for adaptations or changes in direction, taking into account information gained during the implementation process.

For stepwise regulatory and policy decisions to be credible, they must be reversible or at least modifiable in the light of new information, to the extent that this is practicable. The reversibility of a planned decision should probably be discussed ahead of time. Whether expected or not, modification of any given decision always exists as a contingent possibility, even when the decision maker's intention is clearly to eliminate all but the selected option. The question is whether to incorporate planning for this contingency within a defined decision-making process, in analogy with emergency preparedness, or to choose to discount or ignore this possibility, which, in case of surprise reversal, could lead to loss of confidence in the foresightedness and adequacy of programme arrangements. Moreover, when decisions are reversed by authority in an ad-hoc fashion, this may be seen as arbitrary and create mistrust. One may conclude on this basis that reversibility should be framed by a transparent, predefined process.

In stepwise decision making the decision maker normally identifies hold points at which a deliberation should be made whether or not to reverse earlier decisions, and the resulting determination be recorded. Criteria for this determination ought to be agreed to ahead of time. The societal reason for introducing reversibility into waste management arrangements should not be to make reversal painless; it should be so that "*if you do determine you need to reverse, the amount of effort needed to reverse is reasonable*". In the same vein, reversibility of decisions implies, for the organisations implementing disposal, to build in waste retrievability provisions so as not to pose unnecessary obstacles to retrieval.

A major contributor to flexibility, reversibility also provides opportunities for continued dialogue, co-ordination and shared decision making. However, it must be recognised that the flexibility introduced by reversibility decreases with time, and in the interest of transparency this must be communicated to stakeholders.

Observations on retrievability

In the national programmes that include retrievability as a declared feature in implementing a final repository, the goal is not to make future retrieval easy or cost-free; it is simply to ensure that waste retrieval is feasible, assuming a future society that is both able to carry it out and willing to do so (*e.g.*, having determined that retrieval is financially viable). Those programmes that include retrievability mention three main reasons: (a) having an attitude of humility or open-mindedness towards the future; (b) providing additional assurance of safety; and (c) heeding the desires of the public not to be locked into an "irreversible" situation.

While some national programmes require retrievability before closure for operational safety reasons, none require retrievability after closure for basic safety reasons, *i.e.* as a fundamental safety feature of waste disposal. Accordingly, the regulations for these programmes do not require that retrieval be demonstrated in practice. They require only that retrieval could be exercised in principle.

During the operational phase of a repository, reversibility and retrievability translate into practice a prudent approach to waste disposal (*i.e.*, a response to uncertainty regarding the adequacy of our disposal arrangements). During all repository life phases, waste retrieval is facilitated by the very fact of confinement (non-dispersion) and containment of the waste in a limited volume, which is part of the concept of any geological repository. In the distant future, waste will be still retrievable, although with greater effort and expense as time passes. Retrievability is thus a matter of degree, rather than of the presence or absence of any possibility to retrieve the waste. Actions today may be taken to facilitate to some extent the ability to retrieve (retrievability), and research and development may in future provide ways to improve retrievability and reduce the degree of difficulty of retrieval.

At the technical level, the application of retrievability provisions will depend on such factors as the host geology, engineered barrier concepts, and the lifecycle phase(s) of the repository during which retrievability is desired. The incorporation of retrievability into a repository design will require a willingness to question whether proposed barriers or the construction materials and geometries would not constitute unnecessary obstacles to retrieval, if that was later decided (clearly some materials are more easily removable than others, *etc*.). At the same time, any choices that could facilitate retrieval must also be such that they would not jeopardise the integrity of the facility. Examples of provisions increasing retrievability include: more durable waste forms and waste containers, longer periods granted before closing galleries and the final repository, and buffer and backfill materials that are easier to remove.

Although the long-term safety case must be able to stand on its own without post-operational institutional oversight (*i.e.* must demonstrate passive safety), specific oversight provisions, such as monitoring and memory keeping, may nevertheless be decided upon. If so, these may further contribute to decision making relative to retrieval post-operation, and to the freedom of choice provided to future generations.

A mechanism for communicating the relationship between retrievability and the phases of development of a repository has been developed within the project, and tested in a number of national programmes. This "R-scale" provides a graphical depiction of the phases of development of a repository and demonstrates the evolution of the ease of retrieval, elements of passive safety and elements of active control as the repository evolves. This scale has been found to be a useful communications tool when applied in some national programmes.

Retrieval of more than few waste packages, if carried out one day, would be a major decision. If decided upon at later stages of a disposal programme, retrieval would be costly and would pose safety hazards. Handling of the retrieved waste would pose radiation hazards to workers, and new facilities may have to be constructed to contain and process the wastes safely. Retrieval would be a new, regulated activity and it would require the same high-level societal scrutiny and authorisations that were needed originally to permit the emplacement of the waste in the repository. Justification and optimisation would be required, as for any other activity involving radiological hazard. These points must be communicated and taken into consideration when making decisions about retrievability provisions.

Principal project activities

The R&R project was framed by two outreach activities: a questionnaire sent to NEA member countries in 2008 at the beginning of the project, and the Reims International Conference and Dialogue in December 2010 near the end of the project.

Between these two activities there was a series of meetings at which working group members and invited experts defined terms and discussed a variety of topics related to reversibility and retrievability. Their findings are detailed in the present report. An extensive stand-alone bibliography was compiled [Ref. 2]. In parallel a leaflet containing the "R-scale" graphical depiction of repository development was discussed and tested with stakeholders of various countries. The four-page leaflet "International Retrievability Scale" is being translated into several languages (the English version is presented in annex to this report). Each of the project documents (including the summarised questionnaire replies [Ref. 3] and the Reims Conference Proceedings [Ref. 4]) may be obtained on line at www.oecd-nea.org/rwm/rr/.

The R&R questionnaire

The responses to the 2007 questionnaire revealed a wide diversity of approaches to R&R in national policy and legislation, ranging from requirements in law for reversibility or retrievability in some countries, to no formal mention in others. Nevertheless, even in those countries where R&R were not enshrined in law or policy, the institutions involved generally recognised these to be potentially important issues. Some of the differences seen between countries could be attributed to technical differences in host geology and reference repository design (affecting, for example, the ability to keep galleries open for extended periods after emplacement). Perhaps more importantly, the variations appeared to reflect the distinct histories of repository development in different countries, as well as their particular social, cultural and legal environments. Given these underlying differences, the diversity in approaches to R&R is not unexpected. The analysis of the questionnaire and later discussions revealed however that, at the policy level, there is general agreement across different programmes and nations that waste should be emplaced in a final repository only when there are policy and regulatory decisions ensuring that:

- The "waste" is actually waste and not a potential resource. By definition, "disposal" implies no intention to retrieve. If there is some *intention* to retrieve, the situation calls for interim storage, not final disposal. In a disposal programme, retrieval is at most a contingency, and retrievability is the means to plan for that contingency;
- The regulations on the protection of man and the environment are complied with. This means that disposal rooms in their final configuration, or a closed repository, must be licenced as safe without consideration of retrievability. The ability to retrieve is not an excuse for moving forward on a disposal project if passive safety has not been demonstrated convincingly;
- Stakeholders have been involved appropriately.

Some of the above terms are not given identical meaning in different programmes. Care is thus advised to define the above terms clearly in programme documents and to use them consistently. In particular, it is important that provision of the *ability to retrieve* (retrievability) should not be confused with the *actual process of retrieval*. The terminology clarified through the project is discussed in the present report.

Reims International Conference and Dialogue

The International Conference and Dialogue on Reversibility and Retrievability (Reims, France, December 2010) brought together over 180 participants from 14 countries, including regulators, policy makers, experts in social sciences, representatives of civil society and stakeholder groups in addition to waste management implementers. The meeting of these diverse "communities of interest" greatly aided in elaborating viewpoints on theoretical and practical issues. Conference discussions helped communicate the work of the project to a wider audience and facilitated new understanding within the R&R working group. In particular the dialogue produced a heightened realisation that reversibility is not so much about reversal of decisions itself as it is about ensuring continued participatory decision making. The discussions at Reims also highlighted the importance of integrating expertise on the social sciences into the repository development, R&D and decision-making processes. The spirit of conference findings was captured in the following statement: "R&R are not a destination, but a path to be walked together"

Like the initial questionnaire, the International Conference and Dialogue revealed the diversity of terminology between programmes and communities of interest. It once again demonstrated the importance of distinguishing clearly among the concepts of reversibility, retrievability and retrieval, and of developing shared understandings on concepts.

Overall observations

Reversibility and retrievability requirements have been introduced in a number of countries at the legislative or policy levels. The social pressures leading to these requirements may have been more in the direction of avoiding irreversible steps or even of preserving the ability to participate in future decision making, rather than of specifically requiring ease of retrieval. The ability to access materials that may become valuable at a future time and the ability to continue to directly monitor conditions in the repository are dominant social demands. Further demands for provisions that would ease retrieval may be motivated by unfamiliarity with (or lack of confidence in the maturity of) the disposal technology, by discomfort with the concept of purely passive safety without any means of oversight or active control, and/or by a desire to avoid making decisions today that may preclude different actions in the future. A number of these drivers may decrease over time as the level of familiarity and trust in a programme increases and as actual performance and tests justify more and more confidence in the disposal system. An extended period of control may also increase familiarity and willingness to accept passive/intrinsic safety.

In this context, the inclusion of retrievability provisions and the application of reversibility in approaching decisions making may be seen as mitigating a risk, namely the risk that a repository project will not go ahead and that the wastes will be left in a state that may be untenable in the long term.

Geological disposal, as currently envisioned in all national programmes, is in principle always a reversible technology. Even long after institutional oversight may have ended, and beyond the time when the integrity of waste containers can be assumed, waste recovery would still be possible, although it would be a major engineering endeavour that would require high resolve, resources, and technology.

When considering the incorporation of retrievability into a repository programme, it is understood that during the lifetime of a repository, retrieval would become successively more difficult as the repository takes on its final shape and function. In particular, safety considerations, as well as obligations related to physical protection and safeguards, impose constraints on the degree to which retrievability provisions may be incorporated into a repository programme.

While reversibility and/or retrievability are important aspects of policy or legislation in an increasing number of national programmes, there is a wide variety of approaches to the subject. Indeed, no two programmes appear to be the same in this respect. The social, legal and technical environments within which programmes are situated vary from place to place, and also change as time passes. It is clear that there is no "one size fits all" approach that can be applied to all situations. Nevertheless, there are some factors and aspects that are common to many, if not all, programmes.

The current predominating view is that reversibility of decisions and retrievability of the waste can be beneficial features of any deep disposal programme provided the limitations of the concepts are recognised. The position of many national programmes is that, from a technical point of view, flexibility in implementing the repositories is a recognised management approach, and represents a means for process optimisation. Reversibility can be a major contributor to this flexibility.

Overall, it seems that the nature of the process of repository implementation and decision making is vital. In a long-term project such as a repository for high-level or spent fuel waste, the end-result of the undertaking may well be different from the original design, taking into account changes that may be introduced during the development phase for various reasons. There must be continued research and continued questioning and, because of that, adaptability to new learning. Intermediate decisions must be, to some degree, reversible or modifiable if they are to be credible. The sensible approach to this situation is a stepwise process of learning, testing, questioning, implementation, and more questioning. Reversibility is an intrinsic part of this process, and retrievability is a technical means for achieving reversibility.

Deep geological repositories of radioactive waste are designed and licenced based on long-term safety not requiring the active presence of man. Reversal of decisions and retrieval of the waste are not design goals. Reversibility and retrievability, however, are attributes of the decision-making and design processes that can facilitate the journey towards the final destination of safe, socially-accepted geological disposal. Having reviewed the literature on reversibility and retrievability and reflected on how these concepts have been discussed and introduced in connection with national waste management programmes, it can be concluded that countries should have a position on reversibility and retrievability.

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1. INTRODUCTION

1.1 Background

Reversibility and retrievability (R&R) are concepts that have been considered for many years in radioactive waste management, as witnessed by the following:

- In 1969, the United States National Academy of Sciences, in its report to Congress titled *Technology: Processes of Assessment and Choice*, observed that: "Other things being equal, those technological projects or developments should be favored that leave maximum room for maneuver in the future. The reversibility of an action should thus be counted as a major benefit; its irreversibility, a major cost." [Ref. 5]

- One of the *Proposed Goals for Radioactive Waste Management*, in the NUREG-0300 document dated 1978 [Ref. 6] and prepared by a task group for presentation to the United States Nuclear Regulatory Commission, reads as follows: "If wastes are disposed on earth, their retrievability - assuming a technology as advanced as present - should not be precluded."

- The WIPP disposal facility for low- and intermediate-level long-lived radioactive waste is licenced based on its waste being, in principle, retrievable over a period of a few centuries after closure of the repository [Ref. 7].

- Low-level short-lived radioactive waste disposal facilities in some countries are operating based on the retrievability concept. In some cases (Spain) specific design adaptations were required by the regulator.

Interest in reversibility and retrievability of high-level radioactive waste and spent fuel has been steadily increasing since the late 1970s, as can be observed from a bibliography prepared during the R&R project [Ref. 2], and from the remainder of the present document. There still exist open issues. In 2008 the NEA RWMC, in its Collective Statement on "Moving Forward with Geological Disposal of Radioactive Waste" [Ref. 8], concluded that: "There is general recognition that it is important to clarify the meaning and role of reversibility and retrievability for each country, and that provision of reversibility and retrievability must not jeopardise long-term safety."

This report deals with the concepts of reversibility and retrievability for the deep disposal of high-level radioactive waste and spent fuel. It documents the results of an initiative which was started by the NEA in 2007 (see Box 1) with the goal of providing a neutral overview of relevant issues and viewpoints in OECD countries, drawing on the current understanding and views of specialists from the technical waste management community as well as from other stakeholders and opinion leaders and from researchers in the technical and social sciences. The present report does not attempt to detail all of these discussions, but focuses on some of the most important issues and findings.

Although some issues that would be faced when actually planning to retrieve wastes are mentioned, the point of view and intended audience for this report are primarily related to planning or designing a repository for high-level wastes or spent nuclear fuel, not to retrieval *per se*. Some of the discussion will also be applicable to related situations such as that of planning a repository for low- and intermediate-level wastes.

BOX 1: The NEA R&R Project

The NEA R&R initiative leading to this report is documented at www.oecd-nea.org/rwm/rr/. The modus operandi of the project has been one of continuous refinement of its findings through the involvement of an increasingly wide spectrum of interested parties and viewpoints.

The project was carried out in several phases:

- The first phase, in 2007-2008, was the compilation of a bibliography of references on the topics of reversibility and retrievability [Ref. 2]. The bibliography was updated through 2010.
- The second phase gathered data through a questionnaire on the current status of disposal programmes in NEA member countries with respect to the role(s) of reversibility and retrievability in those programmes [Ref. 3]. The questionnaire was issued in May 2008. A working group was convened and a series of meetings were held at which the responses were analysed, following which topical discussions were held on a variety of subjects arising from the analysis.
- The third phase was the preparation and holding of an International Conference and Dialogue, 14-17 December 2010 in Reims, France [Ref. 4]. A previous draft of the present report and of the project's leaflet on R&R (see annex) served as discussion documents for the conference.
- The fourth phase consisted of the finalisation of the project and its documentation in the latter half of 2011, leading to this publication, and the publication of a short NEA brochure synthesising main messages [Ref. 1].

1.2 Structure of the report

This report is structured as follows:

Chapter 1 introduces the report and provides background.

Chapter 2 provides an overview of the historical evolution of the retrievability and reversibility concepts since the late 1970s. It observes that R&R are linked to the guiding principle of preservation of options for future generations. It notes that one important reason why there is difficulty in discussing reversibility and retrievability is that important basic terms and concepts are understood differently by different stakeholders or used differently in the different countries. This chapter also defines the terms used in the report.

Chapter 3 reviews some of the major considerations in relation to reversibility in the context of decision making for repository development. Decisions will follow one another sequentially and will be reviewed, and at times determined, by the regulator or safety authority. Hence substantial attention is given in this chapter to regulatory issues. Communication aspects are also covered and a generic, international "Retrievability scale" is presented, which describes how retrievability evolves across the major phases of management and disposal of waste and the subsequent states of a repository.

Chapter 4 outlines some of the major considerations in relation to retrievability during the various repository life phases. It identifies the determining factors that impact the potential for waste retrieval and/or reversal. Technological challenges and non-technical aspects as well as associated costs and safeguards issues are discussed in this chapter. Benefits and shortcomings are summarised.

Chapter 5 summarises the similarities and differences of reversibility and retrievability in various NEA countries and the views of the R&R working group members to that effect. Countries deal differently with the subjects of R&R. While there is considerable agreement on many of the principles underlying reversibility and retrievability, there is less degree of unanimity on whether and how these principles may be put into practice in disposal programmes, reflecting the diversity of cultural and historical environments in which these programmes exist. This chapter also summarises the key outcomes of the International Conference and Dialogue on Reversibility and Retrievability held in Reims, France in December 2010 [Ref. 4].

Chapter 6 presents major observations and conclusions of this report.

2. HISTORICAL PERSPECTIVE AND TERMINOLOGY

As observed in Section 1.1, reversibility and retrievability (R&R) as concepts have been considered for many years in radioactive waste management. R&R are responses in part to a guiding principle of preserving for future generations a certain degree of freedom of choice. This guiding principle has arisen both in technical documents and through societal feedback, and must be taken into consideration together with other principles identified in international guidance governing radioactive waste disposal.

Terminology matters a great deal when discussing repository concepts and R&R. In this chapter we define terminology for the purpose of this report, in order to avoid potential diverging or confusing uses of major terms and concepts. Ultimately, it is important when communicating on the subject that basic terms and concepts be understood by the parties involved. It is also paramount that differences in national terminology be recognised and taken into account when performing international comparison studies.

2.1 Overview of developments during the past three decades

Since the late 1970s, there have been discussions and positions taken on R&R in almost every national repository programme.

From the 1980s the example may be given of the KBS-3 disposal study report [Ref. 9], which observed: "It must be assumed that future generations will bear the responsibility for their own conscious actions. What is of importance in this context is to provide them with the best possible information as a basis for their decisions, *i.e.* to make sure that information on the location, design and function of the final repository is carefully recorded and preserved. If, at some time in the future, people wish to retrieve and recover the copper or the spent fuel present in the final repository, they will then be aware of and able to cope with the radiological risks." Dating from the 1980s is also the generic regulatory position of the US Environmental Protection Agency (EPA) applicable to any spent nuclear fuel or high-level or transuranic waste disposal facility in the USA, which states that "Disposal systems shall be selected so that removal of most of the wastes is not precluded for a reasonable period of time after disposal" [Ref. 10].

- It is of interest to observe that, in the KBS study of 1983, retrieval of the waste is predicated not on safety, but on allowing future generations a freedom of choice on retrieving useful materials. Retrievability is presented not as requiring special technical provisions, but as a feature that is inherently present at all stages of a repository's lifecycle and that needs to be supported through information preservation provisions.

- The EPA regulations explain that retrievability is mandated in order to provide *added confidence* in meeting the containment requirements of the regulations. That is, if waste stays retrievable over a certain period of time, this also means that it will not have dispersed in nature. In this sense, retrievability offers an additional assurance of safety, although it is not a requirement for safety. The inclusion of retrievability in regulation is described, additionally, as allowing further freedom of choice to future generations, including for safety reasons: "The intent of this provision (191.14(f)) was not to make recovery of waste easy or cheap, but merely possible in case some future discovery or insight made it clear that the waste needed to be relocated." Because in this context retrievability is meant to play a confidence-boosting, just-in-case role, EPA indicates that retrieval needs to be feasible, but not that it need be prepared for: "To meet this assurance requirement, it only needs to be technologically feasible (assuming current technology levels) to be able to mine the sealed repository and recover the waste—albeit at substantial cost and occupational risk." Later, the WIPP repository was certified for operation in 1998 based on the above requirements[1].

In the 1990s the debate over retrievability moved from the question of *not unnecessarily impeding* retrieval towards the question of *facilitating* potential retrieval, *e.g.*, through specific design provisions and adaptive decision making. This happened on grounds not only of further favouring the freedom of choice of future generations and in response to concerns that safety issues may arise in the course of time, but also in order to respond to demands from some segments of society.

- In 1991, the French Radioactive Waste Act requested a feasibility study of a deep geologic repository, with or without the provision of reversibility. During the siting phase of the Underground Research Laboratory (URL) (1992-1998) reversibility appeared to be a significant issue for public acceptance and decision makers, and the government requested that "a logic of reversibility" be followed in developing disposal systems [Ref. 11].

- Another example is the conclusions of the Seaborn environmental assessment panel's 1998 report on the original Canadian repository concept [Ref. 12]. The panel stated that there was not yet sufficient societal acceptance of the concept to proceed. Among the reasons given for this lack of acceptance was a desire on the part of many stakeholders for the concept to better accommodate monitoring, retrieval, recycling and the emergence of new technology.

- An NEA survey published in 1999 [Ref. 13] observed that: "The implementers and regulators are more willing than ever to heed the wishes of the public in so far as these do not compromise the safety of disposal facilities. One common wish is for strategies and procedures that allow long-term monitoring, with the possibility of reversibility and retrievability. A number of programmes now consider these issues explicitly."

- In June 2000, the German Government declared a moratorium on further developing the Gorleben site for HLW and spent fuel disposal [Ref. 14]. One of the reasons given was the need to wait for further developments in the field of retrievability.

A strong technical focus on retrievability was also maintained throughout the period. International technical workshops were held, *e.g.*, one hosted by Nagra in 1997 and one by Andra in 1998. Experiments on retrieval were carried out by SKB [Ref. 15] and Nirex [Ref. 16]. The Swedish regulator commented positively on the Swedish developments as follows: "Even if there can be no question of planning for retrieval when it ultimately comes to the final disposal stage, *i.e.* of viewing the repository as an interim storage facility, SKI is of the opinion that SKB must develop methods for retrieval. In SKI's opinion, methods for retrieval should be developed and full-scale demonstration conducted no later than when a decision is made to start a detailed investigation. Therefore, it is positive that SKB has started to study retrieval technology and SKI is looking forward, with interest, to the results of the planned retrieval experiment at the Äspö Hard Rock Laboratory" [Ref. 17].

The first major international publication dedicated to retrievability is the proceedings of a seminar held in Sweden in 1999 [Ref. 18]. The papers presented covered a wide range of topics related to the subject, and these proceedings may still be considered the most comprehensive and detailed international

[1] In 1996, the EPA released its regulation specific to the WIPP site (40 CFR 194). According to this regulation waste removal had to be shown to be feasible using existing technology, and the licensing application had to include plans for removal in case the EPA were to revoke certification.

reference on retrievability (prior to the publication of the proceedings of the 2010 International Conference and Dialogue organised by the R&R project [Ref. 4]. At approximately the same time, the European Commission (EC) sponsored a study called the *Concerted Action on the Retrievability of Long Lived Radioactive Waste in Deep Underground Repositories* [Ref. 19]; several of the contributors to this study also presented papers at the Swedish conference. In parallel, the NEA published its summary report *Reversibility and Retrievability in Geologic Disposal of Radioactive Waste – Reflections at the International Level* [Ref. 20]. Box 2 below reports factors invoked by the latter report in favour of and against retrievability.

BOX 2: Possible factors favouring and opposing retrievability provisions [Ref. 20]

Factors potentially favouring the choice to integrate retrievability into a design concept:

- technical safety concerns that are recognised only after waste emplacement and/or changes in acceptable safety standards;
- a desire to recover resources from the repository, e.g. components of the waste itself, or the recognition or development of some new resource or amenity value at the site;
- a desire to use alternative waste treatment or disposal techniques that may be developed in the future;
- a desire to respond to changes in social acceptance and perception of risk, or changed policy requirements.

Factors potentially opposing the choice to integrate retrievability:

- present uncertainty about negative effects of retrievability provisions, including conventional safety and radiological exposure of workers engaged in extended operations and/or associated monitoring, or perception that gains are marginal in regard to such risks;
- the possibility of failure to seal a repository properly, due to the adoption of extended or more complex operational plans to favour retrievability;
- the need to protect against irresponsible attempts to retrieve or interfere with the waste during times of political and/or social turmoil when safeguards and monitoring features are no longer in place;
- a possible need for enhanced nuclear safeguards.

The NEA report [Ref. 20] introduced the reversibility as a concept distinct from that of retrievability. Inspiration was taken from the EKRA-I study [Ref. 21], which is part of the basis of the current Atomic Law in Switzerland, and from a contribution by the Swedish implementer T. Papp (SKB) in 1998 [Ref. 22], where he introduced the concept of “backtracking”, *i.e.* “The ability to retract any step in the stepwise sequence of conditioning, deposition, backfilling and closure”. In practice, in a reversible approach the opportunity of retrieving the waste may be examined at each major decision. A sequence of shared decisions confirming at each step that there were no safety reasons for retrieval could ease any decisions on moving forward and eventually closing the facility.

In 2003, the Committee on Radioactive Waste Management (CoRWM) was established to consider options for safely managing the UK's higher activity waste and to make recommendations on long term solutions. Retrievability of waste was one of the issues considered by CoRWM in the course of its review. In its report [Ref. 23], CoRWM considered both immediate disposal and phased disposal in which backfilling and sealing would be deferred in the interests of flexibility.

Large-scale experiments at the Äspö underground laboratory in Sweden have included not only experiments on canister retrieval [Ref. 15], but also the dismantling of a prototype repository, which is expected to produce information that would be relevant to post-closure retrieval from such a repository [Ref. 24].

In addition to the various developments in individual national programmes, there have been two publications from international agencies that bear importantly on the topic. The first of these is an NEA report entitled *Stepwise Approach to Decision Making for Long-term Radioactive Waste Management - Experience, Issues and Guiding Principles* [Ref. 25], which deals with topics related to adaptive, staged or stepwise decision making, including reversibility. The second is an IAEA report on *Disposal of Radioactive Waste: Technological Implications for Retrievability* [Ref. 26], which focuses on technical issues related to retrievability.

On the technical side, the European Commission-sponsored ESDRED project investigated two case studies, based respectively on the French (Andra) repository concept (horizontal disposal holes excavated in a clay host formation) and the German (DBE-TEC) repository concept (vertical boreholes drilled in a salt host formation). The studies (implemented by NRG – The Netherlands) have confirmed in both cases the technical capacity to retrieve the waste canisters [Ref. 27].

The Implementing Geological Disposal – Technology Platform (IGD-TP) was launched in November 2009 with support from the EC via the Secretariat SecIGD project [Ref. 28]. The SecIGD is driving the development of the Strategic Research Agenda (SRA) for subsequent implementation as part of the Deployment Plan. Retrievability is considered to be one of the key topics of the SRA.

Also in the first decade of the 21st century, two important events took place involving retrievability: (a) the actual retrieval of a waste package at WIPP on two occasions, because of concerns of quality assurance. The first retrieval was requested by an environmental regulator, and the second was undertaken on the initiative of the implementer [Refs. 29, 30; and (b) the active consideration given to the retrieval of waste emplaced at that time in the Asse mine [Ref. 31]. Although the retrieval of waste at Asse is not considered to be representative of the course of events to be expected in a future repository for high level waste, the history and difficulties encountered are nevertheless informative in this context.

In March 2010, the US Department of Energy (DOE) filed a motion to withdraw from the NRC's regulatory process the licence application for a high-level nuclear waste repository at Yucca Mountain. After consideration and testimony from interested parties, the Atomic Safety Licensing Board (ASLB) (an independent adjudicatory body that hears NRC licensing cases) denied DOE's motion on the grounds that, once the licence application has been accepted by NRC for review, the 1982 Nuclear Waste Policy Act does not envision an outcome other than a formal decision on the merits of the application. At the date of the present report, NRC had not yet finalised its review of the ASLB decision [Ref. 32]. DOE's request to withdraw its licence application for Yucca Mountain and subsequently eliminate Yucca Mountain from consideration in the United States has also illustrated the importance and complexity of the topic of reversibility.

Subsequently, retrievability was one of the subjects discussed at hearings of the Blue Ribbon Commission on America's Nuclear Future on waste disposal approaches and options [Ref. 33]. In its draft report to the Secretary of Energy, the BRC considered the role of reversibility and retrievability and recommended that a reversible staged adaptive process be adopted in the US [Ref. 34].Whether or not retrievability is eventually incorporated into future US plans and requirements, it is clearly an important part of the debate leading up to those plans and requirements.

Most recently, the European Council, in the preamble to its 2011 Directive on the management of spent fuel and radioactive waste, recognised the potential incorporation of reversibility and retrievability as operating and design criteria in disposal systems [Ref. 35].

Current interest in the topic of R&R is documented in the present report of 2011, which presents the findings of the latest (2007-2010) NEA initiative in this area. The project's specific goals have been (i) to bridge regulatory, policy and implementation positions; (ii) to bring together specialists and laymen in order to review the efforts and national positions so far; (iii) to engender a more comprehensive understanding of the issues at play; and (iv) to document these findings.

2.2 Underlying principles

The 1995 IAEA *Safety Fundamentals on Principles of Radioactive Waste Management* [Ref. 36] identified the following two principles to guide waste disposal:

- **Protection of future generations**: radioactive waste shall be managed in such a way that predicted impacts on the health of future generations will not be greater than relevant levels of impact which are acceptable today.

- **Burdens on future generations**: radioactive waste shall be managed in such a way that will not impose undue burdens on future generations.

This 1995 document has since been superseded by a newer (2006) Safety Fundamentals document [Ref. 37] which subsumes both of the above principles in a single fundamental principle:

- **Protection of present and future generations**: people and the environment, present and future, must be protected against radiation risks.

The supporting text describing this fundamental principle of protection makes it clear that both of the previous principles are considered to be aspects of this fundamental principle:

> "Where effects could span generations, subsequent generations have to be adequately protected without any need for them to take significant protective actions"; and

> "Radioactive waste must be managed in such a way as to avoid imposing an undue burden on future generations; that is, the generations that produce the waste have to seek and apply safe, practicable and environmentally acceptable solutions for its long term management." [Ref. 37]

The waste disposal literature contains, in addition, frequent references to a third guiding principle, namely that of preserving options for future generations. An early formulation [Ref. 36] which is still valid today is as follows:

- **Preservation of options for future generations** As knowledge is increasing with time, and where value judgements are changing, future generations shall be given the freedom to make their own decisions with regard to the utilisation of resources for safety and long-term protection. Furthermore, a repository should not be designed so that it unnecessarily impairs future attempts to retrieve the waste, monitor or repair the repository.

Examples of recognition of this guiding principle include references to early studies and regulations, such as [Ref. 6, 9, and 10]. In 2010, the positions reported by the Belgian and Canadian programmes are also in line with this guiding principle [Ref. 3]. A more generalised form of this principle is the NAS formulation of the precautionary principle:

- **Precautionary principle in selecting technical options** "Other things being equal, those technological projects or developments should be favored that leave maximum room for maneuver in the future. The reversibility of an action should thus be counted as a major benefit; its irreversibility, a major cost." [Ref. 6]

The EKRA-2000 study [Ref. 21] on which the Swiss "monitored long-term geological disposal" concept relies can be related to the application of the latter guiding principle. After examining various options based on a hierarchy of values as reported in Box 3, the study concludes: "In the event that in-depth investigations as part of concrete projects show that the concept of monitored long-term geological disposal can provide a level of safety which is comparable with that of geological disposal, then the former should be the preferred option given the easier reversibility which it offers."

Both the EKRA and KASAM studies involved ethicists in the formulation of the reference guiding principles. Associated with all the above principles is, in Andra's view, an attitude of "modesty and humility", which promotes a prudent approach when considering the level of scientific knowledge at any given time. [Ref. 39, section 2; Ref. 40]

BOX 3: EKRA-2000's values and objectives and their evaluations for radioactive waste disposal concepts in Switzerland [Ref. 21]

EKRA defines the values and objectives of radioactive waste disposal and organises and evaluates them hierarchically. Highest priority is assigned to safety:

- safety of man and the environment
- freedom for every generation, fairness between social and population groups and between generations
- observing the "producer pays" principle
- acceptance

Much of the controversy surrounding retrievability is associated with the potential conflict between the guiding principle of reducing undue burdens on future generations and the guiding principle of preserving their options. While preservation of future options allows future generations to make their own decisions in the light of new information and changing needs, the mere fact of preserving the option of choice inevitably imposes burdens, including as a minimum the burden of having to conduct a decision-making process. There may also be more tangible burdens. In preserving options for future generations, if it were decided to keep a repository open to facilitate retrieval of its contents, these tangible burdens could include: (i) operational exposures, (ii) continuing risks of accidental releases; (iii) financial provisions to cover operating costs; and (iv) the need to support continuing reliance on institutional control. The NAS guiding principle of avoiding or limiting irreversible choices represents one way of reconciling or balancing these two other principles.

A recent NEA study [Ref. 41] has investigated what countries may consider as "undue burden". The term "undue burden" was interpreted by some country respondents to mean financial burden, and by others to mean the burden of potential radiological exposure. During later discussions including those within the NEA's R&R working group, the burden on immediately succeeding generations of the duty to complete disposal projects initiated in the present was also discussed. The study concluded that it would be helpful to continue discussion of terms such as "undue burden" and their interpretation.

Two important questions arise from the guiding principle of preserving options: 1. "how should options be preserved?"; and 2. "for how long a time is it considered reasonable or desirable to preserve these options?". The answers to these questions depend upon technical, political and social factors, and are therefore variable from country to country. Technological variables may include the nature of the waste (spent fuel containing known energy resources *vs*. high level waste) and the geological surroundings (which affect both the likelihood and consequences of radioactive materials reaching the environment as well as the ease of retrieval). Societal variables may include attitudes towards freedom of choice *vs*. assurance of safety, and the degree of optimism with respect to future technological developments. *It is reasonable to expect that the points of balance among these conflicting factors will differ from one country to another and even from one time to another in a given country.* A recent Swedish study [Ref. 42] observes for instance that retrievability is an issue that was thought closed about a decade ago, but it may now need to be re-opened based on interest expressed by a number of stakeholders.

Regarding the balance between principles, there can exist situations where other principles, such as fairness (informed consent), may take precedence over safety, so "safety first" should not be considered as an *a priori* absolutely overriding requirement, but rather as the outcome of a considered judgment. The issues of imposed risks *vs*. personally accepted risks, and of balancing the needs of society *vs*. the individual also enter into the decision making. In addition, there is a balance to be achieved between intergenerational equity and the cost to present society (*e.g.* balancing worker safety *vs*. future public safety). Since the implementation process can last several generations, the need to balance the risks and benefits among succeeding generations may apply even during operation.

Because they touch on freedom of choice and its relationship to safety, the concepts of R&R link societal and technical considerations. They tend to be central in the debate on "disposal" when the public and society at large are involved; hence the continued interest in these topics.

2.3 Terminology matters!

The terminology of geological waste disposal varies across different national waste disposal programmes. For example, because of differences in language and because of administrative and historical reasons the term "safety case" as defined in international guidance is not used in some national programmes.

The nuances that specific terms such as "waste", "disposal", "storage" and "undue burden" may take makes it difficult to be sure that people from different countries are talking about the same things when they use these terms. Perhaps more critical is the fact that the meaning of terms may be different to different stakeholder participants in the same national programme. A number of examples of such terminological differences were noted in [Ref. 41] but also in NEA-6869, "*More Than Just Concrete Realities: The Symbolic Dimension of Radioactive Waste Management*" [Ref. 43]. That report noted that "The Forum on Stakeholder Confidence … has found that key concepts of radioactive waste management (RWM) (*e.g.* safety, risk, reversibility, retrievability) carry different meanings for the technical community and for non-technical stakeholders. It has also learned that some highly value-laden socio-economic concepts (*e.g.* benefit packages, community, landscape) are interpreted differently by different societal groups, and that opinions and attitudes are not simply a faithful reflection of decision making, actual events and communicated messages. Perceptions and interpretations of events and objects also play a role. Deepseated values and norms, knowledge and beliefs, group identification, cultural tradition and self-interest are some examples of factors that shape perceptions and interpretations."

Clearly it can be difficult to reach agreement on statements on reversibility and retrievability, either nationally or internationally, when the participants use the same terms to mean different things and/or attach different meanings and connotations to important terms used in the discussions.

To clarify the discussion in the present document, and reflections that it may inspire, several relevant terms are defined hereafter. (Examples of divergent or ambiguous definitions are also noted.) In selecting the meaning of terms, where possible we have followed the terminology used in the *Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management* [Ref. 44] that has been ratified by most OECD countries. These definitions are not necessarily those officially adopted by NEA countries.

Box 4, situated below after the discussion of terminology, summarises the main definitions adopted in this report.

Waste

According to the Joint Convention [Ref. 44] "radioactive waste is radioactive material … for which no further use is foreseen".

- Not all programmes use the word "waste". This term has negative connotations, implying something dirty or something to be rejected. Therefore there are countries where radioactive waste management (RWM) institutions avoid using this word in their official documents and communications. A more neutral or technological term may be preferred, as *e.g.* in Italian "scorie" (by-products) instead of "rifiuti" (refuse) [Ref. 43].

- In some countries material may be considered to be waste as soon as it is no longer wanted or needed by its owner, perhaps even before it has been packaged for disposal; in other countries, a material is considered to be waste only once it has been emplaced in a repository, or perhaps even not until the repository has been sealed and closed. This difference clearly carries with it implications for the concept of retrievability: which object is a candidate for potential retrieval?

- The notion of ultimate waste is also discussed. For example, according to France's 2006 Planning Act on RWM, "Ultimate radioactive waste shall include any radioactive waste for which no further processing is possible under current technical and economical conditions, notably by extracting their recoverable fraction or by reducing their polluting or hazardous character" [Ref. 45].

In this report, we define **waste** as materials whose owner has decided that they are to be emplaced in a deep geological repository. The term "waste" will also be taken to include spent fuel in those programmes where spent fuel is not considered a potential resource and is therefore to be emplaced, eventually, in a repository.

A subsequent decision to consider the materials to be a resource to be made use of would then be one of the possible reasons for deciding to retrieve them. Clearly, if such future recovery of resources is considered to be more than a remote possibility, retrievability for reasons other than safety must be one of the characteristics of the repository.

Disposal and Storage

According to the *Joint Convention* **disposal** means the emplacement of radioactive waste in a repository *without the intention* of retrieving it, while **storage** means the holding of radioactive waste in a storage facility *with the express intention* to retrieve it at a later time.

- The distinction between storage and disposal is an important issue in the context of retrievability. In principle, storage is only an interim measure, because it relies upon active controls, maintenance and periodic renewal of containers and of the storage facility itself. Indefinite storage is not regarded as a viable strategy for long-term radioactive waste management [Ref. 47].

- In many languages there is ambiguity between the terms "storage" and "disposal". An explicit legal distinction should be and is, sometimes, made between them, where "storage" means that the facility is temporary, while in the case of "disposal" the facility is potentially or actually definitive. As an example of the potential for ambiguity, in France an apparent contradiction may be found between the legal term for disposal, and the everyday meaning attributed to the same term. Parliament enshrined the reference word for disposal ("stockage") in law. In denotative French, by contrast, *"*stockage*"* is a temporary store. In some countries (*e.g.* France, Spain) radioactive waste management (especially low- and intermediate-level waste) facilities are called "storage centres" even if there is no intention to retrieve the waste.

- The term "final disposal" is often used, drawing on a connotation of the intent to dispose of the waste and be able to walk away from it. The terminology has been changed recently in several countries to "deep facility", in order not to be seen as precluding activities such as retrievability and monitoring. Terminology was changed in Finland from "final repository" to "repository" for this type of reason. The same is true for Sweden. In Switzerland, the disposal concept is called "final, long-term monitored disposal", to signify "final disposal" intentions but with an uncertain end to the period of monitoring and accessibility of the waste.

- In some programmes, such as in Canada, the term disposal is not used at all[2].

- In some programmes, a deep geological facility is still only a storage facility until the final decision is made to seal and close the facility, and only at that time would it become a disposal facility. In effect, the purpose of the facility (storage *vs*. final disposal) is left undecided, or at least potentially variable, until the time of the closure decision[3].

- In other programmes, a facility whose final purpose is permanent disposal may be considered to be a disposal facility as soon as it is constructed. For example, in the UK both Government and the environment agencies regard emplacement of waste in a geological disposal facility as disposal, and distinguish between storage and disposal based on whether there is an intention to

[2] In Canada the term "long-term waste management" is used by the Nuclear Waste Management Organization (NWMO) in order to reflect the evolution of ideas in response to societal expectations. The words "waste management" replaced the words "waste disposal" to reflect a change in focus from an engineering project (design and build a repository) to an ongoing societal undertaking that includes designing and building a repository as only one of the elements of an evolutionary and adaptive process.

[3] In France, for instance, the Law of 28th June, 2006 (art. L.542-1-1) [Ref. 46] defines disposal as the emplacing of radioactive waste in specially-constructed installations to "preserve" these substances in a fashion that is "potentially definitive".

retrieve the waste at a later date. This distinction has important implications, firstly for allocating regulatory responsibilities to the relevant body, and also for requirements on the operator to demonstrate management arrangements for retrieval.

In this report, in order to be able to compare similar situations in different countries we will use a single interpretation: regardless of the national terminology, a deep geological repository will be considered to be a **disposal** facility from the beginning of its life, and wastes emplaced in the repository will be considered to have been disposed of. In a disposal facility, regardless of whether retrievability is incorporated in the design or not, when the decision is made to emplace waste there is no intention to retrieve it later. In the context of this report, **storage** is not considered to be an alternative to disposal; rather it is a step in the management strategy leading to final disposal.

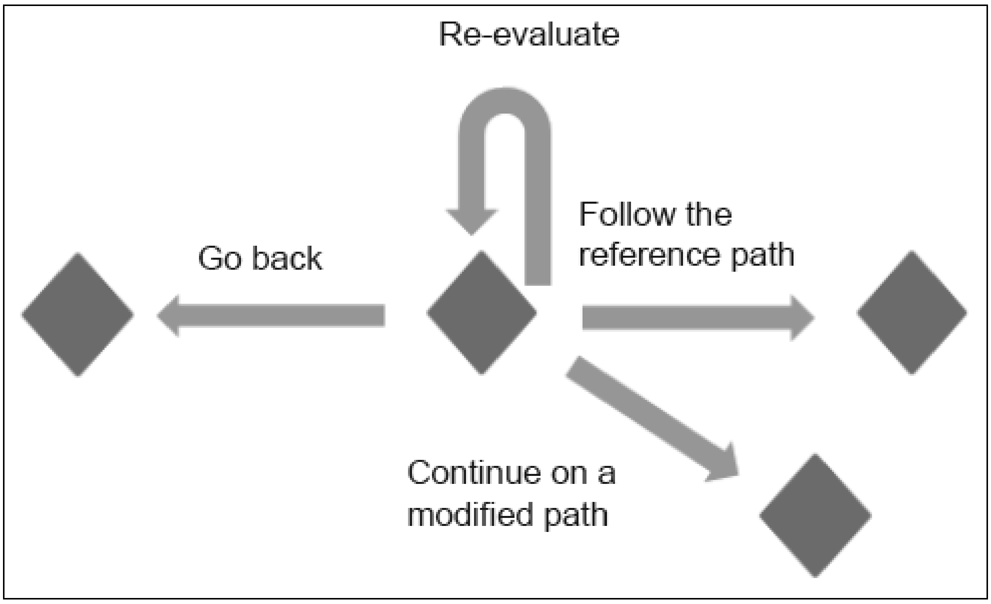
Reversibility and Retrievability

Reversibility describes the ability *in principle* to change or reverse decisions taken during the progressive implementation of a disposal system. Reversibility requires conceiving and managing the implementation process and technologies in such a way as to maintain as much flexibility as possible so that, if needed, reversal or modification of one or more previous decision(s) in repository planning or development may be achievable without disproportionate effort. The implementation of a reversible decision-making approach implies the willingness to question previous decisions in the light of new information, possibly leading to reversing or modifying them, and a decision-making culture that encourages such a questioning attitude.

- "Reversibility" is a concept that has generated debate. Some interpret reversibility as a means for facilitating the correction of potential mistakes in the future, which would imply that it primarily addresses uncertainty regarding the long-term safety of waste management facilities. Others, however, argue that reversibility draws on the positive connotation of flexibility and freedom of choice provided for future generations. According to this interpretation, reversibility represents a commitment to the values of intergenerational equity and democracy [Ref. 41].

- "Reversal" is the action of going back on (changing) a previous decision, either by changing direction, or perhaps even by restoring the situation that existed prior to that decision (see Figure 1). Depending on the importance of the decision, reversal may require less or more important co-ordination with other interested parties: regulators in the first place and other stakeholders. Indeed, the regulators may mandate the reversal of a technical decision.

FIGURE 1: Reversibility of decisions - potential outcomes of options assessment, including reversal



Retrievability, in waste disposal, is the ability *in principle* to recover waste or entire waste packages once they have been emplaced in a repository. Retrievability is the final element of a fully-applied reversibility strategy.

Retrieval is the actual action of recovery of the waste, whereas retrievability is the potential for such retrieval. Retrievability provisions form part of the activities carried out under a licence for the construction and operation of a repository. Actual retrievals, on the other hand, would in many cases be considered new activities that would require separate licensing before they could be carried out.

Finally an important concept is that of **closure**, which is also somewhat variable. In a facility that consists of several galleries or emplacement vaults, some vaults may have the emplacement of wastes completed, and the vault may be backfilled and sealed, while other vaults are still being constructed. After all galleries have been backfilled and sealed, access shafts may be left open for some time. Even after access shafts are closed and sealed, a repository may not be considered officially closed for some period of time while surveillance and institutional control measures continue, and closure may only be considered to have happened when the surveillance and control measures end (if ever). *In this report we will consider closure to take place when the last access shaft is sealed*. It is clear, however, that a repository that is not yet sealed may be seen, during its active operation, as not being fully open but in a situation of partial closure.

Oversight vs. Control

Control can take place through measures that do not necessarily rely on man. For instance, the barriers that constitute a nuclear waste repository do exercise some types of control functions long after closure of the repository: they control the access of groundwater, the temperature of the near field, the release of radionuclides, *etc*. These are forms of intrinsic, passive controls. Active controls require instead the presence of a regulator or other oversight organisation, *e.g.*, in the form of inspections, verification of records, verification of quality assurance procedure, verification of safeguards, *etc*. Oversight is the more general term that refers to society "keeping an eye" on the technical system and the actual implementation of plans and decisions. Monitoring, if used by regulators to check whether regulations are being met, can be seen as an active control measure; if it used by society to check that the environmental conditions are not degrading, it is an active control measure but under an oversight rather than a regulatory regime. In this sense we may refer to it as an "active oversight" measure.

For the time period following closure, when the presence or the role of the regulator is not assured, we consistently use the more general term of "Institutional Oversight" rather than of "Institutional control", reflecting the fact that the regulation-enforcing aspects after closure may be weaker than in the earlier period (Fig. 4 in section 4.1 gives an indication of the very long-term time scales in question). This institutional oversight may also be considered to be indirect oversight, as compared to the direct oversight before closure, as there is no longer access to the underground facilities.

BOX 4: Main definitions adopted in this report

In this report, we define **waste** as materials whose owner has decided that they are to be emplaced in a deep geological repository. The term "waste" will also be taken to include spent fuel in those programmes where spent fuel is not considered a potential resource and is therefore to be emplaced, eventually, in a repository.

A deep geological repository will be considered to be a **disposal** facility from the beginning of its life, and wastes emplaced in the repository will be considered to have been disposed of. In a disposal facility, regardless of whether retrievability is incorporated in the design or not, when the decision is made to emplace waste there is no intention to retrieve it later. In the context of this report, **storage** is not considered to be an alternative to disposal; rather it is a step in the management strategy leading to final disposal.

Reversibility describes the ability *in principle* to change or reverse decisions taken during the progressive implementation of a disposal system. Reversibility requires conceiving and managing the implementation process and technologies in such a way as to maintain as much flexibility as possible so that, if needed, reversal of one or more previous decision(s) in repository planning or development may be achievable without disproportionate effort. The implementation of a reversible decision-making approach implies the willingness to question previous decisions in the light of new information, possibly leading to reversing or modifying them, and a decision-making culture that encourages such a questioning attitude. **Reversal** is the action of going back on (changing) a previous decision.

Retrievability, in waste disposal, is the ability *in principle* to recover waste or entire waste packages once they have been emplaced. Retrievability is the final element of a fully-applied reversibility strategy. **Retrieval** is the actual action of recovery of the waste.

3. REVERSIBILITY AND DECISION MAKING

As used in this report, "reversibility" is primarily a management or decision-making concept, rather than a technical one. In terms of its more technically-related consequences, reversibility indicates a willingness to identify and correct actions and decisions that have subsequently been found or considered to be inadequate. In the societal realm, reversibility also indicates a willingness to adapt to societal preferences. Indeed, one of the motivations for requesting that a programme adopt reversibility may be a desire to ensure that participatory decision making continues during the lifetime of a project. Reversibility does not guarantee that decisions will systematically be overturned, but it does allow for the possibility that if a decision is later found to be faulty or questionable then it may be adjusted.

As compared with retrievability, for which many of the issues are technical in nature and are often discussed by experts in the physical sciences and engineering disciplines, discussions of reversibility may benefit from participation of experts in the various social sciences, ranging from philosophers and ethicsts to sociologists and economists. To date, the degree of involvement of social scientists in discussions of reversibility and retrievability has been relatively small, but experience in the R&R working group meetings and especially the project conference in Reims in 2010 suggests that multi-disciplinary dialogues could be very fruitful in improving understanding of the issues. An important step in this direction was the publication by Andra of a book on reversibility and governance in the French waste disposal programme [Ref. 48]. Contributors to this work included social scientists (sociologists) and technical experts, and it is expected that this transdisciplinary dialogue will continue to gain strength during the coming years.

There is a close connection between reversibility and the concept of stepwise or staged decision making. As noted in [Ref. 25], a key feature of a stepwise decision-making concept is a plan in which development is by steps or stages that are reversible, within the limits of practicability. The rest of this section of the report begins with a discussion of the links between reversibility and stepwise decision making.

The remainder of this section reviews the relationship between stepwise decision making and reversibility and in particular the relationships between reversibility and regulatory decision-making processes. The implementation of the repository is followed though its various life phases in order to understand what could favour or diminish reversibility. Because of the connections between reversibility and public participation in decision making, communicating and dialogue on reversibility are also addressed here, and a proposed communication tool, the "R-scale", is described at the end of this section.

3.1 Stepwise decision making

In long-term radioactive waste management, consideration is increasingly being given to concepts such as "stepwise decision making" and "adaptive staging" in which the public is to be involved in the review and planning of developments. The key feature of these concepts is development by steps or stages that are reversible, within the limits of practicability. This is designed to provide reassurance that decisions can be reversed if experience shows them to have adverse or unwanted effects. However, it is important not to use a stepwise or adaptive process as an excuse for delaying decisions, particularly in cases where such delays could have negative impacts on future safety.

In a stepwise procedure, sustainability and short-term efficiency often contradict when decisions are to be made about the size and timing of steps. Often, the smaller the individual steps, the better the chances for social acceptability. Since society is a complex system with many unknown relationships among its components, it can be assumed that in the case of smaller steps, the number of affected components as well as the magnitude of effects will be smaller, and thus the chance for unpredictable responses will be reduced. It is also important that sufficient time be allowed after each step so that the system can respond to the intervention and its consequences can be identified. However, an increase in the number of steps and the intervals between them will also increase the duration and costs of the decision-making process and in some cases may result in additional risks being imposed between steps. Trade-offs between social sustainability of the process and short-term efficiency must be carefully evaluated in designing a stepwise process.

Repository development requires a sustainable relationship between a repository programme and its host communities because of the long time scale for development. There are many decision points along the path of programme development. In a stepwise process, one of the features of decision making at each stage is a reconsideration of whether to confirm the previous small step and proceed with the next one. Taking these decisions in concert with appropriate stakeholders at each step helps to build a durable relationship between the programme and communities. By keeping previous decisions "alive" in memory through repeated reconsideration and reaffirmation, the process of making the next decision at each step is made less overwhelming [Ref 25].

It was noted in the analysis by the working group of questionnaire responses that many programmes do not yet have processes for stepwise decision making worked out in detail, nor an outlined methodology and principles for stepwise decision making and related public consultation, even in cases where a stepwise approach is national policy. It was felt that this is not necessarily a negative observation - designing a detailed process too far in advance of when it will be used is probably not appropriate. The general principles should, however, be clear from the beginning.

The relationships between an implementer's decision making, regulatory decision making and societal decision making are of interest. The basis for the regulatory process is not necessarily the same as for a flexible stepwise decision-making process. The steps in typical licensing processes are very broad, and may limit the steps that are possible during implementation. For example, a proposal to dispose of a small fraction of the wastes and wait for several decades before proceeding with the rest of the wastes may not fit within the normal series of licensing decisions. On the other hand, it must be recognised that there is more to regulatory oversight than licensing, and that the day-to-day regulatory oversight process can be compatible with a flexible process involving many small steps.

The existence in many countries of more than one regulator or decision-making body also complicates the decision-making process. It is important to keep dialogue and negotiation open among all parties, and not to become too tied down to a fixed framework for decision making. However, this must be done in a way that respects the need for independence of the regulators. It is also important to avoid "group-think" and to ensure that the overall goal of public safety is always kept in mind and that third party interests are accommodated in the process.

3.2 Reversibility and authorisations for repository development

At one time disposal was often treated as if it were a relatively short-lived activity to be completed in the timespan of perhaps a single generation – the goal being to provide a facility that could safely contain radioactive waste without any further action or intervention by future generations. Increasingly, the implementation of a disposal project has come to be viewed as an incremental process, in a series of successive steps, likely taking several decades to complete. Besides the concept of protection of future generations, this changing vision incorporates as well an assumption of the involvement of the succeeding generations in the process and a need to preserve as much as practicable their ability to exercise choice. As a result of this evolution, monitoring and surveillance are now activities under consideration after closure of the facility.

In its various forms (adaptive phased management, adaptive staged management, phased geological disposal, reversible disposal, …), stepwise decision making in geological disposal represents an approach to making a gradual transition over one or more generations, from active assurance of safety (interim storage) to passive safety (final disposal with no requirement to retrieve the waste). As part of a stepwise decision-making process, it may be considered that the possibility should exist to reverse or revise previous individual decisions along the way, for example in the light of knowledge gained or of changing capabilities. Thus, stepwise decision making may bring with it a need for some degree of reversibility, including retrievability, at least up to the point of final closure if not beyond. Stepwise decision making forms an important part of the context for a study of reversibility and its expressions in retrievability provisions.

Reversibility refers to the possibility of reconsideration of one or a series of steps at various stages of a program. This involves a review of earlier decisions with the appropriate stakeholders and requires that the necessary means to reverse a step be available. Reversibility also denotes that, when practical, fallback positions may be incorporated both in the long-term waste management policy and in the actual technical program. Not all steps or decisions, however, need be or, indeed, can be fully reversible. Certain decisions can be used in the process as hold points for programme review and confirmation. Reversibility may therefore be considered to be a way to close down options in a considered manner [Ref. 25], while still respecting the need to take decisions in a timely fashion. If the need to reverse or change course is carefully evaluated with appropriate stakeholders at each successive stage of development of a facility, a higher level of confidence may be achieved, by the time a final closure decision is to be taken, that there are no technical or social reasons to delay the final decision, or to undertake waste retrieval at that time or subsequently. However, in order to embark successfully on a logic of reversibility in waste disposal, it is important to ensure that the need to consider decisions at each step is not used as an excuse for unnecessarily delaying the process. It is also advisable to clarify ahead of time the principles or values that should be followed in such decision making steps, and their importance relative to one another.

Regulatory Control (authorisations)

As described in an NEA study of regulation of waste management [Ref. 48], in a broad sense the regulatory control process for radioactive waste management includes not only the process of formal control by a nuclear safety and/or environmental safety regulator, but also the wider processes related to political and societal decision making regarding waste management strategies and projects. This process often starts with the development of a policy. In nuclear waste management, radiation protection is usually a major component of the policy, since its ultimate objective is to preserve the safety of the public and the environment. Following the establishment of the policy is the creation of legislation. In the development of legislation, standards and guidelines are sometimes published to provide legal details. As an example, in countries such as Germany, United States and Hungary, legislation addresses both wider policy issues and fine regulatory details whereas in some other countries, technical standards for radioactive waste management are defined by the technical authorities responsible for implementing and enforcing the law, rather than in the legislation itself [Ref. 48].

With respect to the pre-closure activities related to repository development, just as with other activities involving radioactive materials, consent to act within the bounds of legislation and regulation is generally by way of some formal, legal instrument such as a licence, a permit, or authorisation. These documents typically contain detailed terms and conditions and are issued to the person or company that is recognised legally as the operator of a process or activity subject to regulation. In some cases a licence may cover all aspects of regulation related to the regulated process, from initial planning and development, through matters such as occupational health and safety of workers and accident prevention, to the final act of disposal. In other cases they may address aspects separately but having regard to the interactions between them. Compliance with the terms and conditions of a licence is then checked by inspection and monitoring of the operator's activities. Cases of non-compliance are often dealt with by way of notices or requirements placed on the operator. If necessary, non-compliance is subject to some form of enforcement action. To evaluate the overall success of the regulatory system in meeting the objectives of policy, reviews are often arranged and if necessary, corrective action may be taken during the licensing stage, where terms and conditions of the licence may be modified. In addition to such corrective action, most regulatory systems have the capacity to follow up the granting of a licence to ensure that safe performance is actually being achieved, which includes taking remedial action if necessary.

Different countries have different arrangements for implementation and enforcement of the law. In some countries such as Belgium and Finland, one technical authority deals with the licensing, inspection and enforcement of on-site occupational health and safety matters and of waste disposal, while other technical authorities deal with siting and development of disposal facilities. In other countries such as Germany and the United States, the Federal States have responsibilities of their own, *e.g.* a State Licensing Authority may issue a licence but not take any repository supervision role. Regardless of the variations, these technical authorities often consult other parties with relevant interests or responsibilities before reaching a decision. In regard to licensing, there is usually a mandatory requirement for consultation with, or reference to, other bodies. In many cases there is a legally established system of public consultation during the licensing process, and the observations collected from the public consultation are taken into account when a decision is issued.

Overall, a policy of openness towards the general public is a basic feature of modern regulatory frameworks. Its implementation has become a more and more important task in recent years, highlighting changes in the perception and role of the regulator [Ref. 49].

There are formal licensing actions at steps such as siting, construction, operation, and closure, but not necessarily at various other points such as partial emplacements, backfilling, *etc*. Nevertheless, these actions may be considered to be key points that would be submitted in any case to regulatory review, either through the terms and conditions of the authorisation or being considered as "significant modifications", requiring a licensing decision. If as a consequence of stepwise decision making there is a significant change, *e.g.* backfilling that makes retrieval more difficult, the regulator would need to be involved, *i.e.* a staged process would also involve staged authorisations even if the licensing process was not explicitly staged. For example, in the US any condition that would substantially affect the retrievability of waste prior to closure would require a licence amendment.

Prior to closure, for operational safety the regulator may demand that there always be a safe position to return to in case of problems. For practical purposes, this would imply that retrievability of packages be an operational requirement during the emplacement phase. On the other hand, the internationally accepted safety principles require that a final repository must not require societal control, including retrievability. Therefore although it is expected that regulators may require retrievability pre-closure, post-closure they may not do so unless retrievability is a legal requirement. Even in programmes where retrievability is not a requirement, it need not necessarily be prevented. Although closure cannot be approved until the regulator is certain that disposal is the right option and safety is assured, after closure, the logic of retrievability may suggest that the design should not make it unnecessarily difficult to retrieve.

One point of interest relates to delayed closure. If decision making and retrievability requirements lead to a delay in sealing or backfilling galleries, there may be an impact on safety. Therefore the regulator needs to be involved in any such decisions, preferably from an early stage when such delays may be considered or planned as part of the development process (*e.g.* in a "flexible" or "adaptive" staged process).

At each step in the entire decision-making process, a decision to proceed also implies a reaffirmation of previous decisions. In a decision-making process which is reversible, this reaffirmation may be made explicit to a greater or lesser extent. That is, a decision to proceed in a reversible process also involves in effect a decision not to reverse one or more previous steps. For example, a regulatory licensing decision typically involves a review of compliance with the conditions of the previous licence, and only after it is concluded that the previous conditions have been satisfied will a decision be taken on moving forward with the next steps. It has also been pointed out [Ref. 11; Ref. 50] that for the licensing decision at this stage to be meaningful, there must be at least a possibility that the decision will not be to go forward, but rather to step back and correct shortcomings encountered during the previous phase. Thus a decision not to reverse, whether taken implicitly or explicitly, has the effect of reaffirming previous decisions, and the recording of these decisions and reaffirmations at each step serves to legitimise and facilitate subsequent decisions, including the final decision on closure if and when that decision point is reached.

3.3 Repository life-phases and reversibility

The planning and implementation of a geologic repository typically proceeds by an incremental, stepwise approach. Authorisations also tend to be granted via discrete decisions within a licensing process. At each step in such an approach, the decision of whether to proceed to the next step, or to modify the design or the process, is made in light of technical as well as social and political factors and in light of the terms of the licence. The stepwise approach provides opportunities for technical, societal and political reviews and, in principle, allows for the building of shared confidence in the feasibility and safety of the facility, as information and experience are acquired and decisions are democratically made. The stepwise approach also allows the process and its decisions to be progressively informed by data obtained through monitoring. The type of monitoring that may be of interest during such a stepwise process leading from construction to closure is currently being developed as part of the EC-sponsored, FP7 "MoDeRn" project (Monitoring Developments for safe repository operation and staged closure) [Ref. 51].

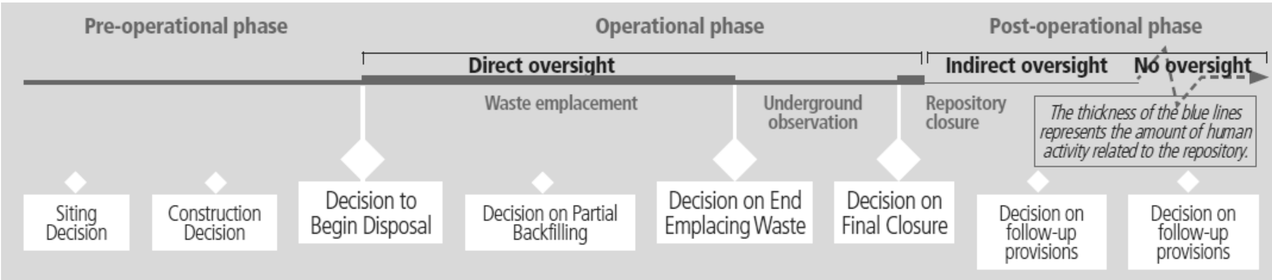
Checking at each stage whether the licence conditions were fully fulfilled requires that, if necessary, the licence could be amended or even revoked. It has been observed, *e.g.*, by the French Government that "a condition for the acceptability of decisions is reversibility" [Ref. 11]. Likewise, participants in R&R working group meetings have suggested that reversibility, at least in the sense that there is a possibility that the decision may be not to proceed, must exist in principle for a regulatory decision to be credible in the eyes of all stakeholders [Ref. 37].

If reversibility is decided upon as a feature of a repository programme, then it would also be necessary to foresee retrievability strategies in the planning, design and implementation of the disposal facility. In particular, it would be necessary to consider what the operation of retrieval would entail at various stages during the repository lifecycle.

During the early stages of a programme, reversal of a decision regarding site selection or the adoption of a particular design option may be considered. At later stages, during construction and operation, or following emplacement of the waste, reversal of a decision could involve the modification of one or more components of the facility, or even the retrieval of waste packages from parts of the facility. However, as repository development proceeds and approaches final closure, going back to earlier phases of the repository lifecycle would become increasingly more complex. In all cases, it would require prior authorisation from the nuclear regulator upon the submission of a safety case for undertaking it. On the other hand, it could be easier to take decisions resulting in a lesser degree of retrievability if there was a trail of earlier decisions indicating that reversal had been considered but not deemed appropriate.

All geological repository projects involve three main life phases, namely (i) the pre-operational phase, including initial construction prior to the first emplacement of waste; (ii) the operational phase, which includes the emplacement of waste, the pre-closure monitoring and performance confirmation period, if any, and the final closure of the facility; and (iii) the post-operational phase, including possibly a post-closure period of institutional oversight and memory and the distant future after oversight and/or memory cease. Each transition from one phase to the next is typically determined by a specific decision. Figure 2 gives a lifecycle overview of the repository throughout the major phases of nuclear waste management.

FIGURE 2: Repository life phases and examples of associated decisions



3.3.1 Pre-operational phase

During the pre-operational phase, the site is selected and characterised, the repository is designed, the man-made materials are tested and the engineering demonstrated, the support facilities are built, the licences for building and operation are applied for and received, and construction begins. A baseline of environmental conditions is also obtained.

The majority of pre-operational activities do not involve significant irreversible actions. Decisions taken during the pre-operational phase may cost both time and money, but these costs would usually be relatively minor compared with the costs of reversal or retrieval during later phases. The most important decisions related to reversibility and retrievability during this phase would be decisions on whether or not to incorporate reversibility and/or retrievability provisions in the design in order to facilitate their implementation during the remaining stages of repository development.

Reversal of decisions during subsequent phases can be facilitated by adopting, during this phase, a stepwise approach to decision making.

3.3.2 Operational phase

The operational phase consists of three main stages: (i) the emplacement cell construction and waste emplacement stage; and (ii) the observation stage; (iii) closure of the facility. Interestingly, different parts of a repository may be in different stages at the same time, *e.g.* construction of new disposal areas may proceed in parallel with emplacement or post-emplacement surveillance and monitoring activities in other areas.

In the waste emplacement stage, the waste packages are emplaced within their immediate engineered barriers. Depending on the waste and host rock characteristics, there are different options for the time at which the various barriers may be put in place. Requirements for waste retrievability, if any, may also affect the options selected. During the waste emplacement stage, the repository is monitored for operational safety. Where an observation stage occurs after waste package emplacement has been completed, the repository would be monitored. The monitoring results would be compared to the baseline data to confirm that emplacement has been carried out in conformity with requirements and, to the extent possible, to ensure that the repository is performing as designed. Research and development continue, and the regulator performs regular reviews of the long-term safety case.

Before closure, retrievability may be considered to be an operational issue or feature, and may be required as part of the performance confirmation process. The ability to retrieve deficient or damaged or non-quality-assured waste packages during the emplacement phase of repository operation may be considered to be one of the features contributing both to operational safety and to assurance of long-term safety, in the latter case by providing the ability to ensure that the assumptions underlying the long-term safety case have been validated and confirmed. During the emplacement phase, retrievals are likely to be rare events and would likely only be carried out for a small number of containers (if any) and only for operational reasons.

During the early stages of waste emplacement, retrieval may be one of the means by which a decision could be reversed. At later operational stages, when a number of packages have been emplaced, but before backfilling and sealing of the disposal cells, retrieval may still be relatively easy, and may involve little more than the reversal of the emplacement process. However, during later parts of the operational period, retrieval would become successively more difficult and costly. This is not only because of the need to reverse more and more actions (*e.g.* the removal of backfilling material), but also because of the effects of equipment aging and possibly non-favourable evolution, *i.e.*, creep, of the surrounding geological materials.

Depending on the design of a repository, retrievability requirements could result in the repository remaining open for a period of time that could be longer than would be necessary without retrievability. This postponed closure strategy may be considered necessary for a variety of reasons, among them regulatory compliance, thermal management of the waste output or to enable a performance confirmation programme (a monitoring programme to confirm that waste has been emplaced in compliance with design requirements) to be completed, as well as providing an opportunity to build additional societal confidence in the implemented disposal method.

In the closure period, all access ways including shafts will be backfilled and sealed to isolate the repository. The decision to close the repository will depend on a number of factors including technical considerations, societal choices and the implications on safety and safeguards of keeping the repository open.

It is worth noting that postponing closure, for example by postponing final backfilling of access shafts, may ultimately delay the achievement of a favourable situation in which the repository is passively safe and this would be an aspect to be taken into consideration, especially by the regulator(s). The period during which it would be practicable to postpone repository closure without compromising long-term performance may vary for different host rocks and for different repository construction techniques.

It has also been pointed out (*e.g.* [Ref. 52]) that the use of certain construction techniques during operation, such as the use of tunnel-boring machines for excavation, may facilitate post-closure retrievability. When performing cost-benefit analyses for such techniques, their impact on future retrievability and on such issues as future safeguards concerns should also be taken into account.

3.3.3 Post-operational phase

Following repository closure, waste retrieval would become significantly more difficult. Some form of mining operation would be required to retrieve waste containers or to retrieve wastes in the event containers have lost their mechanical integrity.

The post-operational period may begin with a period of formal institutional indirect oversight. It is reasonable to expect that monitoring and surveillance would be maintained for as long as society considers it beneficial, even though it is a characteristic of geological disposal – and part of the basis for the closure licence granted by the regulator – that safety does not depend on post-closure monitoring. On the other hand, the fact that all concerned stakeholders have agreed to move to post-closure (in some countries a process formalised by a parliamentary decision) should also mean that no further *in situ* data are required for safety. Otherwise, it could be argued that it was premature to move to post-closure. In some programmes, partial closure of parts of a repository may offer an opportunity to monitor conditions in the early post-closure period prior to formal closure of the entire repository.

It should also be noted that any post-closure monitoring decided by future generations should be designed in such way that no significant negative impacts on the performance of the containment barriers and therefore on the long term safety of the repository would occur. Due consideration must therefore be given to reach a balance between what is expected of monitoring and what is technologically feasible. It may possible to obtain *in situ* data even after closure. However, such monitoring ambitions will be constrained by limits on the amount and duration of data collection. Surface-based techniques providing data on the macroscopic evolution of the closed repository and ongoing-monitoring in deep boreholes can be carried on, however, as these activities are not technically influenced by the process of closure.

Safeguards controls may continue to apply. Societal memory may continue, and archives and landmarks may record details of the repository or remind future generations of its existence [Ref. 53]. In the longer term, loss of control and memory may eventually take place, for example through situations of war or anarchy, or as a result of natural events including major climate changes (*e.g.* glaciations).

After closure of the repository, and even after the end of any period where retrievability may be required post-closure, retrieval of complete containers may still be possible, particularly if the containers were still intact. As long as societal institutions similar to those in place today continued to exist, retrieval, if decided upon, would be a nuclear activity, which would require a permit from the nuclear safety authorities, as would the treatment and storage facilities that would be required to receive any wastes that were retrieved. It may also require research and development and demonstration of feasibility before being approved, particularly if it required new techniques rather than simple reversal of the emplacement techniques. The potential for retrieval (retrievability) would be facilitated if a continuous link with the past existed and information was preserved about how the repository was designed and implemented.

Once the integrity of containers can no longer be relied upon, retrieval of the materials by techniques similar to those used in mining would likely still be possible. Maintaining institutional memory of the original design could be one means by which this could be facilitated.

When today's societal institutions may no longer continue to exist, retrieval, as well as the management and storage of the retrieved waste, would continue to be a major but still possible engineering endeavour. They would be more difficult than during the period of societal continuity (prior to loss of institutional memory). They would require resolve, resources, and technology, and would probably be a major engineering undertaking. Similar challenges have been faced when deciding and planning to save ancient monuments, such as the Abu Simbel temples dating from the times of the pharaohs. An additional challenge in the case of retrieval of radioactive or otherwise hazardous materials from a repository would be the need to construct and operate facilities to manage the retrieved materials safely.

3.4 Decision making for retrieval

Decision making on retrieval would likely be a complex process if these containers are already in sealed vaults or galleries. The example of the Asse site in Germany [Ref. 31] shows that a variety of criteria would need to be considered, relating to topics such as operational safety, environmental consequences, long-term safety, feasibility, cost, time requirements, the requirement for new interim storage and management facilities and possibly for a new repository for wastes generated during retrieval and processing of retrieved materials, and transportation of waste materials. The difficulty would increase with the number of containers to be retrieved and if they were already in sealed vaults or galleries. It is likely that some form of weighting of criteria would be needed, and this weighting is likely to depend upon standards and attitudes to safety prevalent at the time of retrieval, which of course cannot be predicted at the time of emplacement of the materials. Experience also suggests that the costs of retrieval are likely to be comparable to, or even to exceed, the costs of disposal.

After closure, it is generally agreed that retrieval would be a new nuclear operation requiring a new licence. One question that may need to be resolved in some countries is ownership of the material after closure. A related issue is the possible distinction between physical closure (sealing of the last access shaft) and regulatory closure, which may be some time later in order to accommodate a post-closure surveillance period during which the operator may continue to be responsible. If the time period foreseen for such a surveillance period is very long, it may be necessary to have some method to transfer responsibility to the state, since the organisation originally responsible for the production of the waste may not continue to exist, especially beyond the end of nuclear energy production in a country. Even if retrievability following closure is a national requirement or policy, retrieval will not be undertaken lightly.

3.5 Communicating on R&R

In some countries, social pressures for reversibility have tended not towards specifically requiring ease of reversibility, so much as towards avoiding irreversible steps. These pressures translate a desire to avoid making decisions today that may preclude different actions in the future. Other strong societal motivations for reversibility appear to be the desire to provide future access to resources, and to attempt, to the extent feasible, to confirm or demonstrate repository performance before closure. Alongside these concerns may lie unfamiliarity with (or lack of confidence in the maturity of) the technology, and discomfort with the concept of purely passive safety without any means of control. It is also possible that demands for reversibility may be considered the logical consequence of recognising the perceived need for ongoing monitoring and control even after closure. Stakeholders and the general public appear more and more interested in having open options allowing for reversal and retrieval, as well as seeing research that can demonstrate that, although there is a cost, retrieval will still be feasible should it be desired [Ref. 54].

Communication on disposal issues is difficult because of the great disparity between geological time scales and human or social time scales and because of the uncertainty that must be communicated when describing potential impacts that may only occur in the far future. Also, there is a tendency among many non-technical stakeholders to look for absolute yes/no answers and to have difficulty understanding statements about consequences that involve low likelihoods of occurrence. This is a topic that will no doubt undergo development in most countries.

The R-scale

A key issue for local stakeholders considering hosting a geological disposal facility is ease of waste retrieval. A scale has been developed to illustrate qualitatively the degree and type of effort needed to retrieve the waste before and after its emplacement in a repository, *i.e.* gradations in retrievability during the repository lifecycle. Lifecycle stages considered in the scale are described in Table 3.1, which also shows the correlation between the effort needed for retrieving the waste and the corresponding degree of passive safety of the repository. These stages may be of long or short duration, and decisions to move from one stage to the next may be more or less formal and involve more or less public input, depending on the individual programme. For each stage, the table identifies the main elements of passive safety and active control, as well as degree and type of retrieval effort. The scale is presented in graphic form in Figure 3.

TABLE 3.1: Waste lifecycle stages, ease of retrieval, and specific elements of passive safety and active control.

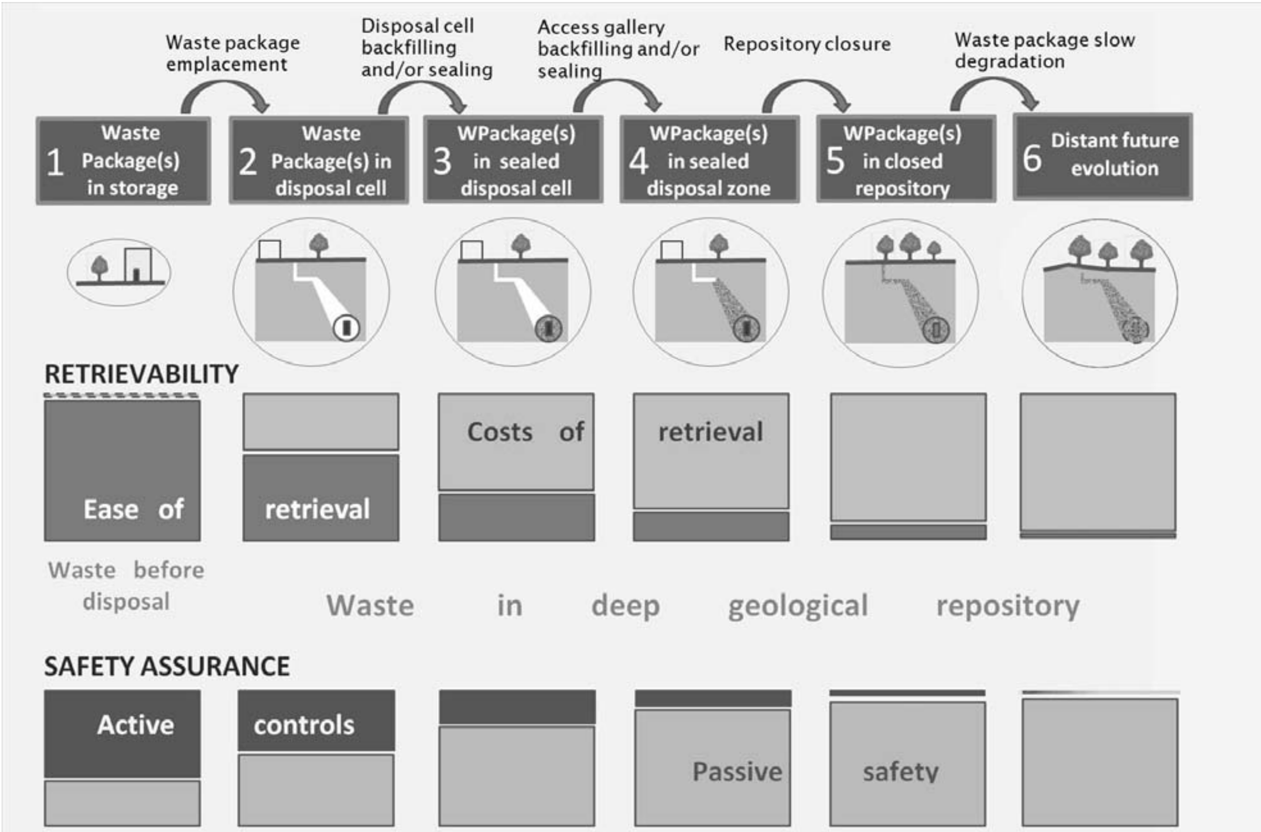
Stage and Location of the Waste *		Ease of Retrieval	Specific Elements of Passive Safety	Specific Elements of Active Control
1	**Waste Package(s) in storage**	Waste package retrievable by design.	Waste form and its storage container.	Active management of storage facility including security controlled area.
2	**Waste Package(s) in disposal cell****	Waste package retrievable by reversing the emplacement operation.	Waste form and disposal container. Hundreds of meters of rock. Engineered disposal cell.	Active management (including monitoring) of disposal cells and disposal facility. Security controlled area.
3	**Waste Package(s) in sealed disposal cell**	Waste package retrievable after underground preparations.	As in previous stage, plus backfill/sealing of disposal cell.	Monitoring of disposal cells possible. Active management of access ways to disposal cell seals. Security controlled area.
4	**Waste Package(s) in sealed disposal zone**	Waste package retrievable after re-excavation of galleries.	As in previous stage, plus backfill/sealing of underground galleries allowing access to cells.	Monitoring of disposal cells potentially possible. Security controlled area. Detailed records and institutional controls for a specified period, including international safeguards.
5	**Waste Package(s) in closed repository**	Waste package retrievable after excavating new accesses from surface. Ad-hoc facilities to be built to support retrieval.	As in previous stage, plus sealing of shafts and access drifts to ensure long term confinement of the waste within the underground facility.	Maintaining records. Regular oversight activities as long as possible (e.g. environmental monitoring, possibly remote monitoring, security controls and international safeguards).
6	**Distant future evolution**	Waste package degrading with time. Waste ultimately retrievable only by mining.	Geology and man-made barriers. Reduction in level of radioactivity.	Specific provisions for longer-term memory preservation, e.g. site markers.

* During the operational phase, not all waste packages present in the facility will be at the same lifecycle stage.
** Depending on the national programme and on the type of waste, the waste package emplacement room may be a vault, a cell, a section, *etc*. The term "cell" used here is generic to all these cases.

With reference to Table 3.1, several stages can be identified in the waste lifecycle:

Stage 1 is waste conditioned, packaged and kept in an interim store. Stage 2 is the waste moved from its interim store to an underground disposal facility a few hundred metres deep, which may require further re-packaging. The cell in which it is emplaced needs active monitoring. In Stage 3, passive components enclosing the waste emplacement cell are put in place: backfill (against rock disruption) and/or sealing (against water circulation). The access galleries to the cell still need active monitoring and maintenance, *e.g.* ventilation. In Stage 4, these galleries are backfilled and/or sealed. This latter stage may coincide with the closure of the whole disposal zone in which the gallery is located or indeed of the whole disposal facility. In Stage 5 the repository is closed: access from the surface has been sealed, and surface facilities have been dismantled. During Stages 4 and 5 monitoring or maintenance of the disposal zone (or the whole underground facility) is no longer necessary, but the facility may still be monitored remotely. Stage 6 is the final disposal state. Although the integrity of the waste packages cannot be guaranteed, the waste is still confined within the facility. By this time, the level of radioactivity has been reduced significantly. Safety does not depend on maintenance or monitoring. However, measures intended to ensure preserving memory of the site may continue.

FIGURE 3: "R-scale" - Lifecycle stages of the waste, illustrating changing degree of retrievability, passive *vs*. active controls and costs of retrieval in a deep geological repository. During the operational phase, not all waste packages present in the facility will be at the same lifecycle stage.



Note: exact proportions of illustrated rectangles may vary depending on the repository design.

A leaflet describing this R-scale has been used and tested at meetings with stakeholders in France and Scotland, and in consultation documents issued by the Scottish Government [Ref. 55]. It was also referred to in the Swedish National Council's 2010 report [Ref. 42]. The "International Retrievability Scale" leaflet is reproduced in annex. It is hoped that the scale will prove useful for describing the evolution of retrievability during repository development in other national programmes as well.

4. RETRIEVABILITY: IMPLEMENTATION AND CHALLENGES

The mission of a geological repository is to provide protection of man and the environment from any hazard that the radioactive waste would pose over time, without the need for active control and intervention. According to the international Joint Convention's definitions of waste and disposal, once the waste is emplaced in a final repository, there is no intention to retrieve it. Also, since long-term safety is intended, closing the repository once all the waste is emplaced must be planned for. The final licence of a repository is explicitly granted on the judgement that, in principle, no active oversight or intervention are needed in order to assure long-term protection of man and the environment.

Retrievability, if explicitly provided for in the repository design and implementation, reflects a willingness not to preclude the possibility of a future change of intention, but it does not imply a definite expectation that such a change of intention will necessarily take place. Similar considerations apply for reversibility provisions in project management.

A retrieval capability is probably most important in addressing unanticipated conditions in the repository that have the potential to affect long-term performance. Such situations could happen for a number of reasons, and may occur despite the best efforts of the implementer and regulator. Stakeholders may expect that appropriate steps would be taken to address such a situation. The ability to take such steps, although not forming part of the long-term safety case, may nevertheless prove valuable in such an unanticipated contingency.

In such an event, analysis of the situation may show that the disposal system was still operating in accordance with the specified safety criteria, and was likely to do so in the long term, in which case retrieval would not be required. Even if not, it may still be the case that retrieval efforts would present a greater risk to the workers than the risk incurred by leaving the repository as is. If retrieval were decided upon, there would also need to be a viable alternative for managing the retrieved waste, whether re-emplacement, placement in interim storage, or emplacement in a different repository. Stakeholders would be more likely to understand and accept these as conclusions of a planned process, versus having no contingency plan at all. This suggests that implementers, in consultation with regulators, should give some consideration to what would be required to enable retrieval of some or all of the waste packages in the early stages of design, even if there are no statutory or regulatory requirements to do so. Such consideration would provide at least a starting point for action in the unlikely event that retrieval becomes necessary.

Retrievability may also contribute to decision making about other issues such as fuel cycle options (for example, see [Ref. 56]). However, before deciding upon the inclusion of retrievability in a repository programme, it is important to understand the limitations and challenges imposed upon its implementation by technical and other constraints (*e.g.* [Refs. 26, 46]).

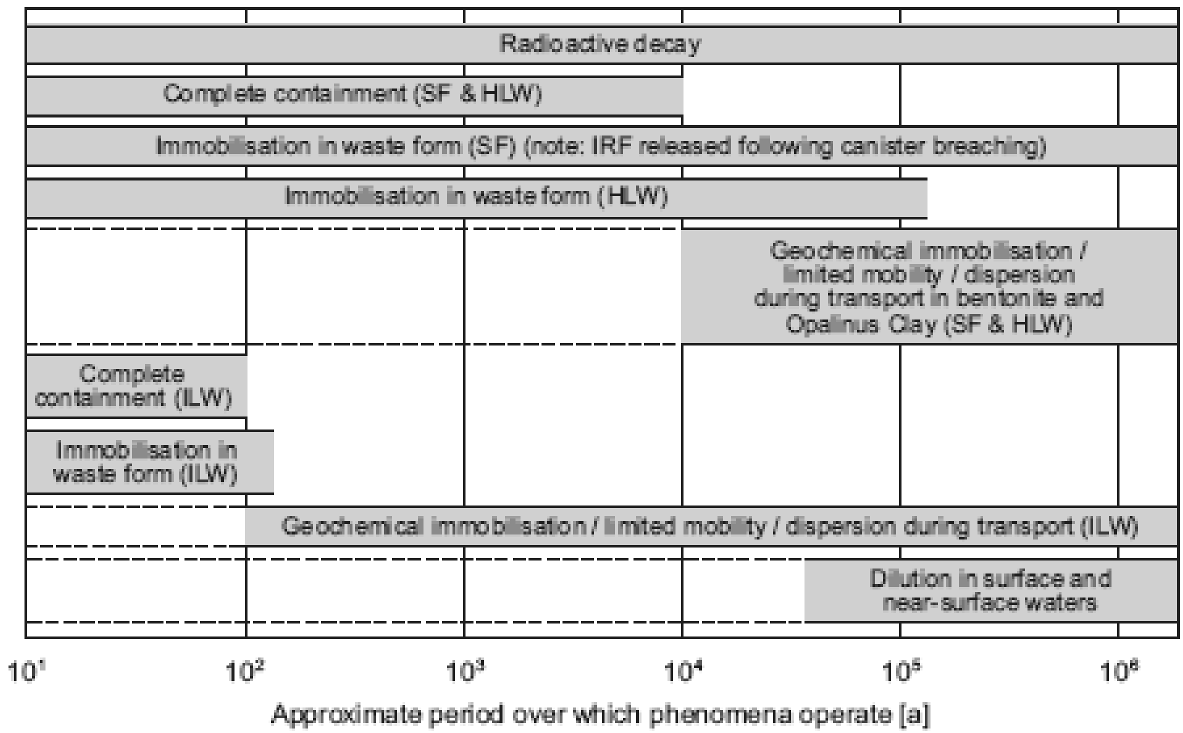
The remainder of this section reviews the main components and design features of a repository and observes which provisions may favour or impede retrievability. Similarly, the implementation of the repository is followed though its various life phases in order to understand what could favour or diminish reversibility. Finally, technical and non-technical factors and challenges in implementing reversibility and retrievability are reviewed.

4.1 Repository design and components in relation to retrievability and reversibility

The long-term safety of a geological repository is based on the concepts of containment and confinement of the long-lived waste, provided by multiple natural and engineered barriers. This creates a situation in which the waste could potentially be accessed and retrieved over very long time scales. One example is the safety-case analysis produced by Nagra ([Ref. 57]; see Figure 4, where it is reported that complete containment of the radioactive materials can be expected over a period of 10,000 years or more. Most of the radioactive materials will stay very close to the original emplacement also at later times. Similar conclusions apply to other geological repository designs.

While the design features of geological repositories may vary in different countries, a geological repository for long-lived waste typically comprises nuclear waste forms, containers, emplacement cells with or without buffer materials, repository access ramps or shafts and the surrounding host rock. A horizontal or near-horizontal lay-out is universally implemented. The orientation and layout of the repository must take into account the directions and magnitudes of the relevant rock stresses.

FIGURE 4: Time scales over which relevant phenomena operate (from [Ref. 57])



A brief description of each of the repository components and the impact that waste retrievability may have on them, and *vice versa*, is given below.

4.1.1 The waste form

The waste form itself may be a barrier to prevent escape of radionuclides or other hazardous substances. Depending on the robustness of that waste form, its preservation may be an issue to be dealt with during potential retrieval operations. For example, if spent fuel is disposed of directly, the fuel cladding is a barrier to release of radionuclides from the spent fuel. All other things being equal, it would be preferable to preserve this barrier until retrieval is completed; otherwise, fuel particles may be released from the fuel rod into the container, increasing the radiological hazard during retrieval. This may impose constraints on the eventual retrieval process which can have an impact on retrievability design provisions. For some types of fuel, if retrievability is foreseen as an option, this consideration could have an impact on the design of the waste container. The issue of interim storage (before re-emplacement, re-conditioning, further processing, *etc*.) of retrieved waste may also lead to consideration of the ability of the waste container to be either transported outside the repository surface facilities or dismantled before transportation.

4.1.2 The waste container

The waste container serves as an engineered barrier, and is designed to provide safe containment of the waste during a specified design lifetime. The physical configuration of the waste container will depend on the repository concept. However, major parameters that need to be considered in designing the container include: (i) the waste form itself; (ii) container materials compatible with the host media; (iii) mechanical properties of material and mass of container; (iv) radiological protection; and (v) heat output.

One additional parameter to be considered may be the ease of retrieval. In terms of retrievability, long lived waste containers are clearly beneficial for waste retrieval in that the container retains its integrity over a longer period. Container longevity is often achieved by the choice of material, a specific thickness of the container and the control of the emplacement cell environment so as to endure the specified design lifetime. In addition to container integrity, any external handling features of the container ought to be designed to survive any retrievability period, if such a period is imposed. In this regard, materials that resist corrosion over a long period of time are favourable. The robustness of the waste container will need to be sufficient so as to maintain its structural integrity during any preparation processes for retrieval. In some cases, the waste containers are vented to prevent gas pressurisation. The possible implication of container vents is considered when there is a possibility that gaseous radionuclides may migrate through the vent leading to contamination of the backfill, which subsequently may affect the retrieval operations. The size and weight of the waste container are also important factors when retrieving waste. Large containers could be more difficult to handle and possibly impose more shielding requirements, but small containers would imply more packages to be retrieved.

4.1.3 Emplacement cell

Depending on the repository design, an emplacement cell could be a vault, a chamber, or a borehole (vertical or horizontal). In designing an emplacement cell, features that need to be considered include: (i) size of the emplacement cell and capacity, *i.e.* number of waste containers; (ii) use of buffer between the waste container and the sidewall of the cell; (iii) orientation of the waste container within the placement cell; (iv) the requirement of rock support / lining; and (v) the orientation of the emplacement cell in relation to the prevailing rock stress. To facilitate waste isolation and repository closure, emplacement cells are often backfilled with sealing materials. Typical sealing materials include swelling clay such as bentonite and/or a mixture of clay and sand aggregate. The purpose of sealing the placement cell with low permeability material is to limit the rate of transport of contaminants and also to stabilise the access opening. Just as with the waste container, in some programmes ease of retrieval may be an additional factor to be considered during design.

The size of the emplacement cell has implications for retrievability. Shorter cells may require less complex machinery for waste package emplacement and retrieval. However, this provision needs to be balanced against the capacity and footprint of the repository. Materials used in the emplacement cell for retrievability purposes should also be designed to be chemically compatible with the container materials and should not induce any disturbance of the sealing material or host rock.

4.1.4 Repository access and repository lay out

Repository lay-out and access is also related to retrievability. For example, deep boreholes offer a much more difficult access to emplaced wastes. In fact, this is one reason in some countries (*e.g.* Sweden; see [Ref. 42]) for rejecting borehole disposal and opting for a more conventional repository.

Access from the surface to the repository level is typically achieved by shafts and/or access ramps. The designs depend on the repository layout, waste inventory, the waste emplacement process and the host rock type. Access openings are often sealed with backfill in order to seal the emplacement cell and also to restrict inadvertent intrusion. For access shafts or ramps that are excavated through aquifers or fracture zones, a barrier to prevent or minimise groundwater ingress is required and must be maintained for as long as the access shaft remains open. If a period of waste retrievability is required for social, political or other reasons, and the access shafts were part of the retrieval concept, all rock support, access drift and shaft linings used must be designed to retain sufficient integrity during that period.

More generally, the repository access and layout influence the reversibility of decisions which can be made during the disposal process (flexibility), as the design of the repository accesses is related to the dimensions of the casks used for the transfer of the waste packages. If some change is envisaged in the dimensions of the casks during the operation phase, due for example to modifications in the radioprotection standards or the dimensions of the waste packages, this change will have to be compatible with the existing access routes dedicated to waste transfer from the surface.

4.1.5 Host rock

Within the multi-barrier repository system, the host rock acts as a natural barrier to maintain favourable hydrogeological and chemical conditions for long-term isolation of the waste and to protect the repository from disruptive events and human intrusion. The specific characteristics of the host rock will depend on the local geology of the site selected for a repository.

The host rock has implications in terms of retrievability. For instance, some strong competent rocks (*e.g.* crystalline rock, volcanic tuffs) are self-supporting and minimal engineered support and maintenance are required to prevent failure of the rock walls in the emplacement cells. In such situations waste packages, therefore, may be expected to remain accessible for retrieval without the need for significant additional engineered features during repository construction. On the other hand, argillaceous rock formations in France (Callovo-Oxfordian), Canada (Ordovician argillites) and Switzerland (Opalinus Clay) are consolidated sediments. These and other similar rock formations may have excavation damage zones (EDZs) around excavations in the repository, depending on the rock characteristics. Rock support by means of rock bolts with metallic arches, metallic meshes, shotcrete and/or concrete tunnel linings may be required to provide mechanical stability for a long period of time in order to support retrievability. Salt formations may be even less amenable to retrievability without significant construction features to support it, as salt tends to flow and close around the containers, especially when the latter are heat-emitting.

4.2 Technical factors and challenges

4.2.1 Factors in planning for retrievability

The efforts to be made in order to facilitate waste retrieval, if pursued, would depend on (i) the repository concept, barriers and location, (ii) the timescales during which retrievability requirements, if any, may be imposed, and (iii) the stage of repository evolution when the waste retrieval may take place. The practicability of such actions would have to take into account the associated worker safety, mining expenses and other technical requirements. In principle, whether or not the repository has special provisions for waste retrieval, it would be possible to retrieve waste from closed geological repositories by applying specific mining techniques. Retrievability management strategies are possible with varying degrees of retrievability. Some considerations that should be taken into account for different lifecycle phases when developing such a strategy are described in Tables 4.1, 4.2 and 4.3.

TABLE 4.1: Retrievability management strategies and factors to consider during the pre-operational phase

Retrievability Management Strategies	Factors to consider
<u>Develop a retrieval plan</u> ▪ A well devised retrieval plan is useful in implementing retrievability in the design. The plan must consider all important factors that could influence the radiological and environmental safety as well as the feasibility of retrieval. In developing the retrieval plan, changes may occur because of policy shifts, emerging situations, change of process data, *etc*. ▪ The plan may be based on the selection of retrieval situations which may occur during the operational phase or after closure. This does not mean that waste retrieval is intended by the repository designers, but retrievability implementation requires that concrete retrieval situations be envisaged, in order to assess the effective ability of the design to allow retrieval. ▪ Considering that present generation has no control on the decisions which will be made by future generations, situations of retrieval after closure could be also envisaged, in order to minimise the risk for people if post-closure retrieval is ultimately decided.	Important factors to be considered in a retrieval plan include cost, timescales, risk reduction, hazard identification and mitigation, the complexity of the aged waste and waste package, the extent of inventory knowledge, the scale of the task (volume to retrieve), and the required downstream processes (repackaging, conditioning, treatment, final waste disposition). Factors of particular interest for the development of retrieval strategies in the pre-operational phase may include the properties of the host rock and specific aspects of repository design such as the degree of backfilling and sealing of repository openings and connection of the repository to the surface. In addition, the timing of retrieval, the delay between waste emplacement and its retrieval may also affect the feasibility and practicability of retrieval.
<u>Implement retrievability in the design</u> ▪ Features are incorporated in the design of the repository components in order to fulfil the criteria identified by the retrieval plan. ▪ There may be hold points where implementation cannot proceed until the results of previous steps (*e.g.* feasibility study or preliminary design) are known. In these cases, a flexible retrieval plan which allows new decisions / circumstances to be incorporated would increase the successful chance of a potential retrieval operation. Periodic review of the retrieval strategies based on ongoing or phased development work would also increase confidence in the operation <u>Demonstrate retrievability</u> ▪ During the course of the design, tests of components and sub-systems which play a role in retrievability are performed. These may be preliminary tests dedicated to elementary components and/or retrieval process feasibility at the beginning of the process, and more comprehensive tests at the end of the pre-operational phase.	Depending on the repository concept, site specific environment, and subsequent degradation processes, the waste container may be subject to particular design requirements such as extra long design life, more robust container design to ensure safe retrieval, and/or the provision of lifting/handling features on the container. In this regard, materials selected must resist corrosion over a long period of time with adequate corrosion allowance, the robustness of the container will need to ensure continued integrity during any preparation processes for retrieval (*i.e.* during removal of buffer, cleaning or other preparation processes of the emplacement cell), and any handling features provided must survive the retrievability period.

TABLE 4.2: Retrievability management strategies and factors to consider during the operational phase

Retrievability Management Strategies	Factors to consider
Postpone repository closure or partial backfill after waste placement ▪ In such a delayed closure strategy, repository backfill is not emplaced immediately, so that the waste packages remain readily retrievable until the decision is taken to close the repository. ▪ A slight modification of this strategy envisages partially backfilling the repository after waste emplacement has been completed. This method involves emplacing some engineered barriers, typically the type of engineered barrier that can be removed without major difficulties, such as backfilling a filled emplacement cell / room. In such cases, a demonstration of the ability to return to the waste may be required at the date the partial backfilling is decided on. ▪ While this strategy could have the advantages of promoting local employment near the repository site for the prolonged pre-closure period, allowing more time for research and development to be carried out, and also having a higher degree of control over the emplaced waste, the negative impacts of its needs for additional monitoring, safeguards requirement, and institutional controls throughout the time before repository closure cannot be ignored.	The safety implications of such a prolonged pre-closure tactic would have to be evaluated carefully. It could be argued that the impacts on the public and the environment may be lower than would be the case if the facility were closed more rapidly, since the facility will remain under active control when the radioactivity of the wastes is highest. On the other hand, with only partial or no engineered barriers emplaced, radiological impacts on human and organisms (flora and fauna) may be higher than they would be from a closed repository. Conventional safety of workers (*i.e.* likelihood of accidents underground), potential release of toxic materials to the environment, and land requirements (*i.e.* area that cannot be used for other purposes due to the presence of the repository) are also important factors in assessing this strategy.
Re-assess short- and long-term retrievability ▪ The actual evolution of the emplacement cells and waste packages after emplacement may lead to increasing difficulty of retrieval if that is decided upon. If the operational phase lasts several decades, as is envisaged in most countries, it is also likely that the technology for the repository construction and for waste emplacement will not be exactly the same from start to end of the operational phase. It may be considered useful therefore, to re-assess, after some time or periodically, the effective ability to retrieve the waste packages. This applies both to the ability to retrieve during operations, and also to the potential ability for later retrieval after closure if this is envisaged as a possibility.	This will take account of observation measurements in the repository and of the evolution of technology and scientific progress.

TABLE 4.3: Retrievability management strategies and factors to consider during the post-operational phase

Retrievability Management Strategies	Factors to consider
<u>Maintain and enrich knowledge about the repository and the waste</u>	
▪ A major factor for facilitating a potential retrieval after closure is the preservation of knowledge about the repository and the waste. Knowledge of the precise locations where waste is emplaced and the nature of the waste, and information about the integrity of the waste containers and of the emplacement cells walls, liners, *etc*. would be important inputs in deciding upon the retrieval technology and process.	Define those characteristics of the waste, the container and emplacement cell that should be archived.
▪ It would also be important to ensure that the relevant information was retained in a format that future generations can use.	Define the proper data support material and language for transmission through generations.
▪ This may require that memory preservation relies not only on passive features but also on maintaining knowledge and skills within the population around the repository site	
▪ Continuing remote monitoring after closure may contribute to these objectives.	Define the proper data that should be monitored, considering the available technology.
<u>Maintain qualified personnel for potential future retrieval operations</u>	
▪ Qualified personnel with the necessary skills and expertise would be needed for carrying out the retrieval operation or operating the retrieval equipment. Under some circumstances, the option of opening new access routes by re-mining may be worth considering. In addition to maintaining the required expertise in future generations	Consider specific site geological characteristics which may limit the applications of various mining techniques.

4.2.2 Technical challenges in performing retrieval

Provisions favouring the ability to retrieve whole waste packages (retrievability) may bring with them some unavoidable technical challenges in terms of the design of the repository and its associated infrastructures. These implications vary somewhat depending on the repository concepts and locations. Some common technical challenges are discussed in Table 4.4.

TABLE 4.4: Technical challenges associated with retrieval operations

During the operational phase ▪ Waste retrieval during the phase where the emplacement cells are not sealed and the containers are accessible is straightforward. Most technical challenges that may be encountered can be resolved by good engineering planning and design, as equipment and machinery used for waste package emplacement can be used for waste package retrieval by reversing the emplacement steps. Successful waste retrieval would therefore depend on the design measures to ensure safe repository operation. In addressing operational safety in a repository, one must realise that retrieval of a waste package entails an additional package handling operation, which may be more or less hazardous than the original emplacement operation. Appropriate radiation shielding in the retrieval operation is considered important. Also, in any period of operation, there are risks associated with fault situations (*e.g.* loss of electrical power, flooding, rock falls) which may be accompanied by further conventional and radiological hazards. In any case, measures which will reduce the need of manual operating may be advantageous. Measures such as utilisation of robust equipment to handle multiple packages so as to reduce worker exposure time, the use of remote handling equipment or the use of sensors to monitor the working environment may help support operational safety within a repository during the retrieval process.
During the post-operational phase ▪ Many national programs have demonstrated that retrieval during and following repository closure should be possible, although the process may be significantly more difficult than in the earlier phases. Some form of mining operations would be required to retrieve waste packages or to retrieve wastes following closure. Retrieval in the post-closure phase would bring further challenges as significant evolution and deterioration would have occurred which may introduce other uncertain situations to arise during the operation. Particularly in cases where a long period of time had elapsed between emplacement and retrieval, significant container or emplacement cell degradation may have taken place, new equipment may be required for retrieval (*i.e.* different equipment to that used for emplacement), and the associated risk for retrieval operations and the safety of equipment operators would need to be evaluated prior to retrieval. Invasive mining approaches would likely be required, and the hazards associated with conventional mining activities would need to be addressed. ▪ Nevertheless, it is likely that mining techniques involving some form of core drilling and over-tunnelling could be applied should retrieval be required. Retrieval methods for this period would mostly depend on site geological characteristics and also on the provisions for management of retrieved wastes. ▪ If it were decided to retrieve wastes from a closed repository, new equipment and retrieval methods could become necessary to restore access to the waste packages. The type of equipment required would depend on the concept and materials selected for the repository. Qualified personnel with the necessary skills and expertise would be needed for carrying out the retrieval operation or operating the retrieval equipment. Under some circumstances, the option of opening new access routes by re-mining may be worth considering. Ensuring that the required expertise is maintained so as to support potential legitimate waste retrieval without facilitating undesired human intrusion may pose challenges. ▪ Other more specific technical challenges for retrieval after a long period of time may include the unknown physical conditions of the geosphere containing the deteriorated waste packages. The conditions of the biosphere and near-surface geosphere may have undergone significant evolution caused by continuous climatic changes. Just as for retrieval at earlier stages, the risk for public safety must be evaluated and regulatory and safety requirements must be met prior to determining whether waste retrieval would be carried out.

4.2.3 R&D challenges related to retrievability and reversibility

To support the development and implementation of a geological disposal facility for nuclear waste, research and development work are crucial in acquiring new knowledge as well as to apply learned knowledge to improve the design and development of the repository system and its components. As implementing geological disposal is a long-term project with a number of key phases, various kinds of R&D activities will be required through the different phases of implementation. Also worth noting in setting out R&D strategy are the R&D activities need to respond to the changing needs of the geological disposal project as it proceeds through different phases of implementation. R&D activities are primarily focused on demonstrating the long-term safety of the repository. Flexibility of the design should also be looked for, in order not to make decisions related to the disposal process more difficult than necessary for a safe emplacement of the waste. If retrievability is one of the possible features of the repository, part of the R&D efforts may apply to retrievability, and some R&D activities are suggested in Table 4.5 below. It may also be considered that continuing R&D on waste management is necessary for the credibility of reversibility.

Similar to the technical R&D needs, social science research is also important to support effective, sustained engagement with stakeholders, including society at large as well as local communities during the siting process. The creation of a geological disposal facility for nuclear waste in a specific territory should be considered as a public issue, and therefore the robustness of such a project will be measured both in technical and in social terms. Along with safety analysis and performance assessment, matters of concern could include such items as local land-use planning, environmental preservation, techno-economic optimisation, integration of scientific and technical progress, social acceptability.

Moreover, to support R&R activities, which are strongly related to social expectations, the role of social sciences (sociology, economics, political sciences, history, *etc*.), and their incorporation into R&D programs may be of particular importance. Granting future generations the possibility of intervention for a certain period, and thus making choices in intermediary operational stages, calls for much more than technical expertise alone. The capacity of maintaining multiple perspectives, technical as well as social and political, and maintaining a continuous dialogue with all the interested parties must therefore be included in the project design. Research and development activities relating scientific and technical development to decision-making processes and social sciences research may be very useful in order to deal with this complexity, as discussed in Tables 4.5 and 4.6.

TABLE 4.5: R&D activities and relevant challenges in relation to reversibility and retrievability during the pre-operational phase

R&D activities in relation to Reversibility and Retrievability	Relevant Challenges
▪ During the initial period of the pre-operational phase when the site is selected and characterised, the research and development work required to support the site preparatory and investigation phase would focus on providing the necessary support of data and understanding of processes for the development of conceptual designs and associated safety assessment for a range of potentially suitable geological settings. ▪ With respect to retrieval of waste, preparatory R&D activities could include the development of tools and techniques for demonstrating feasible waste retrieval. Specific design provisions (*e.g.* deposition machines with retrievability design functions, placement room layout facilitating easy retrieval and/or removable barriers to allow access) may be evaluated in the preliminary R&D program. R&D activities would focus on the methods / processes that will allow retrieval of the emplaced waste at various life phases, while demonstrating that the presence of such specific retrievability provisions will not detract from the performance of the repository may also require R&D. ▪ The objective of the R&D work in this initial period would be to support the development of a robust solution both in technical and social terms. Apart from safety assessment, issues such as local land-use planning, environmental preservation, techno-economic optimisation, integration of scientific and technical progress, and social acceptability will be of interest. ▪ Any preparatory R&D required for site investigations, including the development of tools and techniques for assessing site-specific information would be undertaken in this phase. In conducting site-specific investigations to evaluate candidate sites, R&D activities would focus on the processes that will determine the performance of engineered barriers or control the movement of fluids and radionuclides. The objective of the R&D work in this initial period would be to support the development of engineering designs and safety assessment that take account of the physical and chemical characteristics of the host rock and groundwater system present at the site. ▪ As the project progresses to the construction phase, underground investigations in the selected host rock geology would provide the site-specific geological information required for the construction of the facility. R&D in this field will aim at defining the engineering of the repository for the beginning of the operating phase, while preserving maximum flexibility in order to accommodate changes in waste inventory, disposal rate, *etc*. which will occur during the operating phase. R&D in this phase is also expected to support the development of designs for backfilling and sealing systems that will be required in closing the facility safety at a later stage. More detailed assessments of the specific retrievability provisions and the provided engineered barriers (*e.g.* removable backfill) would be further studied and tested.	▪ In conducting preliminary R&D work in the initial phase without detailed site-specific geological information, a key challenge would be to ensure that the R&D work program is designed to take account of the potential physical and chemical characteristics of the host rock as well as possible mechanisms for deterioration of the barriers. ▪ As the timescale for practicability of retrieval (on technical grounds) may be as long as hundreds of years, taking into account advances in technology that may affect the actual retrieval operation would pose another challenge in planning for R&D work activities. R&D on information storage and retrieval on these time scales may also be necessary. ▪ Elaborate a robust waste management solution, taking account of the multiple aspects of this issue

TABLE 4.6: R&D activities and relevant challenges in relation to reversibility and retrievability during and after the operational phase

R&D activities in relation to Reversibility and Retrievability	Relevant Challenges
During the operational phase	
▪ Once the repository has started operating, the research and development activity is expected to focus on feeding back experience from operation. Monitoring the behaviour of the engineered and natural barriers in the repository system will be used for comparison with the results of predictive modelling. Extensive R&D on waste retrieval is not anticipated in this phase, but potential improvements that may enhance the retrieval operations may be evaluated (*e.g.* the timescale of backfilling and sealing the emplacement rooms / access shafts). New technologies would continue to be evaluated to ensure that waste retrieval, if required, would be carried out in the most effective manner. ▪ Public views on nuclear waste management and also waste retrieval may change from one generation to another. Aside from technical research, R&D on social sciences is also important to verify the true understanding of how the public perceive nuclear activities or future utilisation of the emplaced waste. Both technical and social R&D in this phase would support decision making on the timescale of sealing and closing parts of or the entire facility. A key objective in this phase would be to identify and implement any improvements that can be made in various aspects of the repository design or operation. R&D in this phase will also support decision making on the timescale of backfilling and sealing of parts of, and eventually the entire, facility.	▪ While some R&D activities would be intended to respond to social drivers and public concerns, new knowledge acquired from social research may complicate the retrievability options already studied. One potential downside of this is that the more work that is done on enhancing retrievability, the greater is the danger of reinforcing the perception that retrieval will be necessary.
During the post-operational phase	
▪ When the repository has reached the closure stage, it is now at the time at which the facility is in a passively safe mode. Supporting development work would continue during this period with an important focus on supporting monitoring arrangements to meet the requirements identified by the regulators and the host community. The main goal of R&D would be to provide confidence that the repository will perform as designed and long-term safety will be achieved. Technical R&D needs on waste retrieval during this phase are likely to be minimal as viable retrieval work plans would already have been devised. However, as new technologies continue to evolve, the R&D focus in this stage may be on applying the latest technologies to enhancing retrieval safety (*e.g.* devices or technology to locate shifted or deteriorated containers). ▪ Depending on the prevailing socio-political environment, certain social research work may need to be maintained in order to sustain stakeholder support. ▪ Research may also continue on aspects related to memory preservation, such as knowledge transfer, durability of archives, passive markers, *etc*.	▪ As above, conducting a balanced and effectively designed social research program is likely to be challenging.

4.2.3 Identifying, scheduling and prioritising R&D

Research and development are part of a process to fill an information gap - the gap between our current knowledge and that which we need to acquire to support the development of the repository. Consistent with the above suggested R&D activities, the overall goal of carrying out R&D work is to improve our knowledge across the decision-making process so as to gain confidence in the design and safe operation of the geological repository. Note that the study of an R&D topic may often affect more than one repository component or system. For instance, the mechanical and chemical properties of the sealing system may not only directly impact the safe isolation of the container; it may also affect the survival growth rate of the surrounding microbes and therefore subsequently may affect the retrievability of the emplaced container. In planning an R&D task, one should take account of the overall impact of the R&D topic and the timeframe at which the R&D task may affect the overall outcome. Factoring time considerations into the R&D planning process is particularly important in long-term demonstration experiments as they may run for timescales of decades. In prioritising R&D tasks, it is important to evaluate the significance or potential impact of the information gap particularly on the design outcomes and safe operation of the repository. Issues that have a significant potential impact on delivery of a safe geological disposal facility should have the highest priority, particularly where there is a large information gap in our existing knowledge and understanding. For R&D areas that require significant resources and/or established technologies, collaborating with other national nuclear waste management institutes may allow efficient use of the best available technologies and resources. Such knowledge sharing not only encourages independent verification of the study result; it may also create the necessary synergies needed for the identifying further research priorities and strategic directions. The lowest priority R&D needs are typically the ones associated with issues that do not have a significant impact on delivery, and in addition, where there is a relatively small information gap. As new technologies continue to emerge, a periodic review of the R&D program to ensure that the existing knowledge remains up to date and no new uncertainties are identified would allow effective use of available resources and budget.

An important question to be resolved in each programme relates to the level of resources to be allocated to R&D on reversibility and retrievability at various stages of development. Programmes in which retrievability is a requirement will have different needs from programmes in which it is optional.

The motivation for research programmes must also be taken into account. Is the research carried out to improve acceptability, to support repository operation, or to allow for flexibility? It is desirable that research should always support safety, and not be done purely in order to improve stakeholder acceptance. On the other hand, research and development that are triggered by stakeholder requests should be integrated into the developer's overall programme and not seen and undertaken as simply an add-on.

It must also be recognised that retrievability is only one small part of the overall design and development process. A strategic decision is needed during the repository development process as to whether efforts in this area should be focused on retrieval methodologies from an unmodified repository design, or on modifications to the design in order to facilitate later retrieval.

Decisions on the type and extent of research may also correlate with a stepwise decision-making process. Depending on the stage currently under consideration, the research and development needs will differ.

4.3 Other factors and challenges

4.3.1 Safeguards – physical protection

The Treaty on the Non-Proliferation of Nuclear Weapons requires safeguards measures for spent fuel and/or other nuclear material disposed of in a repository until the nuclear material is practicably irretrievable [Ref. 58]. The Convention on the Physical Protection of Nuclear Material requires signatory nations to protect nuclear material against unauthorised access or removal for as long as an intrusion could lead to sabotage or illegal trafficking of nuclear materials [Ref. 59]. Insofar as retrievability provisions prolong the period during which the nuclear material remains accessible and these treaties are still in force, these provisions also prolong the period during which future generations will be responsible for maintaining control and physical protection measures to prevent unauthorised access [Ref. 60].

Prior to closure, and even in the absence of any retrievability requirements, active safeguards and physical protection measures equivalent to those in place at other nuclear facilities, including a relevant physical protection system and nuclear material accountability, will be required. The requirements for material and design accounting to support safeguards may also help to support retrievability, and in this sense the record-keeping requirements for retrievability and safeguards may be considered to be complementary. Even after backfilling and closure, the continued requirement on nations to be able to assure non-proliferation and physical protection may result in the need for monitoring for institutional control and possible retrieval of the waste. These record-keeping requirements may be complementary to the monitoring and institutional control measures that would support continued retrievability post-closure, even if retrieval is not intended. Nevertheless, the ultimate goal of safeguards and physical protection after closure is not to retrieve the materials, but rather to continue to isolate them from access and contact with persons and the environment, which is, of course, in agreement with the ultimate goal of disposal but in opposition to the concept of retrievability.

Providing a retrievability period after emplacement operations will require that safeguards and physical protection measures be maintained continuously for the surface and the underground facilities during that period. Typically, the required safeguards provisions will depend on the ease of access to the nuclear material and the ease of retrieval, while the level of physical protection required will likely be comparable to the level required at an interim storage facility or at a near surface facility. To design for waste retrieval, the following aspects need to be considered:

- A repository that stays open to facilitate retrieval will prolong a need of the facility and nuclear material physical protection and the safeguards inspection period. The amount of effort required to maintain an underground inspection regime, a safeguards inspection program as well as underground monitoring systems may be significant. A prolonged period of repository inspection also leads to longer underground occupancy times for safeguards inspectors which in turn may result in additional radiation exposure for both the inspectors and repository operators.

- As long as the repository remains open, there may be greater potential for diversion of nuclear material if physical protection and institutional controls are not maintained. Hence, from the safeguards and protection point of view, the extended time for retrieval may be less effective than if closure occurs immediately after completion of the waste emplacement;

- Safeguards measures must be flexible enough to respond to changing technological developments and to changing needs of today's and future generations. An effective application of safeguards shall assure continuity-of-knowledge that the nuclear material in the repository will not be diverted for an unknown purpose.

Although it is not possible to predict whether a future generation will decide upon retrieval, it may still be possible to take actions during design and implementation of a repository that would facilitate future retrieval, or at least avoid unnecessarily increasing its difficulty. Typically these may include a shorter or longer pre-closure observation phase, monitoring and surveillance and record-keeping after closure, or longer container lifetimes once the waste is emplaced. These can be seen as means by which present generations respect the ethical responsibility to provide freedom of choice of future generations to make decisions different from our own. This responsibility, however, must not be met at the expense of meeting the ethical responsibility to protect the health and safety of both present and future generations, and it must not prevent or impede the ability to comply with agreed measures for physical protection and safeguards of nuclear material. Resolution of the tension between these two guiding principles depends upon many factors, *i.e.* there is no one "best" way. It is important to reach clarity on the relative priorities of these two responsibilities.

4.3.2 Cost

The costs associated with allowing waste retrieval from a repository may be categorised as follows:

- Costs for upgraded repository components as may be required to facilitate waste retrieval. These may include: enhanced containers; emplacement room / cell / vault designs; reinforcement of the underground facilities for long term stability during the retrievable period.
- Costs for monitoring and maintenance during the extended operational period to ensure safety. These may include: maintenance and repairs of equipment / vehicles; groundwater management; provisions for abnormal situations including emergency preparedness; staffing required to maintain safe conditions; security of the repository; safeguards provision (as discussed in section 4.4).
- Costs for waste retrieval when it is to occur. These may include: retrieval machinery and operator costs; additional costs for radiation and contamination controls during the retrieval operation; costs for operating interim storage and possible processing areas for the retrieved waste. Also, depending on the stage at which waste retrieval is to occur, additional cost for dewatering the repository and for the management of secondary wastes may be incurred (note: secondary wastes may include saturated sealing materials or groundwater containing radionuclides).
- Costs for managing secondary wastes; residual contamination and remedial actions. These may include: storage and processing space as required to manage secondary wastes, such as overlying materials excavated during the retrieval process; remediation of environmental impacts.

The costs associated with retrieval operations should also include those related to secondary waste management and additional processing and storage facilities. It should be noted that 'bundling' of costs associated with both development of a repository and ensuring retrievability could make it difficult to identify separately the costs of a requirement for retrievability. There are many factors influencing the cost of retrievability, including repository design, the volume of waste, and the timescale during which retrievability is required. It is seen as important to recognise not just costs of retrieval of waste but also those of new nuclear installations to process retrieved waste and its packaging, and those of alternative repositories for the waste. The costs of retrieval are likely to be comparable in magnitude with those of repository construction and operation.

The question of responsibility for costs is also important. There is a need to distinguish between costs that are the responsibility of the original owner, and those that are the responsibility of the eventual retriever of the wastes. Generally speaking, those costs that support the safety case are considered to be the responsibility of the original owner, but costs for provisions that do not support safety, and are only there to support retrievability, are more contentious. It is difficult to determine where to draw the line between good engineering practice that would have been followed even without retrievability, *vs*. costs that are incurred solely to support possible retrieval. If retrievability is a precondition for social acceptability of a repository program, then in effect the costs of retrievability options (as distinct from the costs of retrieval itself) are simply subsumed into the overall costs of implementation, but this should be communicated.

When considering whether retrievability post-closure should be a requirement, it is important to be aware of the costs, not only of retrieval, but also of establishing and operating new facilities to deal with the retrieved material, possibly including re-disposal. It must be remembered that retrieval is not the end-point. It should also be kept in mind that retrieval is likely to cost just as much as, if not more than, the original disposal, and that regardless of which organisations are directly responsible for costs, in the end it is the members of the public, whether as consumers of nuclear energy or as taxpayers, who will ultimately bear these costs. From this point of view, the costs of retrievability options during repository development must be weighed against the potential resulting cost savings in the event that retrieval may be decided upon in the future.

The cost of implementing a retrievability option will depend on the repository design, the amount of waste to be disposed (and potentially retrieved) and the timescales over which the ability to retrieve waste is required. In particular, the implementation of a retrievability option could substantially increase the repository lifecycle costs if an extended period of repository operations is required beyond the timescales needed for waste emplacement. Finally, it is likely that retrievability provisions will be more costly if implemented later on in the design, rather than from the start.

4.3.3 Institutional oversight and monitoring

One component of demands for retrievability post-closure is a desire for continuing institutional oversight beyond the period during which there is access to the repository or to parts of the repository This may be based partly on a perceived need for further confirmation that the repository is operating as planned, and partly on a concept of safety which includes oversight as an essential component. In this view, the assurance of safety depends not only on predictive demonstrations, but also on continued oversight and monitoring. According to this approach, while post-closure safety assessments are required to demonstrate safety even in the absence of oversight and monitoring, the overall safety provisions would nevertheless include plans for continued institutional oversight, monitoring, and possibly retrievability for a period of time following closure and sealing of the repository.

Institutional control consists of those actions, mechanisms and/or arrangements implemented in order to maintain control or knowledge of a waste management site after project closure and to inform current and future generations of hazards and risks. Any discussion of retrieval of wastes following closure would likely involve consideration of institutional controls already in place prior to the decision to retrieve. Typically, controls may be classified as follows:

- Structural controls which include features constructed to control access (*e.g.* fences; gates; engineered covers) and physical devices (*e.g.* signs and monuments to warn of dangers or restrictions).

- Non-structural controls which include mechanisms that rely on legal and administrative initiatives (*e.g.*, security, preventive maintenance, inspections, vegetative buffer zones, materials labelling, materials handling improvements; hunting licences or permits; training on radiation safety; best management practices).

An alternative classification scheme relates to the activities involved rather than to the physical nature of the controls:

- Active oversight measures rely on the significant presence of humans to fulfil safeguard and maintenance responsibilities (*e.g.*, security guards to monitor and control site access; airspace restrictions; environmental sampling to monitor contaminant migration; site inspection maintenance).

- Passive controls are designed to warn and inform future generations about the nature and location of site hazards without significant human intervention (*e.g.* permanent markers and monuments; barriers such as earthen berms; oversight methods such as maintenance of public records and archives, and land or resource use restrictions).

Planning for the possibility of future retrieval will involve planning for institutional oversight in support of future decision making. When planning for institutional oversight, the use of a graded approach or tailoring controls will allow specific site factors (*e.g.* site history ; local or regional cultural characteristics ; input from stakeholders, *etc.*) to be considered, which enables the implemented controls to be flexible to address unique site features. To assure their effectiveness, institutional oversight measures should be designed to adapt to changes over time so as to ensure that the controls and their maintenance can be sustained in the future.

Institutional oversight measures such as knowledge management and memory keeping are important components of institutional control supporting also post-closure retrievability. It should be recognised that the range of situations in which memory can be lost is quite broad. A specific project, under the aegis of the NEA, has been started to understand these aspects better [Ref. 53]. There are recent examples of disruptions in institutional continuity that could lead to failure of institutional controls (*e.g.* the breakup of the former Soviet Union).

Institutional controls are most often counted upon to reduce the likelihood of inadvertent intrusion, as well as in support of non-proliferation safeguards. Because of the likelihood of eventual loss of memory, inadvertent intrusion is one of the scenarios that are usually addressed in safety cases. Retrievability provisions are intended to facilitate intentional intrusion in order to retrieve wastes, while not increasing the likelihood of unintentional intrusion. Institutional controls may play a role in achieving this dual mission.

While active memory keeping, relying on land-use records, archives and markers, may not depend on monitoring, memory keeping may also be seen as requiring the availability of ongoing current information about the repository. This leads to the difficult question of how to provide such information. There may be a larger need to support continued development of remote monitoring techniques in those programmes that incorporate post-closure retrievability.

Cost is an important factor in selecting institutional controls. Cost estimates for institutional controls will vary from site to site and are affected by factors such as (i) type of institutional control used; (ii) site characteristics; (iii) need for and frequency of inspections and maintenance; (iv) length of time institutional controls needs to be effective; and (v) level of cooperation with other government agencies (*e.g.* local law enforcement). A balance needs to be struck, taking into account both the technical and societal values of monitoring and oversight. Decisions need to be taken on what is to be monitored, how the monitoring is to be conducted and for how long it will continue, and costs clearly will vary with the options.

The rigor of the institutional controls needs to be commensurate with the associated hazards. Institutional controls are often prioritised based on their potential effectiveness and the consequences of failure. In this way, a primary group of controls serves the function of providing primary protection and a secondary group may be used to provide backup protection should the primary control fail. In situations where the consequences of loss of institutional controls are expected to be small, the need for redundant controls could be minimal.

Eventually, it may be necessary to replace, modify, or terminate the controls. Procedures should be established for modifying or terminating institutional controls when warranted. The procedures should (i) provide the basis for the decision that existing institutional controls need to be modified or enhanced, or that the institutional controls are no longer required and can be terminated; and (ii) identify the modifications or enhancements to be made and how these modifications will serve to protect human health and the environment.

Monitoring

Monitoring is important not only before closure, in support of stepwise decision making during repository development, but also after closure. This topic is currently being further developed within the

EC sponsored FP7 project "MoDeRn" (Monitoring Developments for safe Repository operation and staged closure, [Ref. 51]), including both programmatic and sociological considerations of expectations and potential added value as well as considerations of technical feasibility and limitations. Before closure, monitoring is a normal and expected part of the engineered development process, regardless of whether or not a programme incorporates reversibility and retrievability. In addition to monitoring that would be expected in any project, monitoring is also performed to fulfil performance confirmation requirements for a repository. There may be substantial interest from sectors of the public in information that can be obtained from monitoring prior to closure. This may include information of direct interest to performance confirmation, and information of "intuitive" interest (*e.g.* monitoring radionuclide concentrations in the repository and in the surface environment), in addition to the general public interest in obtaining transparent and traceable information based on *in situ* evidence.

Since post-closure safety cases must provide assurance of safety even in the absence of institutional control, monitoring after closure is not part of post-closure safety assessments. However, the provision of post-closure monitoring may still be an important component of building confidence and trust in the repository system and plans. Public concerns about monitoring may continue to be pertinent regarding the post-closure stage. It is important to communicate the distinction between the ability of the safety case to demonstrate safety in the absence of monitoring and institutional control *vs*. the societal decision regarding whether to terminate monitoring and institutional oversight or to continue them after closure, either for a specified period or indefinitely.

There is a significant variety of data that can be made available during pre-closure monitoring, and technical work on monitoring techniques continues. Research and development into monitoring techniques can improve the robustness and lifetime of instruments and improve the capability to measure important parameters. Such work can be expected to take place in all programmes, independently of whether reversibility is required or not.

If retrievability after closure is considered a requirement, there are significant questions that must be answered about the ability of monitoring to supply the information that would be required to support decisions on whether or not to retrieve. While environmental monitoring will likely be required for acceptance and confidence in safety, it is unlikely that remote environmental monitoring will provide useful information about the evolution of a deep geological repository during the timeframes envisaged for monitoring.

Post closure monitoring and institutional oversight are also linked to responsibility for the waste and for safety. In this respect, it should be noted that normally the regulator's responsibility would terminate when the facility is no longer under (or required to have) a licence, which is often coincident with closure. In some countries responsibilities after the repository closure are formally or legally defined (*e.g.* in Spain, the responsibility of the repository once closed falls on the government, by law), but in others this issue remains open.

Monitoring and institutional oversight are subjects that are expected to undergo continued development. There is a significant societal dimension to these topics.

4.4 Technical factors that may either promote or challenge retrievability and reversibility

Geological disposal aims to provide a permanent and safe, long term management solution for radioactive waste. It is universally accepted that repositories should be designed so that safety does not depend on retrieval capabilities of the future generations and that only materials that are declared as being "waste" should be disposed of.

Table 4.7 summarises some of the potential benefits and shortcomings of retrievability in the context of the deep geological disposal of radioactive waste. These identified benefits and shortcomings of retrievability may not be comprehensive and the applicability of each advantage or disadvantage may vary between repository concepts. Their economic, technical, ethical or socio-political nature may also be different due to the specific issues of the waste management programme. Benefits or shortcomings must be assessed prior to the adoption of retrievability provisions during the development of the disposal strategy.

TABLE 4.7: Benefits and shortcomings of adopting retrievability provisions during the development of the disposal strategy

Benefits	Potential Shortcomings
For the pre-operational phase	
▪ In some concepts for repositories with retrievability, it is envisaged that the ability to retrieve waste may play a major role in gaining public acceptance. Retrievability of the waste is thus being viewed as a positive aspect as it allows an action or a decision to be reconsidered and possibly reversed. Retrievability may be seen as a means of ensuring continued control, thus contributing to the perception of safety and to acceptance of a proposed repository project.	▪ Although retrievability can be an important factor in public and political acceptance for the siting of repositories, additional delays and costs may be incurred as a result of provisions for waste retrieval. Also, the issue of safeguards and environmental safety considerations must be evaluated and balanced against the public acceptance benefits, as enhancing the retrievability of nuclear waste should not compromise long term environmental safety of the repositories, nor unduly delay the assurance of long-term safety. In some contexts, retrievability may also be viewed by some stakeholders as prejudicial to safety.
For the operational phase	
▪ During the operational phase, being able to retrieve waste enables a precautionary approach in waste deposition. Retrievability of the waste allows corrective actions to be taken in cases where there are shortfalls in performance of the repository system or if decisions were considered erroneous. Moreover, provision for waste retrieval also allows technological flexibility in a stepwise decision-making process, which is important when taking decisions for complicated actions. Retrievability of the waste overall is a positive aspect as it allows future generations the possibility to take control of the management of the waste. Particularly among segments of the public, many believe that scientific developments may facilitate the potential future utilisation of perceived resources such as plutonium and/or uranium in the spent nuclear fuel.	▪ On the other hand, in safeguards considerations as a result of the existence of the plutonium in spent fuel, retrievability of the waste is a negative aspect as it makes it easier to mine the repository for nuclear weapons material. In situations where a repository is extending its operational period to facilitate the potential retrieval of waste, uncertainties regarding the timing of closure may complicate the development of an acceptable safety case. Long-term safety may be affected if the engineered barriers degrade. The associated costs and risks to workers for prolonged operations will also increase. In ethical considerations of the management of nuclear waste, the need for long term surveillance may also impose additional burdens on future generations. Unstable socio-economic and political situations, which are often unpredictable, may lead to the abandonment of a facility prior to closure with negative implications in terms of long-term safety.
For the post-operational phase	
▪ Geological repositories could be a source of large quantities of plutonium and other potentially valuable elements, such as copper and iron, even when they have been sealed for a long time. Scientific advances and changes in social needs may provide incentives for retrieval of spent fuel for energy generation or as sources of other minerals.	▪ Despite the potential uses of these resources, the present generation that produces waste must ensure safe management of nuclear waste, limit burdens on future generations and ensure no significant impact from radionuclides entering the environment.

5. INTERNATIONAL STATUS AND RELEVANT OBSERVATIONS WITHIN THE R&R PROJECT WORKING GROUP

The R&R project performed a detailed compilation of country-by-country information [Ref. 3]. The compilation shows that while there is considerable agreement on many of the principles underlying reversibility and retrievability, as borne out by the discussion in early sections of the present report, there is less degree of unanimity on whether and, if so, how these principles may be put into practice in disposal programmes. Decisions on whether or not to include provisions for retrievability in a repository design must weigh the potential advantages against the possible disadvantages. These decisions can only be made in the context of a specific repository programme, and not for all repositories in general.

5.1 Status of national requirements

A brief summary of the status of reversibility and retrievability requirements in NEA member countries is found in Box 5. This summary is based on responses to the questionnaire that was distributed to NEA Member countries at the beginning of the project [Ref. 3].

In some countries, notably France, Switzerland and the USA, retrievability during the operational life of the repository is required by law. In Germany, it is a requirement laid down in the "Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste" [Ref. 61]. In some other countries (*e.g.* Canada and Japan), retrievability is not required by law, but national policy calls for it during implementation. In Finland, retrievability is not required in legislation, but it is required in the Government's Decision-in-Principle. In Sweden, retrievability is not explicitly required either by law or by the government, but it is built into the design by the implementer nonetheless and would apply during both the operational and the post-operational phases. In Canada, retrievability is also built into the design by the implementer and would apply during the pre- and post-closure phases of implementation. In most other countries, even though reversibility and retrievability are not current issues in the national debate, they are recognised as potentially important issues by the institutional players.

There are, across the more advanced national programmes, technical differences in how freedom of choice is addressed while ensuring long- and short-term safety. For instance, in some programmes individual galleries are to be backfilled as soon as emplacement is complete; in other programmes all galleries are to be kept open as long as it is safe to do so. These differences will have consequences for retrievability. In the same vein, the design and extent of monitoring before closure also differs amongst programmes.

Many of the observed differences are rooted in the different historical developments of programmes in different countries. This has led to different issues having been prominent at different stages in the process, which in turn results in differences in requirements and the way those requirements are expressed. Different social, cultural and legal environments in different countries also may lead to different attitudes towards reversibility and retrievability.

BOX 5: National Reversibility and Retrievability Requirements [Ref. 3]

Austria: N/A

Belgium: No statutory requirement for retrievability. Current policy is to avoid taking actions that would rule out retrieval, but not to require retrievability. Retrievability provisions must not be adverse to long-term safety.

Canada: No statutory requirement. However, retrievability of used nuclear fuel is a fundamental feature of the approved Adaptive Phased Management approach.

Czech Republic: No statutory requirement for retrievability. The reversibility concept is implicitly included into the stepwise DGR development approach, during which at each decision making stage several options for follow up stages will be discussed.

Finland: Retrievability of canisters is a statutory requirement. It is considered that the KBS-3 design concept meets the requirement without further special measures.

France: Reversibility is required by law during at least the first 100 years. Detailed requirements for implementing reversibility are to be developed.

Germany: Retrievability is now a requirement during the operational phase.

Hungary: Retrievability is required for pre-closure stages only.

Japan: Retrievability is not a requirement, but safety standards under development are likely to impose retrievability pre-closure.

Korea: No requirements for retrievability established. At this moment and according to the current design it is considered that reversibility can be possible during the emplacement of the disposal canister in the deposition hole only before backfilling of the disposal tunnel.

Spain: No statutory requirements exist for the retrievability of HLW, but retrievability provisions were incorporated into the design of the national LLW repository during licensing.

Sweden: There is no statutory requirement for retrievability. Retrievability provisions if adopted must not compromise safety.

Switzerland: Retrievability is prescribed by the Swiss legislation. Waste retrieval should be possible “without great effort” until repository closure. Closure is to be preceded by extended monitoring.

UK, excluding Scotland: Decision can be made at a later date in discussion with the independent regulators and local communities. The planning, design and construction can be carried out in such a way that the option of retrievability is not excluded.

Scotland: No plan for a deep geological repository. Higher activity wastes arising in Scotland are required to be managed in near-surface facilities so that the waste is monitorable and retrievable.

USA: Retrievability is required pre-closure for Yucca Mountain. This legislation also provides that DOE specify the appropriate period of retrievability, subject to NRC approval, as part of the construction authorization process. For WIPP, any certification of compliance issued by the EPA contains a condition requiring DOE to retrieve upon demand, as soon as and to the extent practicable, any waste emplaced in the disposal system.

When it comes to retrieval itself, many of the key factors that will enter into a decision on whether to retrieve will depend critically on the circumstances. For example, many of the challenges and requirements depend on the intended use or disposition of the retrieved materials, and on the motivations for the proposed retrieval. In light of this, it is also the case that some of the factors affecting retrievability (*i.e.*

programme provisions intended to promote or enable retrieval) may in turn also depend on the specific retrieval scenarios being envisaged. For various reasons, technical as well as social, the weighting given to various scenarios may differ between programmes, and as a result, the outcomes of decisions related to retrievability may also differ.

5.2 The 2010 International Conference and Dialogue on Reversibility and Retrievability

In December 2010 the NEA organised an *International Conference and Dialogue on Reversibility and Retrievability in Planning Geological Repositories* [Ref. 4]. Policy-makers, political leaders, international organisations, local stakeholders and experts from the technical and social sciences from 14 OECD countries and two international organisations attended the Conference. They explored in dialogue both commonalities and differences among national waste management programmes, as well as the various stakeholder expectations. The Conference was chaired by Claude Birraux, French MP, and hosted in Reims, France by Andra. It was co-organised with the International Atomic Energy Agency, the European Commission Directorate-General for Energy, and the International Association for Environmentally Safe Disposal of Radioactive Materials (EDRAM).

This international conference was the first in a decade on this subject and the first ever to propose dialogue among such a wide range of stakeholders. Among the key points that emerged are:

- Development of any geological repository for radioactive waste will take place over many decades and should be open to progress in science and technology, to evolving societal demands and to fixing potential implementation errors. In this regard, selecting technologies that are as reversible as practicable is a prudent approach. There is interest in a number of countries to show that retrieval of the waste is feasible during the period of waste emplacement or even for a certain period after closure of the repository.

- While countries differ in their plans to study retrieval before or after closure of a repository, the Retrievability Scale developed by the NEA R&R project (see Annex) is a useful communication tool across contexts. It shows that even if geological disposal is intrinsically a reversible technology, ease of retrieval through the various stages of repository implementation can only be a matter of degree.

- There is strong societal interest in reversibility of decisions or retrievability of waste, as indicated by legal provisions seen in many contexts. (In France, for instance, reversibility is at the core of the current technical and societal debate framed by its stepwise waste management process.) There is universal agreement, however, that R&R provisions are never to interfere with long-term safety. R&R only add value to a final management solution that rests on passive safety.

- Reversibility of decisions and retrievability of waste are rich, complex subjects that cannot be considered in isolation from safety and societal issues. Further reflection and dialogue are needed, in particular to harmonise vocabulary and the meaning of key terms such as “disposal”, “storage”, “waste”, and “closure”. Because there is no one-size-fits-all, however, each concept should be adapted to its national context.

The discussions at the conference were taken into account by the working group of the R&R project and have contributed to the findings of the present report. Some of the observations of the working group on the Conference are listed in Box 6.

BOX 6: Working group observations on the Reims Conference

The Conference brought together a diverse audience. This was of great value in communicating points of view on issues. The broadened discussion brought out new understandings within the working group and helped communicate the group's work to a wider audience.

The Conference was an opportunity for greater involvement of groups other than implementers in discussions on reversibility and retrievability. These groups included regulators, experts in social sciences, representatives of civil society and stakeholder groups.

The discussions at the Conference re-emphasized the importance of reversibility. Arising from the Conference discussions was a realisation that reversibility is not so much about reversal of decisions itself, as it is about ensuring continued participatory decision-making during the lifetime of a disposal programme.

The Conference also highlighted the importance of integrating social sciences expertise into the repository development, R&D and decision-making processes. It was noted that the social sciences are diverse, and that many different disciplines can contribute. It is likely that future contributions to the technical discussion from the domains of economics and political sciences, which to date have been comparatively few in number, could shed important new light on the subject.

The discussions at the Conference once again demonstrated the diversity of terminology between programmes and communities of interest. It is important to develop shared understandings, even if terminology cannot be standardised, in order to facilitate communications among the diverse interest groups involved.

The discussions also highlighted the importance, for communicating about these subjects, of distinguishing clearly among reversibility, retrievability and the actual process of retrieval.

5.3 Main observations and converging views within the R&R project working group

Despite the variability of national positions, a number of important points of agreement have emerged within the working group of the R&R Project.

There is general agreement that, on long timescales, when today's societal institutions can no longer be counted on, hazardous waste must be disposed of in a way that protects the health and safety of future generations without requiring continued care and monitoring. There is also general agreement that waste should be emplaced in a final repository only when there has been a policy decision ensuring that the material to be disposed of is actually waste and not a resource to be used in the foreseeable future. If there is a clear intention to retrieve the material as a resource at any time, storage would be the appropriate option. This is a national policy question to be decided before proceeding with disposal.

There is also agreement that safety regulations for the protection of man and the environment must be complied with before and during the process of repository development. The existence of retrievability provisions as a feature of a repository programme must not be used as an excuse for a disposal project to move forward with an inadequate safety case.

The requirement to meet safety regulations for the protection of man and the environment without the necessity for active control must be met in any country that is a signatory to the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management. This includes all countries with major nuclear power programmes.

It is also agreed that stakeholders must be appropriately consulted during all phases of the programme, starting before approval is granted to begin construction of the repository. Public participation is an essential part of a democratic decision-making process and moreover is required under international conventions, notably the Aarhus Convention [Ref. 62].

The ability or potential for re-accessing and re-capturing the waste during operations may be part of the operational safety concept of the repository. Retrievability provisions may provide, for instance, additional flexibility for the management of an unexpected situation during operation. The action of retrieving waste for operational reasons is not an action that necessarily puts in doubt the safety of a facility, but in fact may increase it. Retrieving waste during the operational phase could be carried out in order to perform maintenance or repair on containers, or it could be intended to better characterise the waste or to recondition it, and to re-emplace it in the repository.

Although it is not part of the long-term safety concept, retrievability may thus contribute nevertheless to the assurance of long-term safety by helping to ensure that the reference design is correctly implemented and that improvements can be effected during the operational phase.

Retrievability also helps provide the technical basis for eventual retrieval of the waste, if needed.

During discussions it was noted that he social pressures for reversibility and retrievability may be more in the direction of avoiding irreversible steps and of keeping active a continuing participatory decision-making process, rather than of specifically requiring ease of retrieval. In addition to accessing resources and the ability to continue to directly monitor conditions in the repository, it appears that the motivations for such social pressures may include unfamiliarity with (or perceived lack of maturity of) the disposal technology and discomfort with the concept of purely passive safety without any means of oversight or active control, as well as a desire to avoid making decisions today that may preclude different actions in the future. A number of these drivers may decrease over time as the level of familiarity and confidence in a programme increases, and an extended period of control may also increase familiarity and willingness to accept passive/intrinsic safety. In this context, the inclusion of retrievability provisions may be seen as mitigating risks related to uncertainty, including the risk that a repository project will not go ahead and the wastes will be left in a state that is not assured to be tenable in the long term.

Attitudes may also change between different localities and situations. In Sweden, for example, it has been observed that different interest groups (non-governmental organisations) have opposing views on the desirability of retrievability. Some feel that retrieval should be made as easy as possible in order to facilitate future freedom of choice, while others consider that retrieval should be made as difficult as possible in the interests of safety, *i.e.* in order to minimise the likelihood that future generations will come into contact with the waste.

In any event, if there is an issue of retrievability provision versus safety, it is generally agreed that safety must come first. In the very long term, attempting to facilitate retrievability by keeping a repository open longer than otherwise necessary could become detrimental to safety (*e.g.* a facility designed to be safe when properly sealed and closed may not be as safe if it is abandoned without sealing and closure, and keeping a repository open for a long period of time may increase the risk of this occurring).

6. CONCLUSIONS

The most widely adopted policy for the definitive management of high-activity radioactive waste involves its emplacement in deep geological repositories that are designed to be robust to a large spectrum of events and to prevent the release of their radioactive contents in amounts that would be harmful to man and the biosphere. The final licence of a repository is granted on the explicit judgement that, in principle, no active oversight or intervention is needed in order to assure long-term protection of man and the environment.

The implementation of a disposal project has increasingly come to be viewed as an incremental process in a series of successive steps, likely requiring several decades to complete. In addition to the original concept of passive protection of future generations, this changing vision also includes an assumption of the involvement of succeeding generations in the process of decision making and a need to preserve, as much as practicable, their ability to exercise choice. As a result of this evolution, reversibility of decisions and retrievability of the waste have come to the fore as important concepts for countries to address and refine. The principle of providing subsequent generations with the possibility to exercise choice, which is found variously in the literature, can be interpreted as implying a progressive rather than an abrupt shift from active control to passive safety. In practice, reversibility and retrievability (R&R) give recognition to the fact that preferences and intentions can change and that mistakes can happen during implementation. R&R in this way can facilitate the considered release of controls.

The policy of concentrating and confining radioactive waste in a final repository creates *de facto* a situation where the waste could be retrieved over very long time scales, extending over millennia, albeit likely at great effort and expense. If provisions meant to favour potential retrieval are incorporated into a repository design, *i.e.*, if the retrievability of the waste is enhanced, this is not done in order to demonstrate long-term safety nor do such provisions imply a clear intention to retrieve the waste in the future. The intent is merely to avoid making potential future retrieval unnecessarily difficult if future society were to decide to retrieve the waste for some reason.

As used in the present report, reversibility describes the ability *in principle* to reverse or modify decisions taken during the progressive implementation of a disposal system. Reversibility affects the entire process of repository development from its inception to final closure, *i.e.* until the absence of any remaining need to retrieve the waste is confirmed by the final regulatory approval to close all access to the repository. Reversibility can be seen as a means to provide flexibility during repository implementation prior to closure. A reversible approach in repository development should not be taken to imply a lack of confidence in the ultimate safety of disposal. It should be regarded rather as a way to make optimum use of available options and design alternatives during the evolution of the programme. Reversibility of decisions can also contribute to the credibility of the decision-making process, and in some cases may even be a prerequisite to acceptance of those decisions. Reversal, however, must not be carried out capriciously and it should always be part of a considered and transparent process.

One important reason why there is difficulty in discussing reversibility and retrievability nationally or internationally is that relevant basic terms and concepts, such as "disposal", are understood differently by different national stakeholders and/or used differently in different countries. It is important from the outset for national programmes to be clear on what is considered waste, for which there is no intention of retrieval, *vs*. what is considered as a potential resource to be stored in anticipation that it will be used in the future. For clarity, it is important to designate a "repository" as a final facility and its contents as waste. In cases where retrievability is not chosen as a matter of basic policy and in the absence of a clear designation of finality, retrievability may still be considered necessary by some to the extent that a repository, before closure, may be viewed as a hybrid between a storage facility and a final disposal facility.

Social policy issues

Decision making and decision-making processes invoke domains of study and competencies that are far removed from the scientific and engineering disciplines that at one time appeared to dominate discussions on disposal. It is becoming increasingly clear that expertise in several domains in the social sciences also needs to be brought to bear on the decision-making processes for these complex projects.

Because they touch on freedom of choice and its relationship to safety, the concepts of R&R link societal and technical considerations, and tend to be central in the debate on "disposal" when, besides the technical audiences, the public and society at large are involved; hence the continued interest in these topics. The social pressures for reversibility and retrievability may be more in the direction of avoiding irreversible steps and of keeping active a continuing participatory decision-making process, rather than of specifically requiring ease of retrieval. In addition to the ability to access materials that may become valuable at a future time and the ability to continue to directly monitor conditions in the repository, it appears that the motivations for such social pressures may in some cases include unfamiliarity with (or lack of maturity of) the disposal technology and discomfort with the concept of purely passive safety without any means of oversight or active control, as well as a desire to avoid making decisions today that may preclude different actions in the future. Some of these drivers may decrease or change over time as the level of familiarity and confidence in a programme increases. An extended period of control may increase willingness to accept passive/intrinsic safety. In this context, the inclusion of reversibility and retrievability provisions in the national programme may be seen as mitigating a risk, namely the risk that a repository project will not go ahead and that the wastes will be left in a state that may be untenable in the long term.

In considering a policy of reversibility and retrievability in order to respond to the guiding principle of preserving options for future generations, two relevant questions arise: "How should options be preserved?" and "For how long a time is it considered reasonable or desirable to preserve these options?" The answers to these questions depend upon technical, political and social factors, and are therefore variable from country to country. Some of the tradeoffs that may need to be considered include:

- Improved acceptance, decreased risk of project failure due to lack of acceptance *vs*. delays, costs, and the risk of perception of inadequacy of disposal as a result of invoking retrievability.

- Ability to correct operational faults *vs*. potential safety impacts and increased cost of postponing closure or backfilling.

- Ability to change strategies as appropriate *vs*. an increased need to take an active role in continued control.

- Increased cost of more robust containers and underground structures *vs*. safety benefits as well as retrievability.

- Increased cost of R&D to support retrievability, risk of increased perception of problems *vs*. benefits of improved knowledge.

- Increased difficulty of safeguards *vs*. benefits of retrievability.

- Ability to access materials that may become valuable at a future time *vs*. the need to ensure safety without imposing a burden of direct oversight.

In addition to such technological factors as the nature of the material to be disposed (spent fuel containing known energy resources *vs*. HLW) and the geological surroundings (which affect both the likelihood and consequences of radioactive materials reaching the environment as well as the ease of retrieval), there are also societal factors that have a major influence on decision making (*e.g.* societal attitudes towards freedom of choice *vs*. assurance of safety, and the degree of optimism with respect to future technological developments). It is reasonable to expect that the points of balance among these competing factors will differ from one country to another and even from one time to another in a given country, so the diversity of approaches to reversibility and retrievability across different countries is not unexpected.

Technical and safety issues

With respect to the technical issue of retrievability, no national programme requires retrievability as a necessary element of the safety case for waste disposal either pre- or post-closure. National programmes that require retrievability mention three main reasons: (a) an attitude of humility towards the future; (b) providing extra assurance of safety; and (c) heeding the desires of the public and political leaders to avoid being locked into an "irreversible" decision from the moment of waste emplacement. The regulations for these programmes do not require that retrieval be demonstrated in practice. They require, at most, that it be argued that retrieval could be exercised. There is, however, a trend, independent of regulation, to confirm experimentally the possibility for effective retrieval of containers disposed in a repository, as such confirmations contribute to the credibility of the commitment to providing for retrievability. Experiments have been devised and run successfully and R&D is ongoing in several countries.

There exist means to enhance the potential for waste retrieval, *e.g.* by implementing more durable containers and waste forms, or by stipulating longer periods for observation before emplacing backfill materials or sealing galleries or the whole repository. There is, however, a delicate balance to consider, *i.e.* whether enhancing retrievability may or may not jeopardise safety and/or the continued ability to ensure physical protection of nuclear materials, both for present and for future situations. Cost is also a factor, as more durable containers may be more expensive, and as keeping a facility open or having stronger safeguards and physical protection measures implies ongoing costs. On the other hand, a better ability to potentially retrieve the waste can be seen as providing further assurance of reaching a final safe configuration, in that, during the operational phase, intervention to correct problems is possible and, in the post-operational phase, waste can be more safely attained should the need arise or if it were decided to regain access to the waste for reasons other than safety.

It is in no-one's interest to use retrievability provisions as an excuse to implement an immature programme. It must be understood that any decision to retrieve wastes after even partial closure would imply a major undertaking. Retrieval would be costly and would pose safety hazards; the cost of retrieval is likely to increase progressively as the system evolves towards its final configuration. If future standards are similar to today's, as it must be assumed for decision making, then retrieval would be a regulated activity. A regulatory approval to remove wastes would require that facilities exist to accept and manage the retrieved wastes safely. In the national programmes that include retrievability as a declared feature in implementing a final repository, the goal is not to make future retrieval easy or cost-free; it is simply to ensure that it is feasible, *i.e.* not to render it unnecessarily difficult, assuming a future society that is both willing and capable of carrying it out.

If retrievability is a pre-requisite in the disposal programme, the repository licence may include retrievability conditions that may apply during specified periods of time, *e.g.* during the emplacement phase, or prior to closure. Retrieval of individual packages for operational reasons during the emplacement phase is often considered to be part of good operating practice, and would be funded as part of the basic programme. Retrieval of a part or the whole of the inventory for other reasons is generally treated as a new activity, requiring a new licence, and that would be funded only at the time it was decided upon.

During the operational phase, parts of the repository may be backfilled and sealed while other parts are still open. For those parts of the repository that remain open, the operational safety case may rely upon retrievability, for example in order to permit correction of problems arising during implementation. However, the safety case for closed portions of the repository, like the safety case for the post-operational phase, should stand on its own, *i.e.* without the need to rely upon retrievability to ensure safety. In practice, during the emplacement phase, unless there are serious problems with the repository concept or its implementation, retrievals are likely to be rare events and would likely be carried out only for a small number of containers (if any) and only for operational reasons. The likelihood of retrieval following the completion of emplacement would be expected to be even less.

Although the long-term safety case must be able to stand on its own without them, specific post-operational institutional oversight provisions, such as monitoring and records and memory keeping, may nevertheless be decided upon. If so, these may further contribute to decision making relative to retrieval post-operation, and to the freedom of choice provided to future generations.

General observations

The NEA's R&R project has touched on and developed many of the issues related to reversibility and retrievability, but it can hardly be considered the final word on the topic. At the end of this project, it is clear that the development of these and related topics will continue. While it is perhaps risky to speculate on where future discussions may lead, a review of the topics discussed during working group meetings and at the 2010 Reims International Conference and Dialogue suggests a number of possibilities, among them: continued consideration of decision making and a move towards more concrete discussions on this topic, with the help of expertise from domains such as political science and decision science; more concrete consideration of costs, perhaps with input from economics (*e.g.* "real options theory"); greater involvement of regulators and decision makers; more direct involvement of civil society stakeholders in discussions; further consideration of the relationship between retrievability and "green" societal trends (participatory decision making, increased emphasis on renewability and recycling); studies of management and governance culture as they pertain to disposal programmes; continued study of whether and how reversibility and retrievability relate to optimisation of the systems of disposal and repository evolution; and further study of the relationships between retrievability and the requirements for safeguards and physical protection of nuclear material.

Having reviewed the literature on reversibility and retrievability and reflected on how these concepts have been discussed and introduced in connection with national waste management programmes, it can be concluded that countries should have a position on these concepts. We also conclude that the current predominating view is that reversibility of decisions and retrievability of the waste can be beneficial features of any deep disposal programme provided the limitations of the concepts are recognised. The position of many national programmes is that, from a technical point of view, flexibility in implementing the repositories is a recognised management approach, and represents a means for process optimisation. Reversibility can be a major contributor to this flexibility.

Reversibility and retrievability are tools that can contribute to a responsible approach to repository development and aid to achieve the final safety objectives through a considered and coordinated process. At the engineering level, they may help achieve the final configuration for the waste to be disposed of, but long-term safety does not rest on retrieval being possible. At the project level, reversibility may be associated with a prudent approach of verification of specific design features so that they do not unnecessarily impair or preclude fallback options. At the policy level, reversibility can be associated with a culture of stepwise decision making by requiring that the validation or the reversal of major decisions is discussed before proceeding to the next step. As well as being requested by interested parties in some programmes, reversibility is also a feature that provides opportunities for co-ordination and co-decision amongst those parties. A sequence of shared decisions confirming at each step that there were no safety reasons for retrieval could ease any decisions on moving forward and eventually closing the facility.

Reversibility and retrievability are not design goals; they are attributes of the decision-making and design processes that can facilitate the journey to the final destination of safe, socially-accepted disposal.

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ANNEX – INTERNATIONAL RETRIEVABILITY SCALE LEAFLET

The four-page leaflet "International Retrievability Scale" reproduced here is available as a stand-alone document suitable for printing at http://www.oecd-nea.org/rwm/rr/. Versions are available in several languages. The NEA will provide upon request high-resolution pdf's for professional printing, and an InDesign file to facilitate the publication of translations into further languages that may be undertaken by national programmes.

INTERNATIONAL UNDERSTANDING OF **REVERSIBILITY** OF DECISIONS AND **RETRIEVABILITY** OF WASTE IN GEOLOGICAL DISPOSAL

Countries around the world are researching, developing and demonstrating disposal of long-lived radioactive waste in engineered repositories located in suitable deep underground geological formations as the reference solution to protect present and future generations and the environment. In some countries, actual implementation of geological disposal projects is only a few years away. Countries are also considering whether and how to incorporate the concepts of reversibility and retrievability into their repository programmes. Reversibility implies a disposal programme that is implemented in stages and that keeps options open at each stage, and provides the capacity to manage the repository with flexibility over time. Retrievability is the possibility to reverse the step of waste emplacement. It is generally recognised that it is important for each country to clarify the meaning and role of reversibility and retrievability for its programme and that long-term safety is paramount. The present leaflet summarises the current understanding developed in the NEA international project on reversibility and retrievability (http://www.oecd-nea.fr/rwm/rr). The leaflet includes a generic Retrievability Scale that is adaptable to most countries' programmes and could help support dialogue with stakeholders.

Repository objective and life phases

The objective of a geological repository is to provide protection of humans and the environment from the hazard that the radioactive waste would pose over time. Once the waste is emplaced, there is no intention to retrieve it. Ultimately, safety is to be ensured by the man-made barriers and the host geology fulfilling complementary functions, and it will be necessary to close the repository according to an agreed plan. For this reason, no material other than packaged ultimate waste should be disposed of in the repository. In this context, waste storage is not an alternative to disposal; rather it is a step in the management strategy leading to final disposal.

A geological repository involves three main phases (Fig. 1) whose durations vary amongst national programmes depending on design and each country's approach to decision making:

§ The **pre-operational phase** is the period during which the repository is designed, the site is selected and characterised, the man-made materials are tested and the engineering demonstrated, the licenses for building and operation are applied for and received, and construction begins. A baseline of environmental conditions is also obtained.

§ The **operational phase** may be divided into three periods:

(a) The *emplacement period*: the waste packages are emplaced. The environmental conditions are continuously monitored and compared to the baseline data; R&D continues; the regulator performs regular inspections for operational safety and reviews of the long-term safety case. New underground galleries may be built and partial backfilling and/or sealing of galleries and repository areas may also take place.

(b) The *observation period*: after all waste packages are emplaced, it might be decided to monitor parts of the repository and to keep some accessibility to part of the waste while additional performance confirmation takes place.

(c) The *closure period*: backfilling and sealing are performed according to design and access from surface to the underground facility is terminated. Surface facilities may be dismantled.

§ The **post-operational phase** may be divided into two periods:

(a) A *period of indirect oversight*: after closure, safety is assured through the intrinsic, passive provisions of the repository design. Nevertheless, it is plausible to expect continued monitoring of the baseline environmental conditions, and some remote monitoring. The relevant international safeguards controls would continue to apply. Archives on technical data and configuration of waste packages and the repository would be kept, as well as markers to remind future generations of its existence.

(b) A *period of no oversight*: eventually, after hundreds or thousands of years, loss of oversight and memory can be expected to take place, either progressively or following major unpredictable events such as war or loss of records.

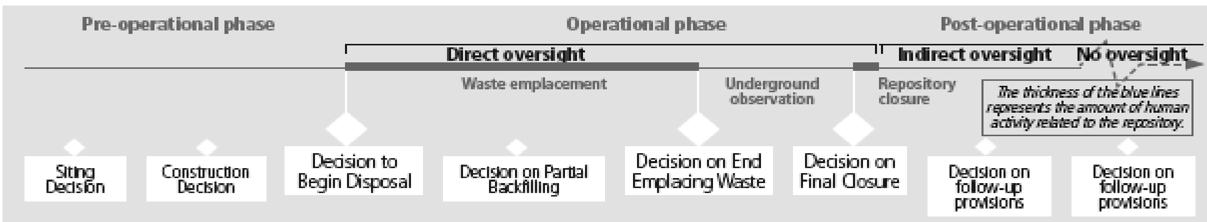


Figure 1: Repository life phases and examples of associated decisions

Reversibility, retrievability: what are they?

Reversibility refers to decision-making during project implementation: it involves ensuring that the implementation process and technologies maintain flexibility so that, at any stage of the programme, reversal or modification of one or a series of previous decisions may be possible if needed, without excessive effort. A decision of partial backfilling, for example, may be made with reversibility in mind. Each major authorisation in repository implementation (Fig. 1) can be seen as an assessment of whether the process can continue as foreseen or whether one of the reversibility options should be exercised (Fig. 2). Reversibility implies a willingness to question previous decisions and a culture that encourages such a questioning attitude. It also implies some degree of retrievability of waste.

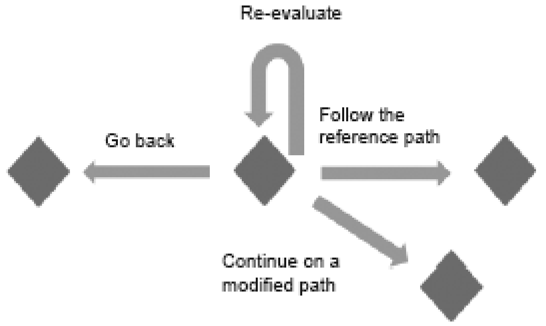
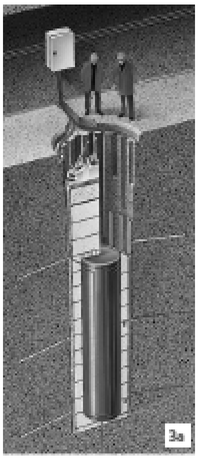


Figure 2: Potential outcomes of options assessment, including reversal

Retrievability is the ability to retrieve emplaced waste or entire waste packages. While retrievability is an intrinsic part of the concept of waste storage, it is not part of the basic, long-term safety concept of waste disposal in a final repository. Waste should never be emplaced in a repository if the long-term safety case is not robust without reliance on retrievability. However, retrievability may still contribute to confidence in safety and retrieval may become desirable for non-safety reasons. Retrievability provisions may also provide additional flexibility during operation.

Even if the package is degraded, retrieval of the waste may still be carried out using appropriate techniques. If the waste materials have migrated away from their initial emplacement location, retrieval of the waste could require mining techniques similar to those used in ore extraction. Retrieval of waste may be desirable for reasons other than safety, e.g., if the waste were to be re-categorised as a resource. The safety case for a repository, however, will always rest on passive safety considerations and not be dependent on the possibility of retrieval.

During the operational phase, reversibility and retrievability translate into practice a precautionary approach to waste disposal. During all repository life phases, retrievability is facilitated by the very fact of confinement (non-dispersion) in a geological repository. In the distant future, waste will still be retrievable, although with greater effort and expense as time passes. The ability to retrieve is thus a matter of degree rather than of the presence or absence of the possibility to retrieve the waste. Research and development may provide ways to reduce the degree of difficulty of retrieval (Fig. 3).



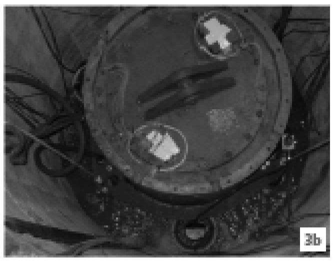


Fig. 3a & 3b: Bentonite rings removal test in view of waste package retrieval in Sweden (Äspö HRL, 2006)
Fig. 3c: Retrieval of a disposal HLW package from a simulated emplacement cell in France (ESDRED programme, 2008)

A retrievability scale for stakeholder dialogue

One of the key issues for stakeholders considering the implementation of a geological disposal facility for radioactive waste is the ease of waste retrieval from a repository. The ease will vary according to the accessibility of the waste during the life phases of the repository. A generic retrievability scale has been developed to illustrate qualitatively the degree and type of effort that is needed to retrieve the waste according to the stages in its lifecycle before and after its emplacement in a repository (see Table I and Fig. 4). The scale also shows the relationship between the effort needed for retrieving the waste and the corresponding balance between active controls and passive safety of the repository. The more difficult the retrieval is, the higher its cost will be.

Waste lifecycle stages and retrievability: a textual description

For illustration purposes, the lifecycle of packaged[1] waste can be reduced to 6 stages, as identified in Table I. For each stage, the table also identifies the main elements of passive safety and active control, as well as the degree and type of retrieval effort. **Stage 1** represents packaged waste placed in interim storage. **Stage 2** is waste moved from interim storage to a repository facility a few hundred meters deep, which may require further re-packaging. Additional protective barriers around the waste emplacement cell are put in place in **Stage 3**: backfill (against rock movement, generally) and/or sealing (against water and gas circulation). The access galleries to the cell still need active maintenance, e.g. ventilation. These galleries are backfilled and/or sealed in **Stage 4**, which may coincide with the closure of the whole disposal zone in which the gallery is located or indeed of the whole underground facility. At this stage, maintenance of the disposal zone (or the whole underground facility) is no longer necessary, but the facility may still be monitored remotely. In **Stage 5** the repository is closed: access from surface has been sealed, and surface facilities have been dismantled. **Stage 6** is the final disposal state. Although the integrity of the waste packages cannot be guaranteed, the waste is still confined within the facility. By this time, the level of radioactivity has reduced significantly. Safety will not depend on maintenance or monitoring, but measures intended to ensure preserving knowledge and memory of the site may continue.

[1]The type of package may be a steel drum, a concrete container, a steel primary package inside a concrete or steel container, etc.

Table I: Waste lifecycle stages, ease of retrieval, and specific elements of passive safety and active control.

	Stage and Location of the Waste*	Ease of Retrieval	Specific Elements of Passive Safety	Specific Elements of Active Control
1	**Waste Package(s) in storage**	Waste package retrievable by design.	Waste form and its storage container.	Active management of storage facility including security controlled area.
2	**Waste Package(s) in disposal cell****	Waste package retrievable by reversing the emplacement operation.	Waste form and disposal container Hundreds of meters of rock Engineered disposal cell.	Active management (including monitoring) of disposal cells and disposal facility. Security controlled area.
3	**Waste Package(s) in sealed disposal cell**	Waste package retrievable after underground preparations.	As in previous stage, plus backfill/sealing of disposal cell.	Monitoring of disposal cells possible. Active management of access ways to disposal cell seals. Security controlled area.
4	**Waste Package(s) in sealed disposal zone**	Waste package retrievable after re-excavation of galleries.	As in previous stage, plus backfill/sealing of underground galleries allowing access to cells.	Monitoring of disposal cells potentially possible. Security controlled area. Detailed records and institutional controls for a specified period, including international safeguards.
5	**Waste Package(s) in closed repository**	Waste package retrievable after excavating new accesses from surface. Ad-hoc facilities to be built to support retrieval.	As in previous stage, plus sealing of shafts and access drifts to ensure long term confinement of the waste within the underground facility.	Maintaining records. Regular oversight activities as long as possible (e.g. environmental monitoring, possibly remote monitoring, security controls and international safeguards).
6	**Distant future evolution**	Waste package degrading with time. Waste ultimately only retrievable by mining.	Geology and man-made barriers. Reduction in level of radioactivity.	Specific provisions for longer-term memory preservation, e.g. site markers.

** During the operational phase, not all waste packages present in the facility will be at the same lifecycle stage.*
*** Depending on the national programme and on the type of waste, the waste package emplacement room may be a vault, a cell, a section, etc. The term "cell" used here is generic to all these cases.*

Waste lifecycle stages and retrievability: a graphical description

The connection between retrievability and passive safety along the lifecycle of radioactive waste is represented graphically in Fig. 4. The figure is generic and can be applied to a variety of national programmes.

The duration of the waste stages and the duration of the repository life phases will depend on decisions that will be made in each national programme during the implementation of the geological facility. At each decision point during implementation, which could last up to 100 years, various factors will be taken into account, including: ease of retrieval of waste packages; the need for active control; changes affecting long term safety; and costs in terms of economics, dose exposures, hazards, etc.

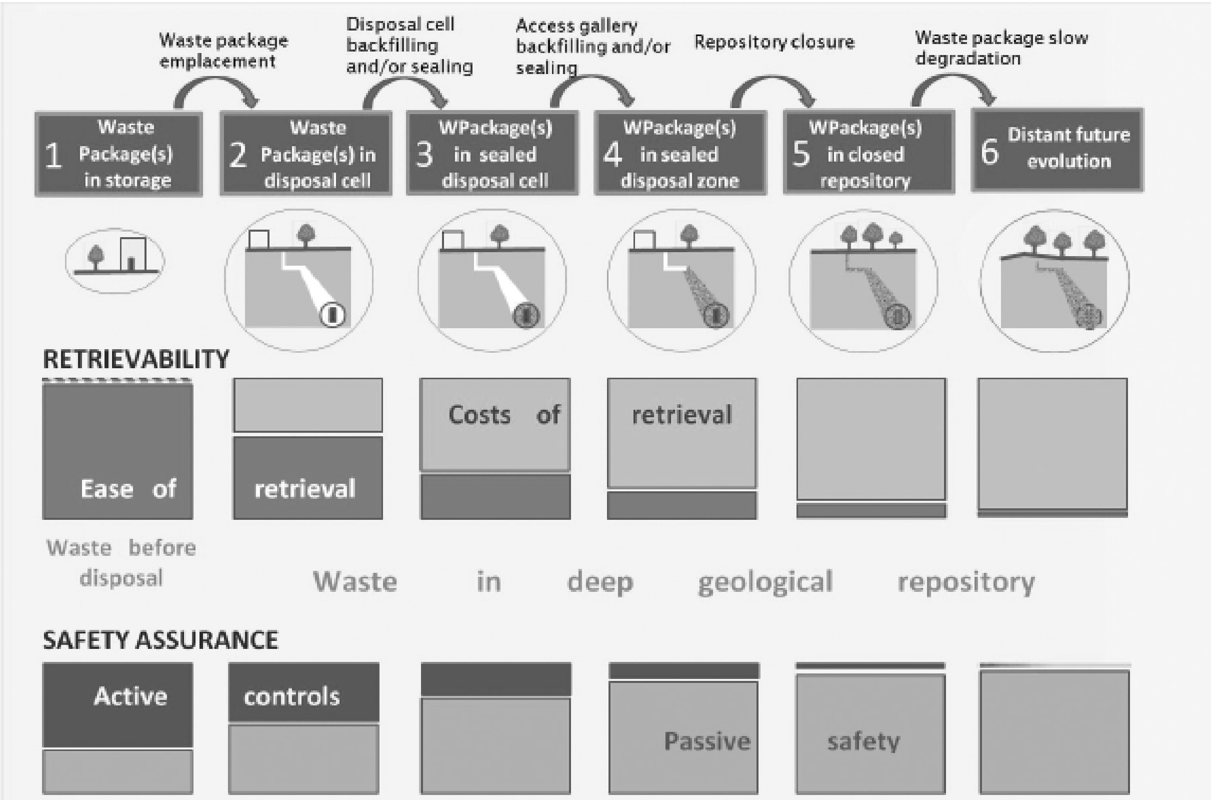


Figure 4: Lifecycle stages of the waste, illustrating changing degree of retrievability, passive vs. active controls and costs of retrieval in a deep geological repository. During the operational phase, not all waste packages present in the facility will be at the same lifecycle stage. Note: exact proportions of illustrated rectangles may vary depending on the repository design.

> REVERSIBILITY AND RETRIEVABILITY APPLIED DURING THE OPERATIONAL PHASE OF A GEOLOGICAL REPOSITORY OF LONG-LIVED RADIOACTIVE WASTE TRANSLATE INTO PRACTICE A FLEXIBLE, PRECAUTIONARY APPROACH TO WASTE DISPOSAL. RETRIEVABILITY IS A MATTER OF DEGREE RATHER THAN OF THE PRESENCE OR ABSENCE OF THE POSSIBILITY TO RETRIEVE THE WASTE. EVEN THOUGH RETRIEVABILITY IS NOT PART OF THE LONG TERM SAFETY CONCEPT FOR DISPOSAL, THE WASTE CONTINUES TO BE RETRIEVABLE, ALBEIT POSSIBLY AT GREAT EFFORT AND EXPENSE. RESEARCH AND DEVELOPMENT MAY PROVIDE WAYS TO REDUCE THE DEGREE OF DIFFICULTY OF FUTURE WASTE RETRIEVAL.