OPERA

Topic report on retrievability, staged closure and monitoring

OPERA-PU-NRG123

Radioactive substances and ionizing radiation are used in medicine, industry, agriculture, research, education and electricity production. This generates radioactive waste. In the Netherlands, this waste is collected, treated and stored by COVRA (Centrale Organisatie Voor Radioactief Afval). After interim storage for a period of at least 100 years radioactive waste is intended for disposal. There is a world-wide scientific and technical consensus that geological disposal represents the safest long-term option for radioactive waste.

Geological disposal is emplacement of radioactive waste in deep underground formations. The goal of geological disposal is long-term isolation of radioactive waste from our living environment in order to avoid exposure of future generations to ionising radiation from the waste. OPERA (OnderzoeksProgramma Eindberging Radioactief Afval) is the Dutch research programme on geological disposal of radioactive waste.

Within OPERA, researchers of different organisations in different areas of expertise will cooperate on the initial, conditional Safety Cases for the host rocks Boom Clay and Zechstein rock salt. As the radioactive waste disposal process in the Netherlands is at an early, conceptual phase and the previous research programme has ended more than a decade ago, in OPERA a first preliminary or initial safety case will be developed to structure the research necessary for the eventual development of a repository in the Netherlands. The safety case is conditional since only the long-term safety of a generic repository will be assessed. OPERA is financed by the Dutch Ministry of Economic Affairs and the public limited liability company Electriciteits-Produktiemaatschappij Zuid-Nederland (EPZ) and coordinated by COVRA. Further details on OPERA and its outcomes can be accessed at www.covra.nl.

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Title: Topic report on retrievability, staged closure and monitoring
Authors: T.J. Schröder, B.R.W. Haverkate, (NRG); A.F.B. Wildenborg (TNO)
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Summary

As part of the OPERA project *Retrievability and Staged Closure* (*RESTAC*), this combined topic report presents information on the concepts of retrievability, reversibility, and staged closure, as well as on the role of monitoring in radioactive waste disposal. This information was in the first instance intended as project-internal input for the subsequent subtasks of the *RESTAC* project, and parts of the present content have also been reported in the combined *ENGAGED*/*RESTAC* final report *OPERA-PU-ECN121*.

Retrievability and monitoring are complex interdisciplinary topics, and the main objective of this topic report is – besides the documentation of background information in agreement with the *RESTAC* research proposal - to provide additional input for the general discussion on retrievability, reversibility, staged closure and monitoring that did not fit properly into the *ENGAGED*/*RESTAC* final report.

The present report is divided into two parts: The main text (Chapters 2 to 5) and three appendices. Chapters 2 to 4 give a high-level overview and focus on practical and strategic implications concerning the disposal of radioactive waste for the coming years. Chapter 5 provides concrete recommendations for the coming years. In three appendixes, general concepts of reversibility, retrievability and staged closure are discussed (Appendix A), the role of monitoring is elaborated (Appendix B), and lessons learned from monitoring of CO_2 storage (Appendix C) are provided.

Samenvatting

Dit gecombineerde topic rapport is onderdeel van het OPERA project *Retrievability and Staged Closure* (*RESTAC*) en bevat informatie over terugneembaarheid, omkeerbaarheid, en stapsgewijze sluiting, als ook over de rol van monitoring in de geologische berging van radioactief afval. De informatie in dit rapport diende in eerste instantie als projectinterne inbreng voor navolgende *RESTAC* taken en is deels ook gebruikt in het gecombineerde *ENGAGED*/*RESTAC* eindrapport *OPERA-PU-ECN121*.

Terugneembaarheid en monitoring zijn complexe, interdisciplinaire onderwerpen, en het hoofddoel van dit rapport is - naast de documentatie van achtergrondinformatie in lijn met het *RESTAC* onderzoeksvoorstel - om bijdrages aan de algemene discussie over terugneembaarheid, omkeerbaarheid, stapsgewijze sluiting en de rol van monitoring te bundelen, die minder goed in het eindrapport pasten.

Het rapport is in twee delen gesplitst: de hoofdtekst (Hoofdstukken 2 tot en met 5) en drie appendices. Hoofdstukken 2 tot en met 4 geven een gecondenseerd overzicht van praktische en strategische aspecten, en Hoofdstuk 5 bevat een aantal aanbevelingen voor het afvalbeleid in de komende jaren. In de drie bijlagen worden achtereenvolgens besproken: de concepten van terugneembaarheid, omkeerbaarheid, en stapsgewijze sluiting (Bijlage A), de rol van monitoring (Bijlage B) en ‘lessons learned’ van monitoring activiteiten rondom de opslag van CO_2 in de ondergrond (Bijlage C).

1. Introduction

1.1. Background

The five-year research programme for the geological disposal of radioactive waste – OPERA- started on 7 July 2011 with an open invitation for research proposals. In these proposals, research was proposed for the tasks described in the OPERA Research Plan [2]. This topic report combines the outcomes of the internal interim reports IR1.2.3a and IR1.2.3b of the OPERA research project *Retrievability and Staged Closure* (*RESTAC*), as part of OPERA Task 1.2.3, '*Retrievability and staged closure*'.

In the OPERA research programme, all safety relevant aspects of a given generic reference disposal concept for radioactive waste in Boom Clay [1] are evaluated and assessed in order to evaluate the long-term safety of such a facility [2]. The programme follows in general terms the methodology known as '*safety case*' [3, 4, 5, 6, 7, 8], and aims to assess the long-term safety of a geological disposal concept and elaborates the methodical and scientific arguments in support of this. Although the OPERA Safety Case and its statements on the long-term safety might be the most visible outcome of the programme, OPERA also recognized the relevance of understanding societal aspects in more detail. Within OPERA Work Package 1, the projects *CIP* [9, 10, 11], *ENGAGED* [12, 13] and *RESTAC* [12, 13] contributes to the contextual topics of communication, participation and structuring of the disposal implementation process.

1.2. Objectives

As part of the *RESTAC* project, this combined topic report presents information on aspects of retrievability, reversibility, staged closure and the role of monitoring that was used as input for the subsequent subtasks of the *RESTAC* project reported in [12, 13].

During collection and processing the information for these subtasks, it appeared that the topics of retrievability and monitoring were not easy to debate with a broad group of stakeholders, partly due to the complexity on the topics, partly because the topics are currently not elaborated sufficiently well, with insufficient robustness[1] of arguments to allow a useful discussion. In particular, discussing the role of monitoring as part of the intended stakeholder interactions of the *RESTAC* project seems to be 'a bridge too far' in the current early stage of the implementation process in the Netherlands. Therefore the main objective of the present report is to provide additional input for the general discussion on retrievability, reversibility, staged closure and monitoring that did not fit properly into the main report [12] – in addition to the objective to document background information in agreement with the *RESTAC* research proposal.

1.3. Realization

This topic report combines the outcomes of the internal interim reports IR1.2.3a and IR1.2.3b of the OPERA research project *Retrievability and Staged Closure* (*RESTAC*), being prepared by NRG and TNO. The report is divided into two parts: The main text presents a condensed, high-level discussion on the main topic, focuses on practical and strategic implications for the coming years and provides in Chapter 5 concrete recommendations,

[1] The definition of '*robustness*' given in [17], p.185, is followed here: "*arguments are robust if they can be supported without too much efforts, throughout accepted principles, widely recognized policy, accepted results of research agreed goals, or (other) robust arguments.*"

additional to those listed in the ENGAGED/RESTAC main report [12, 13]. For the interested reader, in five appendixes supplementary information is provided [2]:

- Appendix A: General concepts of reversibility, retrievability and staged closure (NRG);
- Appendix B: The role of monitoring (NRG);
- Appendix C: Lessons learned from monitoring during the final stages of the CO_2 storage lifetime (TNO).
- Appendix D: Description of Key Decisions Steps
- Appendix E: Analysis of endpoints for radioactive waste disposal

1.4. Explanation contents

Some general observations on retrievability and monitoring are shared in Chapter 2. Chapter 3 provides a condensed, high-level discussion on key concepts and questions on ‘retrievability’. In Chapter 4, the role of monitoring in the disposal concept is briefly summarized. Chapter 5 provides conclusions and recommendations relevant to policy development.

In Appendix A, a more detailed discussion on the general concepts of reversibility, retrievability and staged closure is given. Appendix B discusses the role of monitoring, and in Appendix C ‘lessons learned’ from monitoring during the final stages of the CO_2 storage lifetime are provided. Appendix D summarizes general features of the main disposal stages. Finally, Appendix E contains an overview on argumentation scenarios and their resulting endpoint for waste disposal, based on an earlier evaluation.

[2] Because the information presented here is partially used as input for [12] some overlap exists.

2. General observations

The concepts of retrievability, reversibility and staged closure are common principles in radioactive waste management (RWM) and broadly discussed in literature [e.g. 5, 14, 15, 16]. While reversibility and staged closure seem to be generally accepted principles[3], *retrievability* is - after more than two decades of discussion - still a topic about which different visions remain and for which no robust argumentation exists that is shared by all stakeholders.

Retrievability

The different visions on retrievability often manifest judgements on the ability to dispose radioactive waste safely in the deep underground, or reflect stakeholder requests to keep options open for future generations. Hence, the different ideas and expectations on retrievability reverberate essential concerns, ideas and values in the controversial societal discussion on radioactive waste disposal (see e.g. [17]) and seem to answer to a more general societal request to be able to correct mistakes or misjudgements or to respond to (unforeseen) calamities. Understanding positions and arguments behind retrievability are of relevance for the implementation process, because they are linked to different conclusions on how to dispose of radioactive waste safely in general [17].

However, it appears that the term '*retrievability*' is currently not well enough defined to allow informed discussion, as e.g. observed at the combined *ENGAGED/RESTAC* workshop [12, Chapter 8.3.2], and it was also found that discussions on this subject can easily lose focus since retrievably can serve several objectives, not necessarily shared by all stakeholders [14, see also Appendix A].

In the *ENGAGED/RESTAC* workshop, but also on other occasions (e.g. [18]), it was observed that there is some general agreement that retrievability can have its benefits, but is also related to risks and costs. The advantages and disadvantages of retrievability can result in a conflict of objectives, with the relevance of each aspect judged differently by stakeholders, eventually leading to different conclusions [17]. It can also be concluded that there is currently insufficient insight on what can be achieved by a requirement on retrievability, and how it should be implemented in RWM. Sufficient detailed scientific or technical information that would allow to quantify and weighing up benefits, risks and costs of retrieval against each other and to articulate and discuss robust argument for or against a certain management option is lacking (see also [19]).

Monitoring

Likewise, the role that *monitoring* can have in disposal implementation is under development, with currently insufficient basis to allow informed discussions with a broader range of stakeholders.

On the one hand there is a shared belief that monitoring can have a beneficial role in increasing public and stakeholder confidence, and useful strategic and technical input that allows to bring monitoring better into perspective was provided by the EU-FP7 project *MoDeRn* [20, 21].

On the other hand, the overall theme of '*monitoring*' is technically complex, the link with the safety case still needs to be elaborated more clearly, and the topic seems to be too 'overloaded' with respect to the different roles and objectives that are attributed to '*monitoring*' in the different national contexts. While it was judged that it will be difficult

[3] with minor side effects to be considered (see e.g. [12, Chapter 9])

to perform useful debates with stakeholders of the Netherlands in the current phase and as part of the *ENGAGED/RESTAC* workshop, it was also evident that the ability to monitor is related to key questions and concerns with respect to the implementation of a safe disposal strategy (see e.g. [20, 17]), in particular regarding a definition what a requirement on retrievability can add to the overall confidence in safety.

Reversibility in decision-making

Discussion at the *ENGAGED/RESTAC* workshop on the concept of *reversibility in decision-making* made clear that this is generally seen as a beneficial concept because it allows future generation to make their own decisions, eventually also providing the opportunity to 'correct' previous decisions.

While the responsibility of this generation for future generations [22] was emphasized, it was apparent from the discussion that there is no clear agreement on what has to be achieved or arranged by the current generation, and what are probably topics that can be reasonably 'left' for future generation. This is of particular relevance for the Dutch policy of long-term interim storage, where apparently only very little logistic or legal urgency seems to exists, and a certain degree of '*wait and see*' may provide strategic benefits.

Noting that different positions exists on this question as well, as discussed in the outcome and recommendations of the *ENGAGED/RESTAC* main report [12], however, a need for a clear position was sensed on what questions need to be addressed in the coming years, and what aspects may – although often not of less relevance – be postponed to a later stage.

Developing the subject of retrievability further

Based on the consideration above, in the remainder of this topic report an attempt is made to develop the subject of retrievability further with respect to the practical implications for the current Dutch situation. To be able to do so, it seems necessary to first unload this topic from its inherent complexity by

1. focussing what aspects are important for the specific Dutch situation, in particular with respect to the envisaged long-term interim storage and the potential interest in establishing a multinational repository, and
2. elaborating what is of particular relevance for the near future, and what concrete activities can be recommended for the post-OPERA period.

In the next chapter, key concepts and definitions related to '*retrievability*' are provided that are judged to be useful to allow more informed discussions in the coming years. As such, the concept of '*retrievability*' is closely related to the so-called '*IBC-criteria*'[4], a cornerstone of the Dutch RWM policy [23, 24, 25]. However, the scope of the *IBC-criteria* goes beyond retrievability: '*surveillance*' and '*control*' also implies the ability to monitor the status of the waste. Chapter 4 discusses the role of monitoring in relation to retrievability and the potential to provide evidence of safety.

[4] "Isoleren, Beheersen en Controleren" (isolation, control, and surveillance). In some translations this is also indicated as "ICM-criteria" (isolation, control and monitor).

3. Retrievability of radioactive waste

As already noted in the previous chapter, *retrievability* is difficult to discuss as long as it is insufficiently well defined. As the *ENGAGED/RESTAC* stakeholder workshop [12, Chapter 8.3.2] underlined, '*retrievability*' is a rather ill-defined concept when it is discussed without further clarification. In order to facilitate meaningful discussions on this subject it is therefore recommended to

- distinguish between different objectives for waste retrieval, and to
- clarify the content of the attribute '*retrievable*'.

3.1. What does 'retrievability' *mean?*

To provide input for a broader discussion on the implementation of a deep geological disposal for radioactive waste, and to address the perceived differences in societal expectation and stakeholder opinions on this matter, the term '*retrievability*' need to be further clarified. Currently only general views exists on the technical feasibility of waste retrieval for the disposal concepts considered in the Netherlands [26, 27, 28], and it is unclear what retrievability mean in terms of time, costs, and risks. Differences in positions between countries are noted, leading to different usage of terms and different underlying concepts when defining the term '*retrievability*' (see e.g. [29], p.6*f*).

Furthermore, as pointed out in the *ENGAGED/RESTAC* workshop, one may consider *every* concept as retrievable *in principle*, i.e. when costs plays no role, and technology - if not available - can be developed for this purpose in future. To allow meaningful discussions, it is therefore recommendable to extend the definition of *retrievability* by a clear-cut description on its technical feasibility, and to link '*retrievability*' to specific technical measures that allow the retrieval of waste (e.g. corrosion-resistant and mechanical stable containers, additional borehole lining or stabilization of disposal galleries, design of machines for waste recovery). An indication on the period of retrievability should be given, since it is clear that existing technical options do not allow an indefinite retrieval of the waste (e.g. [30]). Furthermore, it should be distinguished between a "planned" retrieval, and the "unplanned" retrieval of the waste [31][5].

As a working definition of the term we suggest:

> ***Retrievability*** *is the ability to retrieve emplaced waste or entire waste packages in a previously planned manner. A claim of retrievability should be supported by a thorough assessment on how the retrieval of the waste can be technically realised. Such an assessment should be based on available technology, and should include information on the technical procedure, costs, operational risks, interim storage provisions for the retrieved waste, and the timescale on which the waste is assumed to be retrievable on the described manner.*

When '*retrievability*' is understood as a (technically) realistic management option, it should be supported by in depth analyses, and – where necessary – experimental evidence and technical demonstrations. This can be developed in a stepwise manner: while earlier steps focus on the principal feasibility, in later stages clear-cut technical requirements on retrievability have to be defined, eventually linked to decisive technical guidelines or legal requirements. From the discussions on the role of monitoring [20] it is evident that

[5] In this report the use of the term '*recovery*' is avoided, because its meaning differs between publications.

additional support by *in-situ* demonstration projects can relevantly contribute to confidence. Stakeholder may also actively request to provide additional evidence for the retrievability by *in-situ* demonstrators in a later stage.

3.2. Why considering the retrieval of waste?

A large number of reasons or objectives to implement a retrievable disposal are discussed (e.g. [14, 18], see also Appendix A). The most important are:

- to allow reduction of the radiotoxicity inventory of the waste in case suitable technologies become available in future
- to allow reuse of waste in future
- to allow safer solutions for the disposal of waste in general
- to allow the future correction of ‘mistakes’ or to anticipate (unexpected) calamities

It makes sense to distinguish between these objectives when discussing retrievability, because not each objective will be judged as equally relevant with respect to the efforts, costs and (operational) risks that one may consider acceptable. Two main groups of objectives can be distinguished, based on their scopes and implications:

- ***Retrievability as management option***: The first three objectives in the list above have in common that they can potentially improve the long-term safety above the safety already provided by a disposal concept, or are related to other (e.g. economic) benefits. While it could make sense to enable current and future generations to re-evaluate previous RWM decisions, there is no strict necessity from safety point of view to do so: a disposal concept realized in line with the safety case methodology and general safety standards [32] represents a solution broadly accepted as safe by society. I.e. not considering these management options will have no adverse impact on the safety. Benefits, costs and risks of waste retrieval for these purposes should therefore carefully be weighed against each other.
- ***Retrievability to assure safety***: In this case, retrievability is considered because of concerns that safety limits might be exceeded and a given, accepted safety standard cannot be guaranteed. This objective for retrieval is related to principle safety concerns. It must however be emphasized that disposal decisions will not take lightly with insufficient evidence for safety, trusting on the option of retrieval that allows to correct potential ‘mistakes’: there is a general agreement that safety should not rely on human intervention, but should be *passive*, and that the primary intention of geological disposal is a permanent emplacement of the waste ([33], §2.d). *Retrieval to assure safety* should therefore be regarded as *ultima ratio* to guarantee the safety of future generations.

Both objectives have different characteristics and urgencies: *Retrievability to assure safety* is a fundamental question, where cost is a less relevant aspect. *Retrievability to assure safety* answers societal and stakeholder concerns and mistrust to “experts”, the government and decision-making in general by allowing the correction of ‘mistakes’, or to respond to (unforeseen) calamities or events. As emphasized in the previous paragraph, retrieval of waste is a last resort, and should be considered highly unlikely due to the solid evidence for safety provided by several safety cases. From current point of view the technical feasibility is the main limiting factor, i.e. the retrievability of the waste mainly depends on what is technically achievable within reason. As will be elaborated below, the scope of *retrievability to assure safety* is a key question that is recommended to be discussed in the coming years.

On the other hand, *retrievability as management option* is a somewhat theoretical question, because due to the lack of applicable technology it is presently unclear whether related benefits could ever be realized on a relevant scale. No opposing opinions against altering or reuse of waste were found in [17], and such voices were also not registered at the *ENGAGED/RESTAC* workshops and interviews [12, 13]. In other words: because there is a general agreement that altering or reuse of the waste can be regarded as beneficial, societal discussion on this matter boils down to the question how the benefits, costs and risks of a particular management option are weighed up against each other by each stakeholder. However, this is a rather factual topic that is somewhat pointless to discuss without a specific technical option in mind, as long as it is taken care of that no 'irreversible' decisions are made that hinder a later implementation on *retrievability as management option*[6]. From the current point of view, the need to balance benefits, costs and risks of waste retrieval most likely limits *retrievability as management option* to the end of the operational phase, where retrievability can be achieved with reasonable efforts. The technical implication for a disposal design seems to be comparably small, assuming that *retrievability as management option* is always linked to *retrievability to assure safety* and the primary intention of geological disposal is the permanent emplacement of the waste. I.e. conditions that allow postponing discussions on *retrievability as management option* can be met relatively easy.

It is also expected that any position on *retrievability as management option* will be developed further and/or will alter in future. In particular, once a construction decision has been made, the timeframe to develop and realize an alternative management option will get increasingly shorter, and eventually a decision has to be made to drop this option and close the disposal facility. An important decision point here will be the moment all waste is disposed of, which is expected somewhere around 2170 [1].

While the main motive behind *retrievability as management option*, namely to keep options for future generations open, is an accepted objective of RWM, it must be noted that it goes beyond the primary responsibility of society (and the main function of a geological facility), namely to dispose radioactive waste in a safe manner. To address this responsibility, and because of the impossibility to define robust arguments at the current stage, it is suggested to postpone discussions on *retrievability as management option* to later stages when sufficient understanding and societal agreement has been gained on the principal role of *retrievability in assuring safety* and its technical implementation. This may be beneficial in order to get a more focussed societal discussion on the general subject in the coming years.

However, it must be emphasized that postponing discussions on *retrievability as management option* does not mean that this topic is of no relevance: the topic has to be revisited in a later stage, since it refers to suggestions often made by stakeholders and answers to the legal requirement to preferably reduce or reuse waste. The (financial) efforts that should be taken to actively explore alternative management options and their benefits, costs and risks - including the requirements they superimpose on current management practice - might be a specific point of discussion with stakeholders, and their preferences should be considered when defining post-OPERA research priorities.

[6] Most relevant in this phase are probably decisions related to conditioning and classification of the waste in the interim storage.

3.3. How long should the waste be retrievable?

Another point of discussion is how long the waste should be retrievable. Most discussions are limited to the operational stages before the closure of the facility, and often a prolonged pre-closure phase is suggested that allows to retrieve the waste over a long period, i.e. the disposal facility is kept longer open than technically necessary in order to allow retrieval. While a prolonged pre-closure phase has its advantages with respect to retrievability (easier surveillance/monitoring and retrieval of the waste), it obviously has also its disadvantages: increased operational costs and risks. This is often brought into discussion as main argument against retrievability (e.g. [18]).

However, when discussing *retrievability to assure safety*, retrievability during the post-closure phase should be considered as option, too. The additional risks attributed to an open, accessible disposal facility, often used to argue against retrievability, are of lesser or no relevance in the post-closure phase, and the operational costs are rather small[7] compared to the substantial costs to keep a facility open (see e.g. [34]). The costs of waste retrieval in the post-closure phase can assumed to be high, however, following the line of discussion in the previous section, retrieval must be presumed as an unlikely event rather than a secured expenditure.

Discussions concerning financial provisions for retrievability are complex[8] and seldom performed, and it must be noted that future generations can also decide against a retrieval of waste because of the high costs involved. Likewise they can decide for retrieval even if this was not foreseen in the disposal concept[9]. The point to be made here is that although the financial burden for future generations in case of a waste retrieval needs to be discussed, it is hardly an argument for *not* considering retrievability in the post-closure phase.

Thus, for future generations, a concept that allows retrievability in the post-closure phase is expected to be more cost-efficient with respect to operational costs than a concept based on a prolonged pre-closure phase, and main safety concerns with respect to retrievability in the pre-closure phase are not applicable in the post-closure phase. While these aspects are in favour of retrievability in the post-closure phase, this option also has its challenges: an important bottleneck is the technical feasibility of monitoring in the post-closure phase[10]. Without going too much into detail here - this topic will be discussed more closely in the next chapter - the most important question is how long a reliable monitoring infrastructure can be operated after closure. Currently, mature technical solutions that allow for monitoring in the post-closure phase are still under development (e.g. [35, 36, 37]), and no robust arguments can be provided that this stage.

In conclusion, while a discussion on the principal stages in which retrievability should be considered can be performed on basis of existing knowledge[11], a concrete definition of a time interval in which the waste should be disposed of in a retrievable manner is currently

[7] necessary for processing the monitoring data and maintenance of the surface-based monitoring hardware

[8] These costs include next to the costs for retrieval the costs for an interim storage solution, research and qualification of a new disposal, search and exploration of a new site, construction of a new disposal, and evt. costs for waste conditioning and repacking after retrieval. Note that these costs are of relevance for retrieval in *all* operational stages.

[9] at presumably even higher costs compared to a retrievable concept

[10] Note, however, that many technical challenges are not unique for monitoring in the post-closure phase, but apply in general to monitoring activities performed over longer time intervals behind safety-relevant barriers (i.e. also apply in the pre-closure phase).

[11] potentially leading to the identification of further research needs

hardly possible. Due to the complexity of the question, it is not advisable to jump to the definition of a requirement on the time intervals (as e.g. [38]). As will be elaborated in the next chapter, a key aspect to consider in such discussions are technical limitations with respect to the period in which it is technical feasible to keep surveillance on the waste facility.

3.4. Which waste fractions should be retrievable?

When discussing requirements on retrievability, it is advisable to define to which waste fractions it applies: this is of particular interest in the case of the Dutch policy to dispose of almost all radioactive waste in a single deep geological facility. Both the ability and necessity to consider retrievability might be judged differently for each of the waste fractions to be disposed of: features relevant for waste retrieval differ, e.g. with respect to radiotoxicity, number of containers, type and weight of container, matrix and waste composition (see Table 3-1 and Figure 3-1).

Vitrified HLW for example consists of a small number of highly active waste containers, while LILW consists of a large number of containers with much less radiotoxicity per container. A discussion on different requirements on retrievability for different waste fractions should also go beyond the applied classification schemes (LLW, ILW, HLW) and take into account the properties and composition of individual waste collies: long-living, mobile and/or highly radiotoxic components are not equally distributed over the waste, and it is likely that less stringent retrievability requirements can be chosen for a majority of LILW container with less hazardous wastes.

Table 3-1: General properties of waste fraction (based on [39, 1])

feature	vitrified HLW	DU	LILW
number of containers	625	7,700	152,460
radionuclide content	mixture	U_3O_8*	single nuclides or mixture
half-life	short to long	long	short to long
average radiotoxicity per container	$33 \cdot 10^6$ Sv	6,700 Sv	133 Sv
relevant heat dissipation	yes	no	no
weight per container	20,000 – 24,000 kg	20,000 kg	<1,900 kg
matrix	glass	rather pure U_3O_8 stabilized with concrete	varying types and composition of waste, partially stabilized with concrete
container	OPERA super container	cubic steel container	cylindrical steel container, partially with concrete shielding
estimated life expectancy of the container**	1,000 -10,000 years	100 – 1,000 years	100 - 1,000 years

* plus ingrowth of daughter nuclides **rough estimation, more precise numbers have to be established in OPERA

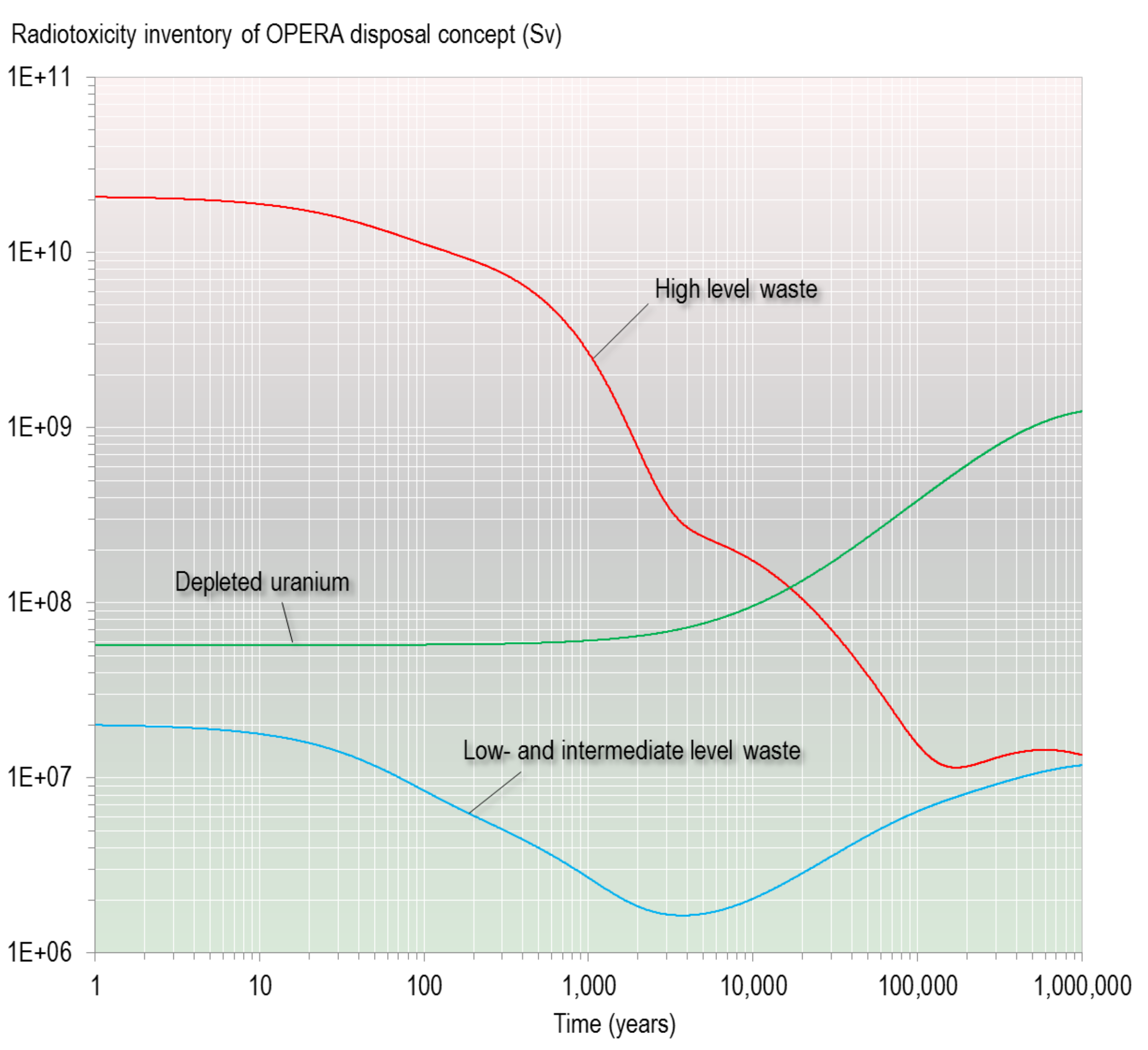

Figure 3-1: Estimated radiotoxicity evolution of several waste fractions considered in OPERA (based on [39] and $e_{50(ing)}$).

4. The role of monitoring in radioactive waste disposal

To implement an effective policy on retrievability, in addition to technical requirements, conditions and mechanisms that could lead to a decision for retrieval need to be defined. As already indicated in the previous section, monitoring might have an important role in providing evidence for (or against) such a decision. As such, monitoring is a diversified, complex socio-technical topic under development (see e.g. [40, 41] and Appendix B), and besides the technical challenges mentioned in the previous section, there is also a need to understand better what monitoring can contribute to safety, how it should be integrated in a safety case or how it can be implemented in a national policy[12].

Instead of providing a lengthy review of all aspects related to the topic '*monitoring*' here (see for this [40, 41, 35] and Appendix B), the remainder of this chapter focuses on two conceptual aspects of relevance for the current stage in the Netherlands:

- monitoring as a means of surveillance
- monitoring to provide evidence for safety

The objectives of *monitoring as means of surveillance* and *monitoring to provide evidence for safety* have some overlap, and many monitoring activities are expected to serve both objectives[13]. However, ideally, *monitoring to provide evidence for safety* takes place in advance of disposal, while *monitoring as means of surveillance* is of relevance once the waste is emplaced[14].

4.1. Monitoring as a means of surveillance

'*Surveillance*' is a more comprehensive concept than '*monitoring*' because it combines two aspects: the ability to monitor safety relevant features of the waste and the disposal facility, and the ability to react if the safety is impaired (e.g. by retrieval of the waste). The general concept of surveillance is in line with the Dutch *IBC-criteria* [23, 24]. As a working definition, the following is proposed:

> *'Surveillance' is the ability to monitor and manage the safe disposal of waste in a facility.*

Retrievability to assure safety is thus an important means of '*surveillance*', and is linked to what monitoring as a tool for effective surveillance can provide from a technical point of view. Retrievability should not be discussed as an objective of its own, but with respect to its role in RWM decision-making. Likewise, monitoring in this context is not an objective on its own, but should support decision-making on retrievability. However, for a better understanding of the ability to keep surveillance during the operational phase and after closure, it is necessary to have a closer look under what circumstances decisions regarding retrieval would be considered, and on what evidence/facts such a decision could be based.

One important outcome of discussions on the role of monitoring in waste disposal is that the available technical options for monitoring can present a limiting factor, and thus may represent a relevant constraint for each concept and host rock with respect to the kind of deviating evolutions or events that can be identified by monitoring. The discussion in the

12 Part of these questions will be addressed in the recently started EU-Horizon2020 project *Modern2020*.

13 For a more detailed discussion on this see Appendix B and the literature cited herein.

14 Monitoring and surveillance will of course also be performed during interim storage, transport and repacking of the waste, but is not point of discussion here.

EU-FP7 project *MoDeRn* [20, 21, 35, 36] shows that long-term monitoring under harsh environmental conditions as prevail in a geological disposal facility is currently technically challenging, and the ability to exclude technical failures as cause of deviating monitoring results might be essential for the usability of monitoring results for decision-making. More clarity is needed on the technical ability to detect events or evolutions that may impair the long-term safety by monitoring in the operational and post-closure phase, in order to get a realistic picture of what contribution monitoring actually can provide for decision-making.

From the above it should be evident that different host rocks may offer different abilities to keep effective surveillance. The ‘level’ of retrievability and surveillance that is provided by a host rock can be an important criterion in the discussion on what different stakeholders judge to be the most suitable host rock. However, while for the Dutch situation the technical implementation of monitoring infrastructure seems to be of relevance only in the far future, some principal technical understanding of monitoring technologies is of relevance when discussing the ability to keep surveillance on disposal facilities, linking the topic to discussions that have to be performed already in earlier stages.

4.2. Monitoring to provide evidence for safety

A second important role of monitoring is to provide evidence for safety on a relevant scale and in a representative environment. A safety case is built on safety assessments, which on their turn are based on a combination of several models that cover all safety-relevant elements of the disposal concept, i.e. waste container, engineered barrier system, host rock, geosphere, and biosphere. These models, or individual elements of these models, are often supported by independent experimental observations, performed on smaller scales in surface or underground laboratories. Concerns exist with respect to ‘overextrapolating’ existing knowledge and model-analyses to a real disposal situation, and results of scientific research may not always be perceived as conclusive and decisive, and may be subject to discussion. *In-situ* monitoring performed in a disposal facility can address these concerns by providing experimental evidence of safety and underlying (model) assumptions over a relevant time frame and on 1:1 scale.

The objective of *monitoring to provide evidence for safety* can also be a reason behind considerations to keep underground facilities longer open than strictly necessary for the disposal of waste (as discussed in the previous chapter), and is in case of a prolonged pre-closure phase related to increased risks and costs. Unlike for *monitoring as means of surveillance*, monitoring in the post-closure phase is no alternative. This is of particular relevance in the Netherlands, where the small waste inventory leads to comparable short periods of waste emplacement. Thus, the opportunity to provide relevant evidence by *in-situ* monitoring of the disposal facility during the operational phase is rather limited without an extended pre-closure phase.

However, unlike countries closer to implementation of geological disposal, the long-term interim storage policy of the Netherlands allows to perform experiments over relevant time periods *in advance* of construction or other important decisions. A relevant consideration could therefore be to use the time interval until 2080 to perform experiments and demonstration in so-called Underground Research Laboratories (URL) in the host rock of interest, e.g. by heater-tests, where surrogate waste containers with internal electrical heating are placed in the host rock to simulate the disposal of heat-producing high-level waste (HLW), by performing long-term radionuclide diffusion experiments, or by demonstrating retrievability of (surrogate) waste containers after relevant period of storage.

While the need of a national URL is a discussion that is expected to come up in the post-OPERA period, it must be noted that the costs of such a facility will be high (see e.g. [34]). However, unlike other countries with a larger nuclear programme, in which more than one URL is implemented or foreseen, from costs perspective it is reasonable to expect that in the Netherlands - if at all - only one national URL will be implemented. This means that prior to a decision for a national URL, a selection of the host rock to be considered has to be made. With such a decision currently not foreseen before 2080 [42], engagement in URLs in other countries is an important alternative for the Netherlands, in order to bridge the interval until the exploitation of a national URL, and to build up the necessary experience. Besides, it can allow for performing experiments and demonstration works in a relevant environment right away, either as national initiatives, or in cooperation with other European partners. The most relevant URL facilities of interest are currently the HADES URL in Mol, Belgium, situated in Boom Clay, and future URL activities in rock salt in Germany[15].

Besides the technical-logistic aspects discussed above, it also must be noted that at present it is not clearly enough elaborated how exactly *in-situ* monitoring can contribute evidence of safety to a safety case[16]. Many open strategic and methodological questions that arise in the EU-FP7 *MoDeRn* project [21] will be picked up in the follow-up EU-Horizon2020 project *Modern2020* [43]. However, it is expected that although *Modern2020* might allow to structure the link between monitoring and the safety case and provide a clearer view on remaining open issues, some aspects of specific interest for the Dutch situation have to be developed on the national level: while participation in *Modern2020* allows the Netherlands to anticipate general developments on this topic, the long-term interim storage policy and the small waste inventory might allow some interesting options not likely to be addressed by the project. This includes the role of post-closure monitoring, the use of long-term (*in-situ*) experiments in support of decision-making concerning the selection of a host-rock, siting, construction, and waste emplacement, and investigations whether the level of surveillance that can be realized in a host rock leads to useful selection criteria. It will also be necessary to provide on national level input from political and societal point of view what expectations on monitoring exist within the specific Dutch setting[17], in order to define carefully the efforts necessary to develop this subject further. Important aspects in this discussion will be a clearer position on the role of retrievability in general, the role and objective of pre-closure measures, the extent of retrievability in the post-closure phase, and the role of long-term demonstrations in URLs.

[15] Currently, research on rock salt is “on hold" in Germany

[16] Unlike in underground CO_2 storage, no detailed legal requirements regarding monitoring are developed (see Appendix C)

[17] I.e. as a country with an explicit choice for long-term interim storage.

5. Conclusions and recommendations

In this final chapter, besides general conclusions on the previous two chapters, recommendations are given on how to proceed after OPERA with regard to the topics of the present report. The information is presented in four sections: (1) General strategic observations, (2) Reversibility & Staged closure, (3) Retrievability & Monitoring, and (4) Lessons learnt from CO_2 storage.

5.1. *General strategic observations*

Providing concrete recommendations is complicated by the fact that different views exist on how much progress has to be achieved in the next years. The long-term interim storage policy of the Netherlands lacks currently a clear political roadmap for the next decade, which goes along with a low interest in RWM of most stakeholders and the public in general. This imposes no obvious societal or logistic urgency to develop the topic further and to resolve existing different views or concerns of stakeholders already noted in [17] and partially still valid today [12, 13]: with respect to political uncertainties and the long timescale of disposal implementation, it was questioned during the *ENGAGED/RESTAC* workshop whether postponing a decision to start the process towards siting in the Netherlands is positive or negative [12, 13]. On the one hand, it was noted that the risk of postponement is a loss of momentum, but on the other hand, it was acknowledged that the quality of decisions can benefit from having more time.

While a more detailed discussion on the general urgency for a detailed RWM roadmap is beyond the scope of this report, it can be assumed that though there is no reason to rush things, a general need exists to develop the topic continuously further, mainly for two reasons:

- the limited research activities in the Netherlands benefit strongly from going along with European research initiatives - keeping pace is therefore important to stay connected to these European initiatives,
- the national policy on long-term interim storage presents a number of options that need to be understood in time in order to benefit from them.

Furthermore, based on international recommendations, it is assumed that interactions with stakeholders and the general public, in order to achieve the necessary degree of confidence and support by societal groups, are determinants of a successful implementation strategy[18]. This is in line with the recommendation of CORA [67. p.10], where it is stated that "*an acceptable solution for the waste problem will eventually only be achieved if, in a public debate, the societal and the technical aspects are considered on an equivalent basis*". While the topics discussed here are clearly of socio-technical nature, a lack of interest and knowledge by the general public and relevant stakeholders is sensed as the most important bottleneck in further developing the topic in a participative manner. For methods to involve stakeholders and to communicate with them and the general public[19] we refer to [12, 9].

5.2. *Reversibility & Staged closure*

Not much can be added here on what is already discussed in [12] about the widely accepted principle of reversibility & staged closure: it answers to the societal concerns and

[18] acknowledging that different, but rarely expressed views on this subject exist
[19] which is beyond the scope of this report

offers the operator flexibility, and in some cases, may provide a tool to 'speed up' the disposal process. The latter objective is of less relevance in case of the long-term interim storage policy of the Netherlands, because it allows a stepwise, sequential implementation without need to rush.

The principle of reversibility provides helpful options to develop the implementation process in the coming years in a straight-forward way, resolving the issue of responsibility of the present generation while still leaving options open for future generations. However, it can also add an element of arbitrariness and, in case of the Dutch RWM, encourage a tendency to '*wait and see*'. The best way to avoid the latter impression is the definition of a clear roadmap, with well-defined milestones in 5- to 10-years intervals.

5.3. *Retrievability & Monitoring*

Clarify the meaning and scope of '*retrievability*'

As pointed out in the previous chapter, while *retrievability* is on the national agenda since 1984, in view of the ongoing development of the RWM its current implementation is insufficiently developed to allow to progress in the societal discussion. Rip et al. observed in ([17], see also Appendix E) that slightly different weighting of arguments for or against retrievability leads to different conclusions on the ability to dispose radioactive waste safely in the deep underground, with the proposed endpoints ranging from '*no geological disposal*'[20] over '*use time of interim storage, but eventually proceed to geological disposal*' to '*geological disposal*', either retrievable or (explicitly) non-retrievable. From fourteen argumentation lines developed, eleven are in some way related to retrievability, which underlines that retrievability is a key question in RWM. While not all argumentations scenarios from Rip et al. are of interest for the current discussion[21], it seems from the *ENGAGED/RESTAC* workshops and interviews [12, 13] that main observations are still valid and controversial views on geological disposal are often linked to expectations or opinions on retrievability. Clarifying the meaning and scope of '*retrievability*' in an early stage is therefore expected not only to be helpful with respect to the specific topic, but also more general in bringing different stakeholders views closer together: a broad agreement regarding the geological disposal of radioactive waste as endpoint, in line with [23, 24, 25] is expected to help focus discussions.

Distinguish between two main objectives for retrievability

For further discussion of the topic or retrievability, it is recommend to distinguish between '*retrievability as management option*' and '*retrievability to assure safety*' and clarify stakeholder views on both groups of objectives. Focus of discussion should be on '*retrievability to assure safety*', while discussion on '*retrievability as management option*' can be postponed to later stages. However, to reach an agreement on such an approach it may useful to investigate closer the different lines of reasoning behind '*retrievability as management option*' of current stakeholders, e.g. by an approach comparable to [17], with the outcome of *ENGAGED* and *RESTAC* [12, 13] providing a first input. This can be used to establish whether the different objectives result in different needs: most of the technical and risk-related open questions are expected to be similar for both objectives.

Perform integrated socio-technical analyses and provide robust input for the discussion on feasibility, risk and benefits of retrievability

While the advantages and disadvantages of retrievability were generally acknowledged, a consensus on the extent and role of retrievability is difficult to achieve, partially due to different preferences or weights given to the arguments, but also because insufficient

[20] in some case 'no solution at all'
[21] The analyses were published in 1994.

insight on main questions exists: what are the costs of retrieval; what are the risks related to retrieval; what are exactly the technical options for surveillance and retrieval? An interesting interdisciplinary approach to address part of the questions discussed in Chapter 3 is followed in the recently started German research project *ENTRIA* [22] [44, 45]: here, instead of a single disposal concept, three options of interest in the public discussion are investigated, covering all endpoints elaborated in [17] ("vertical projects"):

- Geological disposal without retrievability
- Geological disposal with retrievability (and monitoring)
- Long-term surface storage

At the same time, three "transversal projects" are performed, addressing all three disposal concepts:

- Technology Assessment and Governance
- Ethical and Moral Justification, Legal Prerequisites and Implications
- Interdisciplinary Risk Research

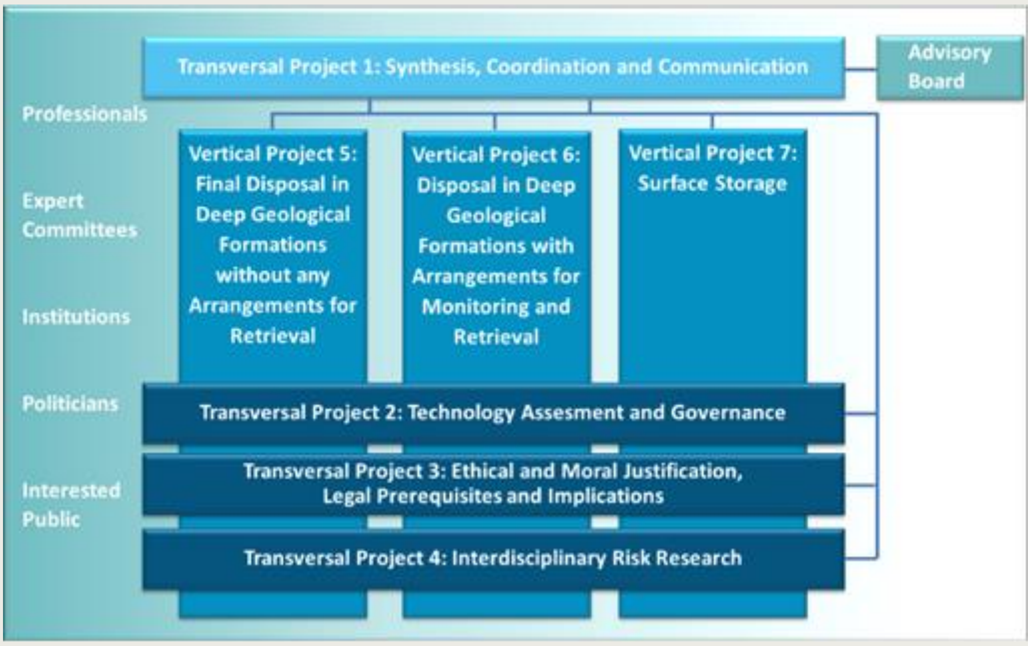

Figure 5-1: Overall structure of the *ENTRIA* project [44]

While the scope of the *ENTRIA* project is probably too large to be transferred 1:1 to the Dutch context, it is advised to consider in how far the transversal projects are of interest for future national research initiatives in order to provide robust arguments for the discussions summarized throughout this document. Input for the vertical projects could be based on existing studies, or on cooperation with *ENTRIA* projects, e.g. by translating the outcomes to the Dutch situation, and can profit from the activities in *Modern2020*.

[22] "*Disposal Options for Radioactive Residues: Interdisciplinary Analyses and Development of Evaluation Principles*" ("*Entsorgungsoptionen für radioaktive Reststoffe: Interdisziplinäre Analysen und Entwicklung von Bewertungsgrundlagen*")

Consider the option of retrievability in the post-closure phase as alternative for a prolonged pre-closure phase.
Limiting the discussion on retrievability to the pre-closure phase overlooks the advantages that retrievability in the post-closure phase might have. When technology allows to monitor and retrieve the waste in the post-closure phase, often decisive concerns [18] with respect to costs and risks related to increased operational periods can be addressed. With respect to retrievability in the post-closure phase, there is a need to better understand whether and in which way requirements from the *IBC-criteria* can be realized in an underground disposal facility *after* closure, and what it can contribute to safety and the ability to correct 'mistakes' or to respond to (unexpected) events in the future. Many of the questions related to monitoring as important element of surveillance and the *IBC-criteria* in general have been addressed in the EU-FP7 project *MoDeRn* [21] and will be followed up in the recently started EU-Horizon2020 project *Modern2020* [37]. NRG is involved in both projects, and activities include questions related to the embedding of monitoring activities in the safety case, development and assessment of monitoring strategies for the OPERA Safety Case, and strategic-technical studies related to the technical feasibility to monitor in the post-closure phase. Monitoring is high on the agenda of the IGD-TP [46, 47], and it is expected that after *Modern2020*, another follow-up project will be initiated, with more focus on post-closure monitoring. It is recommended that ANVS and COVRA will have developed a clear view on their research priorities on this subject in mid-2018, when it is expected that first ideas will be collected with respect to the definition of a follow-up of *Modern2020*.

Next to the *Modern2020* activities, the findings of the *ENTRIA* project [44] or other comparable national initiatives as discussed in the previous section are expected to provide useful input on the feasibility, benefits, risks and cost of post-closure surveillance.

Consider the role of URL activities
The Dutch policy on long-term interim storage allows to perform experiments over relevant time periods *in advance* of siting or construction decisions. Due to the long timeframe, the role of experimental confirmation of key processes in URLs can be much larger than in other programmes where monitoring activities during the operational period of a disposal facility have an important role. It is therefore recommended to develop a clear position on the role of long-term experimental and demonstration work in URLs as part of the safety case. Next to a position on a (future) national URL, cooperation with other European partners in the near future should be considered, e.g. Belgian experiments performed in the HADES URL (Mol) or future activities in rock salt in Germany. Such a position could be developed on basis of the outcome of the EU-FP7 *MoDeRn* project [21], and may benefit from the ongoing follow-up project *Modern2020* [48], but additional efforts are necessary to explore the specific options and possible benefits that are available due to the long-term storage policy of the Netherlands, which are of lesser relevance for the larger nuclear countries dominating the European research agenda.

Consider options for retrievability from point of view of a future host community
As already discussed in [12], the principles of reversibility & staged closure can be perceived differently when looking from the point of view of a potential future host community: for a successful voluntary process it may necessary to make definite agreements for a number of aspects instead of keeping all decisions reversible. E.g. definite decisions should be made on the amount and composition of the waste to be disposed of, the period of the operational phase, the responsibilities of different parties and the decision-making structures in general. An essential aspect where agreements have to be achieved in advance is the question how retrievability is implemented in the disposal plan. From the point of view of a future host community, retrievability may be the key

question when considering to volunteer for siting: a far-reaching implementation of retrievability could be a decisive answer to their concerns to commit themselves irrevocable to complex technological decisions they have insufficient knowledge about, and fear that they eventually will be 'set-up' with the waste in case problems occurs. Discussions on the role of retrievability in the coming years should anticipate on the needs of future host communities, in order to facilitate a future siting decision.

Clarify the requirements on retrievability before a selection procedure for a technically disposal concept is initiated.
Before technical feasibility studies on disposal design are performed that go beyond 'desk study level', and (costly) constructional, experimental and demonstration works are executed, the requirements on retrievability should be clarified. A selection procedure for a technically disposal concept should include the retrievability of a container design as an important criterion. It is thus recommended to develop the topic of retrievability *before* technical disposal concepts are selected and costly technical investigations are performed. Such a selection process should be organized in an iterative manner, by first providing more guidance on the selection of a (technical) disposal design. When a first set of requirements on retrievability is defined, technical studies should be performed with the explicit goal to refine requirements on retrievability further on basis of improved insight in feasibility, cost, risks and technical options of the candidate disposal concept.

Distinguish between different waste fractions
Given the current Dutch policy to dispose different waste fractions into a single disposal, it is recommended to distinguish between the waste fractions in further investigations and discussions on retrievability.

5.4. *Lessons learned from CO_2 storage*

Lessons learned from CO_2 storage projects are that monitoring is intimately connected to risk management in all phases of the project. Risk management has two complementary parts: Confirming regular behaviour according to the envisioned storage concept and project design, and correcting irregular behaviour deviating from the storage concept and project design. For each individual storage location, the authorities will specify requirements that have to be met before the responsibility of a site can be transferred back from the operator to the authorities, after closure and abandonment[23] of the site. Demonstrating compliance with these requirements may require post site-closure monitoring[24] [94]. It is recommended to develop practical examples of the requirements which are linked to the safety functions (and thus to the safety case) of a radioactive waste repository[25].

Assurance of safety both on operational and long-term post-operational timescales plays an important role in the lifetime of a repository for radioactive waste. Monitoring on the short term during the phases of site selection until the end of institutional oversight (and possible transfer of responsibility of the repository) will support the assurance of safe performance ([12], Figure 9-5) and support decision making in the staged closure of the repository. The decision making in the staged closure of a radioactive waste repository could learn from the insights gathered for CO_2 storage, in particular in the European FP7

[23] Abandonment in the context of a CO_2 storage site includes dismantling of the injection tubing and valves in the wells, sealing the wells and dismantling of the surface installations.
[24] Note that 'closure' in the sense of the EU Storage Directive is a specific moment of time coinciding with the definite cessation of CO_2 injection (see also Figure C.5-1).
[25] Part of this work will be performed in the EU project *Modern2020* [37]

project *CO2CARE* that developed a system of *Site Closure Milestones*, criteria and a system for interventions including monitoring and corrective measures if irregular behaviour should occur. Similarly, these milestones may serve as an example to integrate detailed requirements on monitoring for the staged closure of a future repository for radioactive waste, in particular for the steps of waste emplacement and partial closure after licensing of the repository and before license termination (See Appendix D). The EU project *MoDeRn* ([20], p.29-32) has developed comparable schemes for risk management and decision making. The added value from CO_2 storage is that the procedures provide more practical detail in connecting the scheme with the actual regulatory requirements from risk management, and the transfer of responsibility from the site operator to governmental authorities.

One of the objectives of retrievability is to intervene when the long-term safety of a radioactive waste disposal facility appears to be impaired as indicated by monitoring data from the repository itself or at the surface of the repository site. The principle of comparing expected (modelled) behaviour with actual (monitored) behaviour is central in the ‘traffic light system’ developed for CO_2 storage and could be useful for developing similar procedures for radioactive waste disposal, in particular for supporting the concept of retrievability as a measure to correct unexpected behaviour of the repository. Monitoring has definitely added value in gathering evidence for the safety case but a well-founded plausible PA model of the repository remains the key ingredient in the argumentation of the safety case.

Appendix A: Concepts of retrievability, reversibility and staged closure

A.1. Introduction

In the last decade, the concepts of reversibility, retrievability and staged closure have become *common sense* in RWM [see. e.g. 6, 15, 16, 49, 50, 51, 52, 53], because, as discussed in the next two sections, these concepts address stakeholders and public concern, and allow to deal with future uncertainties.

In Section A.2, key ideas on '*retrievability*', '*reversibility*' and '*staged closure*' are summarized. The implementation of these concepts in a national RWM policy is expected to have a relevant beneficial influence in gaining societal acceptance, although it might be difficult to gain progress if decisions remain permanently open and thus responsive to changes in values, priorities and attitudes [54]. In Section A.3 the Dutch policy on retrievability and reversibility is shortly reviewed, and in Section A.4 a condensed overview on the national policies of a number of countries is given.

A.2. General concepts

Retrievability of the waste is an important requirement of the Dutch waste policy [24]. Principles of reversibility and surveillance are already discussed in the VROM nota on radioactive waste from 1984 [23]. The principles of a stepwise approach are introduced in [12, Chapter 3] and Appendix D. While reversibility, retrievability and staged closure seem conclusive and convincing high-level concepts, their implementation require understanding of the complex scientific-technical limitations and their consequences for the overall process. One of the technical aspects related to this topic coming into focus in the last decade is the role of monitoring in confidence building and decision-making. Basic principles and ideas on monitoring are summarized in Appendix B.

A.2.1. Views on retrievability and reversibility

In 1998 – 1999, a EU Concerted Action was performed to provide a working definition of the term '*retrievability*', to come to a better understanding what the term means and how it can be integrated in a disposal concept [55]. As working definition, retrievability was seen as

> *"the ability provided by the repository system, to retrieve waste packages for whatever reason retrieval might be wanted."* [55, p.21]

In [56, p.31], it is noted that retrievability

> *"implies making provisions in order to allow retrieval should it be required [...]. Retrievability is a technical feature that facilitates the reversal of the decision to emplace waste in a repository"*

while in [57, p.11] it is stated that

> *"Geological disposal, as currently envisaged 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."*

Retrievability can thus also envisaged as a principal option that can be considered anywhere in time, even after end of the '*Institutional oversight*'. Finally, waste can also considered to be retrieved from facilities not foreseen for retrieval [58]. In conclusion, '*retrievability*' is more a conceptual terms, that gain its values from further clarifications of its purpose and extent.

When looking at key objectives for aiming at retrievability, the following list of potential reasons can be found [55, p.19*f*]:

Safety and operational arguments:

- Disposal should be reversible in case something goes wrong with the emplacement of a package.
- Retrieval of a waste package might be necessary in case a waste package malfunctions during or after emplacement.
- Retrieval of waste packages might be necessary if the repository appears to be malfunctioning at a later stage.

Licensing arguments:

- Retrievability should be included in order to facilitate a staged decision and licensing process.

Societal arguments:

- Radioactive waste may contain potentially useful materials, which might become valuable in the future. It could be the wish of a future society to utilise such a resource.
- Disposal decisions should not be irrevocable, in order to provide future generations the option to take their own decisions.
- From a sustainable society viewpoint, high priority is given to reuse of materials and to minimisation of the quantity of waste that needs to be disposed of. Views and/or technology for reuse of materials may be different in future.
- The precautionary approach and the recognition of uncertainty speak in favour of retrievability.

Waste management arguments:

- Future new technology or scientific knowledge could – based on re-evaluation of the cost/benefit balance – motivate modifications in earlier disposal, or retrieval of disposed waste packages.
- A repository that includes design features to keep the waste packages retrievable could offer better possibilities for control and surveillance of the waste after disposal.

Public acceptance arguments:

- A disposal concept might be better appreciated, when key decisions are reversible. Including retrievability might enhance the acceptance of geological disposal.

In [16, p.11], in a more condensed manner, three main reasons for including retrievability in national programmes are observed:

- an attitude of humility or open-mindedness towards the future
- provision of additional assurance of safety
- to heed the desires of the public not to be locked into an ‘irreversible’ situation

While ‘*retrievability*’ always contains a moment of ‘*reversibility*’ (but not the other way around), it makes sense to differentiate between ‘*reversibility*’ and ‘*retrievability*’ [59]:

> *“**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 [...] can be seen as an assessment of whether the process can continue as foreseen or whether one of the reversibility options should be exercised [...]. 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.*
>
> ***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."*

Reversibility is thus related to decision-making, and seen as an important tool for flexibility, because it provides the possibility to review a decision before going to a next step, to correct the decision if appropriate, and if necessary to change course. Reversibility corresponds to a stepwise decision-making approach, and it sends a strong symbolic message that (societal) stakeholders are not expected to accept and adjust to a *fait accompli* without opportunity to input their views or priorities [60]:

> *"The 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. In addition to the institutional actors, the public is involved at each step and also in reviewing the consequences of previous decisions. This is designed to provide reassurance that decisions may be reversed if experience shows them to have adverse or unwanted effects."*

However, contrasting views exists on the meaning of reversibility: in [61], it is noted that

> "'Reversibility' *is just another concept that has generated heated debates. Some interpret reversibility as a mean 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."*

The perspective of retrievability – as an instance of reversibility – implies that systems must be in place to understand, monitor and assess the performance of the disposal system. Retrievability provides reassurance that in case of error or of other necessity, humanity has some means of control over the emplaced waste, and is expected to reconcile the requirements of technical safety and societal control [62]. Some concerns exists with respect to a false impression of safety that the concept of reversibility and retrievability might create: in [63, p.34] it is stated that reversibility and retrievability

> *"should not be used as programme features to divert the attention of civil society from the range of safety issues, nor to falsely reassure potential local hosts that their own hosting decisions are of little lasting consequence."*

As part of the NEA '*Reversibility & Retrievability*'-project, a leaflet [59] was presented wherein a "retrievability scale" was proposed, that should illustrate qualitatively several aspects of retrievability, under which the degree and type of effort that is needed to retrieve the waste in different stages of the disposals life cycle (Figure A.2-1). The main message of Figure A.2-1 is that in course of time, the ease of retrieval is decreasing, and the costs of retrieval are increasing. The other message is the belief that finally, safety should not rely on active control, e.g. the ability to monitor.

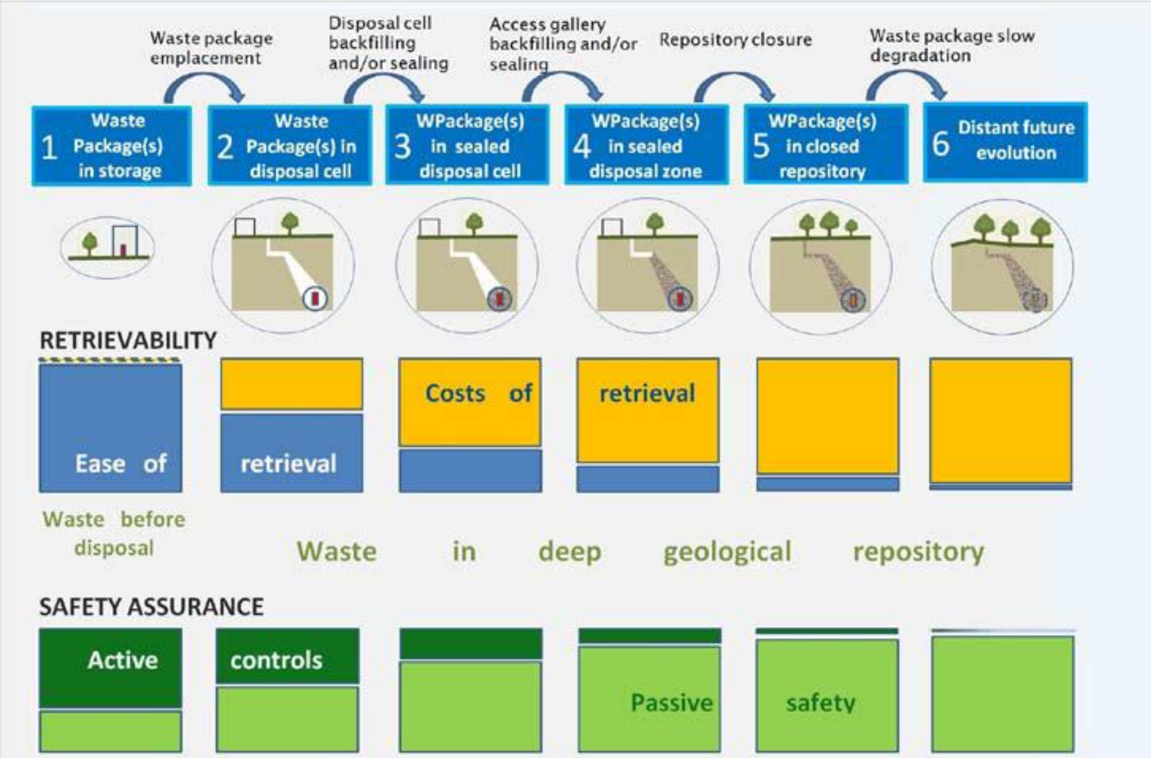

Figure A.2-1: A retrievability scale for stakeholder dialogue [59]

A.2.2. Reversibility in decision-making and staged closure

Implementing a geological disposal facility considers large time spans that can be divided into different stages. The implementation process is based on step-wise, incremental decisions to ensure that the implementation process and technologies maintain adjustable so that, at any stage of the programme reversal or modification of one or a series of previous decisions may possible if needed, within the limits of feasibility. Hence, each major authorisation in repository implementation can be seen as an assessment of whether the process can continue as foreseen or whether one of the alternative options should be exercised (Figure A.2-2).

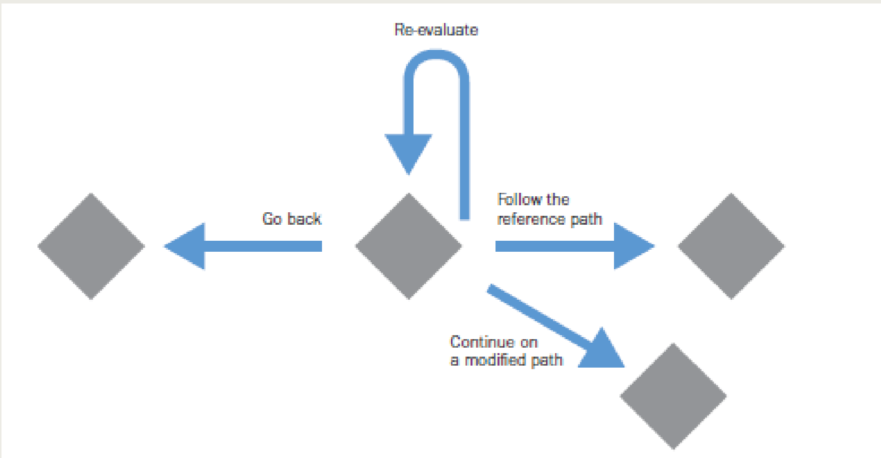

Figure A.2-2: Potential outcomes of options assessment [15]

The main elements of each decision form the *decision basis* and the *decision-making bodies* ([64 ; p.12]), as is depicted in Figure A.2-3; both ingredients differ from case to case and the stage in the repository implementation process. The decision basis should be an enacted legal document concerning the economic, social, technical or political condition(s), which will be evaluated by a *decision-making body*.

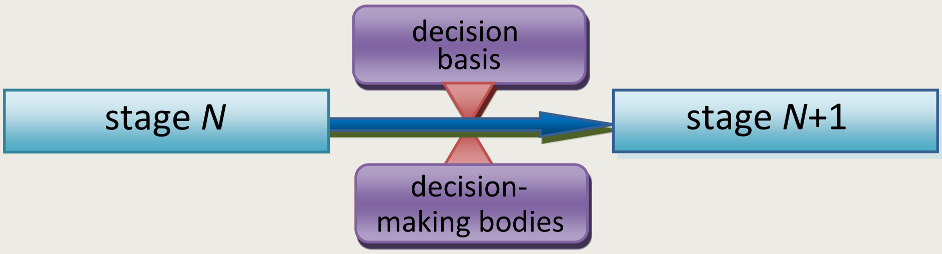

Figure A.2-3: The main elements of a decision point

The information for the *decision basis* comes mainly from an updated safety case that conglomerates results from monitoring or other observations, practical experiences - national and international, and ongoing research. But also new or changing values, preferences or priorities can form input for the decision basis. Based on the stage in the implementation process, the participants of the *decision-making body* are established, e.g. authorities, implementing body, regulator, independent experts and/or advisory bodies.

It is obvious that for the stepwise decision-making process – as described above – it must be clear and agreed in an early stage what the decision basis should contain, which stakeholders should participate in the decision-making, and what respective role regarding their contribution and responsibility in the assessment. It is as well recommended to define in advance the approach for decision-making, e.g. a consensus approach was used for the site selection of the national interim storage facilities at COVRA [65].

A.3. Dutch policy on retrievability and reversibility

Retrievability of the waste is an important requirement of the Dutch waste policy: the so-called '*IBC-criteria*'[26] as discussed in 1984 in principle point toward a retrievable disposal ([23], p.5):

> *"Pit dumping [...] is in principle irreversible and therefore does not fully meet the requirements of isolation, control and surveillance."*

The document refers to [66, p.4], where it is elaborated that the *IBC-criteria* includes access to technical and administrative *measures* that guarantee continuous protection. These *measures* can include requirements of retrievability and financial reservation that allow for anticipating unexpected failures. It is also requires the implementation of measures that allow to judge the condition of the waste in periodic intervals.[27]

In 1993 the Dutch Government issued a policy directive stating that underground disposal of highly toxic waste (including radioactive waste) was permissible provided that it remains retrievable over the long-term [24]. This forms together with the 1984 governmental policy plan [23], where principles of reversibility and surveillance are already discussed, the basis for the national strategy principles to manage radioactive waste.

Three objectives for retrievability are given in [67, p.3]:

- to allow - partial – deactivation of the waste if future transmutation techniques permit
- to keep waste available for recycling
- to be able to remove waste in case of undesirable events

In 2001, it was noted that the policy "*to guarantee retrievability resolves many objections amongst the public. Most of these objections are summarised in the traditional saying: 'seeing is believing'*" [67; p.3].

With respect to time interval in which the waste need to be stored in a retrievable manner, the Dutch government stated in 1984 ([23], p.1) that

> *"main components of radioactive waste policy are the isolation, control and surveillance of waste material either until it is no longer radioactive or until it has been disposed of in such a way that the likelihood of an unacceptable amount of radioactivity finding its way into the biosphere is negligible."*

[26] "Isoleren, Beheersen en Controleren" (isolation, control and surveillance). Note that in some translations these are also indicated as "ICM-criteria" (isolation, control and monitor).

[27] Original quote: "*Naast de isolatie wordt ook het beheersen en toepassingen van bodembedreigende stoffen voorgeschreven. Hiervoor staan technische en administratieve maatregelen ter beschikking om garanties te bieden voor een voortdurende bescherming van de bodem. Maatregelen in dit kader variëren van de eis tot terugneembaarheid en een financiële zekerheidsstelling tot voorzieningen waarmee de gevolgen van een onverhoopt falen van de isolatie kan worden beperkt. Voorts dienen er controlerende maatregelen te worden getroffen om de situatie van toepassing regelmatig te kunnen beoordelen.*"

While it stays open how the "negligible likelihood" can be rationalised, in 1993 ([24], p.5), it is emphasised that

> *"The necessity of measures for surveillance and control remains during the whole period of disposal."*

In 2001 [67], it was argued that retrievability does not require current generations to take irrevocable decisions, but allows continuous monitoring and step-wise incremental decisions, with final decision-making process based on the knowledge and experience acquired during a long period of fact finding and monitoring. The waste retrieval from a disposal concept in rock salt and Boom Clay was judged to be technical feasible over a period of about 100 years, with only minor additional risks involved and yearly costs of less than 1% of the construction costs to keep the facility open [67; p.5*ff*]. [67; p.7] implies that retrievability, at least for the purpose of transmutation, is only foreseen during the operational phase:

> *"Advantages of retrievable disposal are [...] that the possibility of alternative solutions remains open as long as the facility is accessible."*

Mainly due to the very small quantities of radioactive waste, the operational phase in the Netherlands is short, at maximum just a few decades (e.g. [1, p.7]). This relative short time span could have influence on the disposal and decision-making process compared to repository programmes of large nuclear countries.

Of interest for retrievability is that the current Dutch strategy foresees to dispose almost all radioactive waste fractions in a single deep geological facility [1]. Furthermore, a multinational solution is not excluded, and it is not unlikely that an international cooperation will make it necessary to reconsider the Dutch policy on retrievability and other aspects as the intended disposal of low- and intermediate-level radioactive waste in the deep underground or the intended interim storage period of 100 years.

A.4. Country concepts on retrievability and staged closure

In this section, a brief compilation of national policy and international concepts on retrievability and staged closure will be given from countries of interest for OPERA, viz.

- Belgium: because of their cooperation within OPERA
- France: The OPERA research plan [2] mentioned that a basis for a staged closure of a repository could be the process as elucidated in France Dossier 2005
- Germany: It is decided to retrieve (a part of) the waste as disposed of in the *Asse II* mine. A process that very likely will dominate and evolve the (technical) measures of retrievability the coming years
- United States: In the US WIPP facility a demonstration of the retrieval process takes place. Just as in Asse, a practice that could have influence on retrievability (in salt formations).
- Switzerland: As stated in the OPERA outline report [1], in the Swiss concept retrieving the waste is based on the monitoring phase of the pilot facility [68].

A.4.1. Belgium

At present there are no generic legal requirements for reversibility or retrievability of waste disposed of in any type of repository in Belgium. No decision has yet been taken on the long-term management of long-lived medium- and high-level waste. The relevant national waste plan was developed by the Belgian *National Agency for Radioactive Waste and enriched Fissile Material* (ONDRAF/NIRAS) and made available for public consultation in 2010 [69]. The final waste plan is submitted to the government, awaiting a decision in principle on the long-term management of these substances.

In the development of a repository, the application of the optimisation principle is the driving force towards safety in the long term. Since it consists of a stepwise process, the development of a disposal system is expected to evolve with time and with the experience gathered on site or on other sites. It is an ongoing process to be applied from the very beginning in the development of the disposal system [15].

The stepwise decision and licensing process associated with the development and realisation of a repository should be flexible, especially in view of the long time frames involved. This means that over time, decisions may be overruled and the process reversed for one or more steps if enough evidence is provided. The capability and the willingness to re-assess earlier decisions and the ability to reverse the course of action or decision to a previous stage are called ‘flexibility’.

According to the *Federal Agency for Nuclear Control* (FANC) the stepwise process of the development and the implementation of the repository should be flexible up to the regulatory closure/release of the facility. FANC considers reversibility to be required and limited to the operational phase. Provisions to facilitate retrieval are recommended and the time period during which these are supposed to hold will be commensurate with the hazard of the waste. Retrieval (as well as recovery) is in principle a new process, requiring a new safety assessment and regulatory authorisation and needs to meet the justification principle (Figure A.4-1).

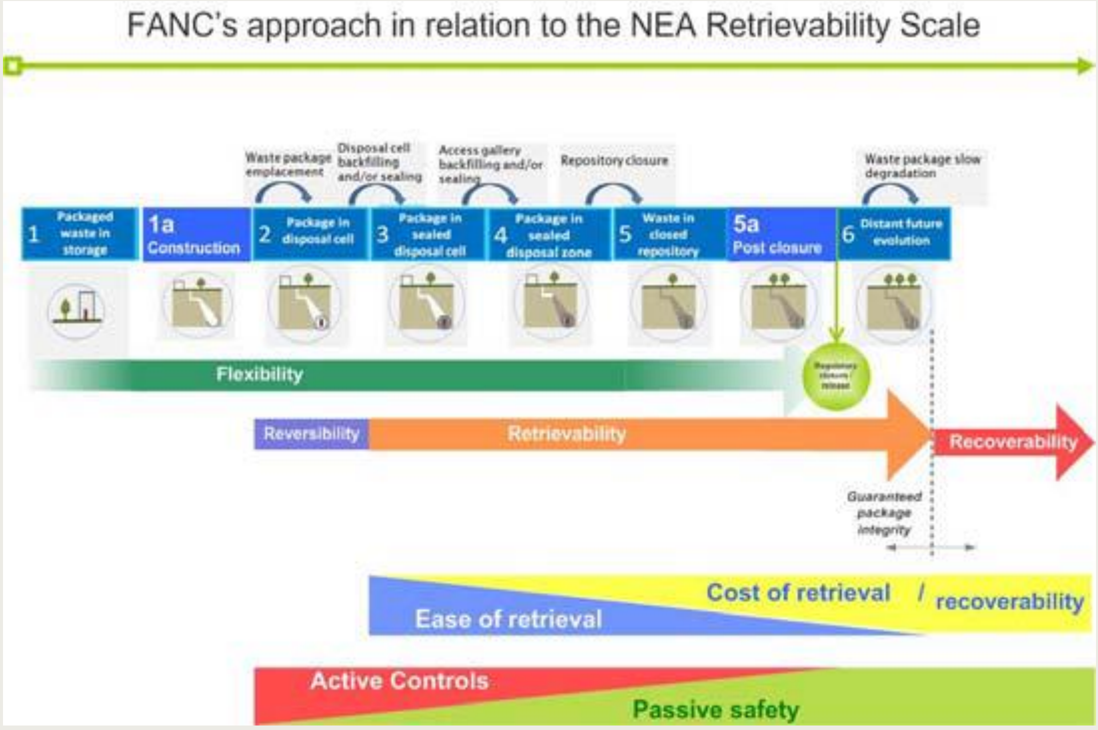

Figure A.4-1: Stages in the life of a deep geological repository, FANC's approach in relation to the NEA retrievability scale [15]

A.4.2. France

In France reversibility is required by law, and reflects social and political demand. The law, however, does not provide conditions for implementing reversibility. Instead, it calls upon scientists to issue specific proposals before a new law is promulgated as a preliminary to obtaining authorisation to build a waste repository [15].

A dialogue between various players, scientists and stakeholders is required to prepare these proposals. To answer the different expectations, the French *National Radioactive Waste Management Agency* (ANDRA) is studying two kinds of proposals. The first type of proposal is technological in nature. It involves all technical measures that can be taken in the design of the repository to favour retrievability of waste packages and reversibility in general.

The EU-FP6 project *ESDRED* showed that ANDRA's design of a repository [70] for retrievable disposal of radioactive waste has shown that in general the design agrees quite well with the present state of the art concerning the retrievability concept.

The second type of proposal involves governance of the waste repository. It concerns providing the resources for continuous, reversible step-by-step control of the disposal process, in an extension of the French laws of 1991 and 2006 pertaining to long-term waste management. Proposals involving governance are based on combining an organisational framework and taking appropriate technical decisions. They involve the period between emplacement of the first waste package and closure of the access shafts, which can be considered the reversibility period, without prejudice to maintaining subsequent waste retrievability.

Once the decision has been taken, construction of underground structures of the repository will be proceeding gradually as waste arrives over a period as long as a century. Given the time span, construction and operation of the repository must be undertaken in successive phases.

The start of each phase of work could then be subject to scientific and technical review and a decision-making process integrating operating experience feedback and technological developments. This implies the notion of a modular, adaptable project that does not limit later generations to technical decisions made today.

A.4.3. Germany

While the wide consensus on maintenance-free and non-retrievable disposal in deep geologic formations as the only long-term management option for radioactive waste has not been seriously questioned for more than four decades in Germany, retrievability is currently a relevant topic of discussion in the parliamentary commission for the disposal of high-level radioactive waste[28] (see e.g. [18]). Thus, in the past retrievability has not been a regulatory requirement in Germany, neither has it been the subject of repository concepts considered [15].

Nevertheless, retrievability has been investigated in several studies, especially for the HLW disposal concept in a salt dome preferred so far. The first comprehensive investigation of this issue was completed in 1995 and demonstrated the general technical feasibility of retrieving disposal casks of POLLUX-type which were to be disposed of in repository drifts in a salt formation. However, the repository concepts considered have not yet been adjusted to fulfil retrievability requirements.

In connection with the increased public and political awareness, safety concerns regarding radioactive waste that was disposed of in the former salt-mine *Asse II* between 1965 and 1975, retrievability has become a requirement. As a consequence, Safety Requirements published in 2010 [30] by the *Federal Ministry for the Environment, Nature Conservation and Nuclear Safety* (BMU) contains provisions regarding retrievability, which stated amongst others that during the operating phase up until sealing of the shafts or ramps, retrieval of the waste must be possible. It also states that waste container must be designed in a way that these can be handled during a period of 500 years after closure in case of recovery operations ([30], p.18).

The Safety Requirements provide the regulatory basis for the safety analysis in order to derive a site suitability forecast and guidelines for further site investigations. Consequently, the Safety Requirements as well as the retrievability procedure will be an integral part of any repository license. In compliance with the Law on Nuclear Energy, only demonstrated technologies can be licensed. Thus, the fulfilment of the retrievability requirements described above has to be demonstrated prior to applying for a license for the repository.

Furthermore, currently the governing authorities decided to investigate the recovery[29] of the waste in the former mine *Asse II*, a storage facility for low- and intermediate-level waste.

[28] Kommission '*Lagerung hochradioaktiver Abfallstoffe*'
[29] '*Recovery*' means the retrieval of waste from a facility that was not planned to be retrievable.

A.4.4. United States

As specified under United States statute, retrievability must be maintained for both economic and safety purposes. *Nuclear Regulatory Commission* (NRC) regulations further stipulate the time during which retrieval capability must be maintained for safety.

Under the *Nuclear Waste Policy Act* of 1982, retrieval is maintained for safety, environmental or economic reasons. The *Department of Energy* (DOE) specifies the period of retrieval, subject to NRC approval. The NRC further requires retrievability throughout waste emplacement and performance confirmation programmes [15].

Maintaining retrievability after closure is not currently required in NRC regulations, though it is understood that the capability to retrieve could remain for some time beyond closure.

The *Waste Isolation Pilot Plant* (WIPP) is a deep geologic repository sited in salt beds in Southeast New Mexico for the permanent disposal of military transuranic (TRU) waste. Conceptual designs, governing rules and statutes for the WIPP have historically included requirements for waste retrieval [15].

Waste retrieval/removal formal requirements have changed as the WIPP project evolved from conceptual design to actual waste emplacement. Early disposal concepts included retrieval to foster public acceptance of a potential site. Later state and federal requirements were more demanding and required that waste retrieval plans and demonstrations were necessary prior to allowing test-phase waste to be emplaced in WIPP.

Retrieval demonstrations have occurred for mock and actual transuranic waste containers. The project has demonstrated to the regulator that waste removal after closure is feasible for a reasonable period of time after closure.

A.4.5. Switzerland

In 1999, the *Federal Department of the Environment, Transport, Energy and Communications* (DETEC) formed the "*Expert Group for Disposal Concepts for Radioactive Waste*" (EKRA), which consisted of experts from a broad variety of fields. Its mandate was to formulate basic principles for a variety of waste management options, and its final report (DETEC), published in 2000, and formed the basis for Switzerland's concept. The concept called "*monitored long-term geological storage*" combines the isolation of radioactive waste in deep geological layers with technical and natural barriers, and the option of retrievability at society's request (being one feature of a reversible process) [15]. Figure A.4-2 shows the concept established by the working group EKRA, which is based on basic technical findings and ethical requirements.

The principle of "*monitored long-term geological storage*" was implemented in the Swiss *Nuclear Energy Act* of 21 March 2003. In 2008, a stepwise and transparent process with the participation of all involved stakeholders was initiated to find the relevant sites. The site selection process for radioactive waste repositories is defined in a "sectoral plan" within the legislative framework of the existing spatial planning and environmental legislation. The *Swiss Federal Office of Energy* (SFOE) is in charge of the site selection procedure.

In the Swiss programme, the principle of reversibility has to be taken into consideration in planning a disposal facility, i.e. later generations should have the possibility to make use of new knowledge regarding disposal. Hence, the implementation of the disposal concept including the site selection procedure is a step-by-step process that allows reconsideration of decisions by future generations. Such reversibility is built into the site selection process. The conceptual part of the "*Sectoral Plan for Deep Geological Repositories*" defines a three-stage site selection process, site selection criteria and the respective roles and responsibilities of the parties involved. It was prepared by the federal authorities, following a broad consultation process. It was approved by the federal government on 2 April 2008.

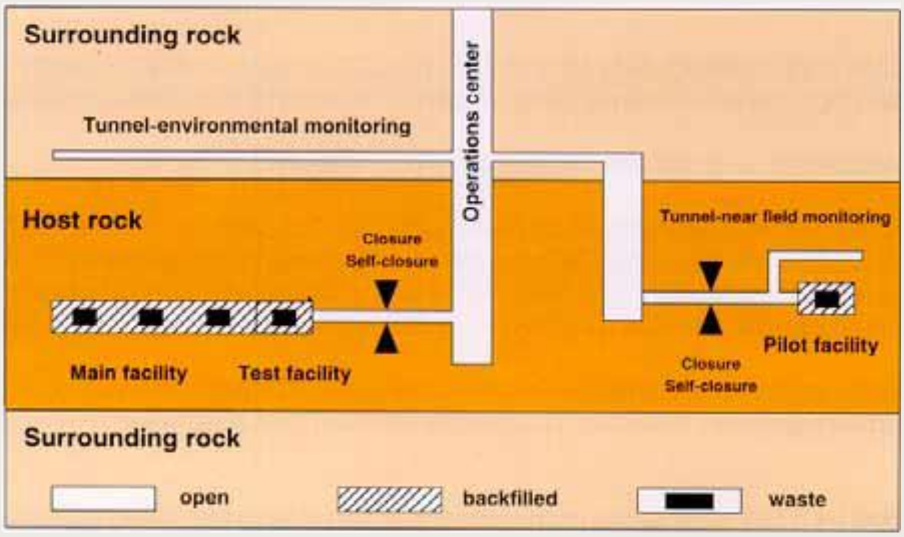

Figure A.4-2 Schematic concept and system elements of the monitored long-term geological disposal facility [15]

According to the Sectoral Plan, the population and interested organisations receive comprehensive information about the progress of the site selection procedure. At the end of each stage, a public hearing is conducted and the stage is completed by the approval of the federal council. At the end of the site selection process, the parliament has to approve the general license of the site.

The decision-making process for repository selection (as depicted in Figure A.4-3) includes a Cantonal veto.

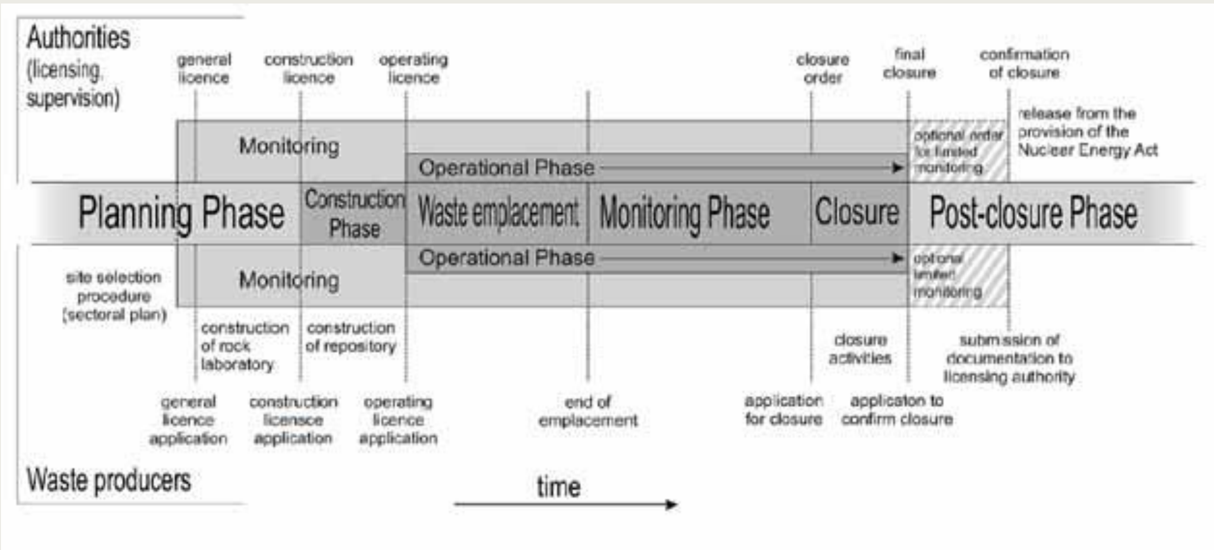

Figure A.4-3 Schematic representation of the decision-making process for a deep geological repository in Switzerland [15]

Appendix B: The role of monitoring in geological disposal

B.1. Introduction

In the last decade, monitoring has increasingly become a topic of awareness with respect to its potential beneficial role for the implementation of a geological disposal for radioactive waste.

'*Monitoring*' in a general technical context can be defined as [71]:

> *“to observe a situation for any changes which may occur over time, using a monitor or measuring device of some sort.”*

In 2001, the IAEA proposed a definition on monitoring in relation to radioactive waste disposal [72 ; p.1]:

> *“continuous or periodic observations and measurements of engineering, environmental or radiological parameters, to help evaluate the behaviour of components of the repository system, or the impacts of the repository and its operation on the environment.”*

Monitoring is seen as a useful tool that allows to demonstrate that the evolution of a repository is in line with what is expected from prior analyses and experimental work and it addresses concerns that safety claims are too much based on models. Besides a role in decision-making, or as part of a licence application ('*performance confirmation*' [73]), monitoring is expected to contribute to *confidence building*, a general objective of the Safety Case [74, 75]. However, from the latter it should be evident that monitoring of radioactive waste disposal is not solely a technical question, but planning, implementing and communicating monitoring activities should also address societal expectations and needs, hence monitoring strategies should consider complex interactions covering the involvement of, and the communication with stakeholders and the general public. And last but not least, monitoring can be a strong tool in supporting retrievability and the concept of staged closure, by either providing relevant information on the actual condition of the EBS, the host rock or other features of the disposal facility, or by allowing to define performance measures that has to be met before proceeding into the next stage.

In this section, the current state-of-the-art on the role on monitoring of geological disposal will be briefly reviewed. In the Section B.2, a short overview on international thoughts on the potential beneficial role of monitoring is given, and some main (groups of) monitoring objectives are identified and discussed. Section B.3 analyses technical aspects of monitoring, including the specific requirements on monitoring application in waste disposal monitoring, methodological aspects related to the definition of system performance and the ability to trace and address potential failures of monitoring systems, and the availability of suitable monitoring technologies. Section B.4 briefly discusses the embedding of monitoring activities in the Safety Case, and the final section B.5 summarizes aspects related to the implementation of monitoring plans.

B.2. Expected beneficial role of monitoring and monitoring objectives

First guidance on monitoring in waste disposal goes back as far as 1991 [76]. In 2001, the IAEA summarized the potential role and benefits of monitoring as [72; p.1]:

> *"monitoring will contribute essential information for the satisfactory completion of the various phases of the repository programme and, in doing so, will strengthen confidence in long term safety, which is the key objective of radioactive waste disposal. [...] Monitoring of various aspects of the disposal system is likely to be an important support to decision-making at all stages of the repository development programme."*

Monitoring can involve activities at all development stages of a repository, from exploration of a candidate site up to the post-closure phase.

In [72], five key purposes of disposal monitoring have been identified:

- to provide information for making management decisions in a stepwise programme of repository construction, operation and closure;
- to strengthen understanding of some aspects of system behaviour used in developing the safety case for the repository and to allow further testing of models predicting those aspects;
- to provide information to give society at large the confidence to take decisions on the major stages of the repository development programme and to strengthen confidence, for as long as society requires, that the repository is having no undesirable impacts on human health and the environment;
- to accumulate an environmental database on the repository site and its surroundings that may be of use to future decision makers;
- to address the requirement to maintain nuclear safeguards, should the repository contain fissile material such as spent fuel or plutonium-rich waste.

In addition to these five key purposes, it was recognized that monitoring can also be performed for operational reasons:

- to determine any radiological impacts of the operational disposal facility on personnel and the (local) population, in order to comply with statutory and regulatory requirements;
- to determine non-radiological impacts on the environment surrounding the repository, to comply with environmental regulatory requirements (e.g. impacts of excavation and surface construction on local water supply rates and water quality);
- to ensure compliance with non-nuclear industrial safety requirements for an underground facility.

The European Thematic Network (ETN) project on Monitoring [77] tried to further elaborate the question of the role of monitoring in the phased development of a geological disposal facility. According to [77], monitoring

> *"provides the basis to determine model parameters and to compare measured data with model predictions. This also includes monitoring of baseline conditions at potential repository sites to detect any potential negative impact on the environment caused by on-site activities during site characterisation, construction and operation of the underground repository, as well as for reasons of liability. [...] Monitoring is [...] a means to assist in checking or confirming*

that key assumptions regarding the safety-related features of the disposal system are valid. [...] It is important to ensure that future generations will maintain confidence in the adequacy of the disposal system by confirming that the repository does not, at any time, pose a threat to the operating personnel and the public, and that the disposal system and the surrounding natural environment evolve as expected. Monitoring and the comparison of monitoring results with the predicted evolution of the system is a possible means of fulfilling this requirement.”

Comparable to [72], five reasons for monitoring were identified in that report:

- Monitoring as part of the scientific and technical investigation programme, including environmental monitoring
- Monitoring of the acceptable operation of facilities
- Confirmation of key assumptions of the disposal concept
- Maintaining the confidence of future generations
- Nuclear material safeguards

Also the Japanese Radioactive Waste Management Funding and Research Centre (RWMC) identified five general objectives for monitoring [78] and delivered a more elaborated description of the objectives as summarized in Table B.2-1.

Table B.2-1: Monitoring objectives and descriptions by RWMC [78]

Objective	Description
1. Confirming safety performance and the adequacy of the repository's engineered measures	♦ Confirming whether or not disposal system components function as planned ♦ Confirming design/construction assumptions ♦ Verifying safety assessment models ♦ Judging the need for facility improvements or repairs related to repository operation/construction
2. Confirming compliance with statutory requirements	♦ Confirming compliance with regulations after a closure of repository ♦ Confirming compliance with safety regulations for workers and local residents during construction and operation ♦ Confirming compliance with environmental impact assessment regulations
3. Providing information for making decisions on policy and operations	♦ Providing information for decision-making ♦ Dealing with the retrievability of emplaced waste packages
4. Understanding the baseline characteristics of the geological environment at Preliminary Investigation Areas, etc.	♦ Clarifying the baseline characteristics of the geological environment
5. Providing information for public decision-making	♦ Enhancing the confidence that the public (particularly local residents) have in geological disposal ♦ Compiling databases for future generations

From the above it is obvious, that although the general expectations on the role of monitoring in waste disposal are expressed in very similar words, the definition of clear, general monitoring objectives is not as straightforward as might be expected. It was noted that some overlap exists, i.e. monitoring can serve more than one objective. RWMC [78] observed several 'correlations' between their five objectives (Table B.2-1):

> *"Objective 1 (Confirming safety performance and the adequacy of the repository's engineered measures) and Objective 2 (Confirming compliance with statutory requirements) have comparatively clear-cut measurement targets and assessment methods. The information related to these two objectives will be actively utilized as the project proceeds.*
>
> *In contrast, Objective 3 (Providing information for making decisions on policy and operations) involves information to help project operators and policy-makers make decisions based on such factors as the progress of future geological disposal programs, the different circumstances surrounding geological disposal, the advancement of geological disposal technologies, and public acceptance.*
>
> *Objective 4 (Understanding the baseline characteristics of the geological environment at Preliminary Investigation Areas, etc.) can be thought of as covering the collection of fundamental data to meet diverse requirements, including the objectives and assessments described in Objectives 1, 2, and 3. For geological disposal that involves the postulation of extremely long periods of time, monitoring in this category is also meant to ensure the traceability of geological environmental information, both spatially between the surface and deep underground, and temporally over extended periods.*
>
> *Objective 5 (Providing information for public decision-making) seems to overlap extensively with the other objectives. What distinguishes it, however, is that it enables the determination of monitoring parameters that should be measured on the basis of full discussion and public decision-making when the time comes to select a final disposal site."*

Besides, it was recognized that monitoring might be influenced by the different national contexts that need to be address.

However, because it is thought that is it important to clearly define *why* monitoring should be performed prior to elaborate *what* should be monitored, from 2009 to 2013, the *MoDeRn* Project (Monitoring Developments for Safe Repository Operation and Staged Closure, [79, 80]) was carried out by international experts from 12 countries as part of the 7th European Framework Programme. The project aimed to

> *"further develop the understanding of the role of monitoring in the staged implementation of geological disposal and to provide examples, guidance and recommendations that may be useful to Waste Management Organizations (WMOs) for their development of a monitoring programme."*

Based on a discussion of previous approaches [76, 77, 78], a levelled hierarchy of two '*overarching goals*' and three '*main objectives*' was proposed, from which the first main objective was subdivided into two underlying objectives [81]:

Overarching goals:

- to support confidence building
- to support decision-making

Main objectives:

- to support the basis for repository performance evaluations
    1. supporting the basis for the long-term safety case
    2. supporting pre-closure management of the repository

- to support operational safety, to support environmental protection
- to support nuclear safeguards

From the general monitoring objectives that have been identified in the different projects, a number of main themes can be identified, which however cannot easily be arranged in a way that these do not overlap and will fit to all conceptual ideas regarding the implementation and the role of retrievability that may exist at different stakeholders. Reasons for this lack of clear structure are:

- monitoring activities can serve several purposes, and monitoring objectives (seem to) overlap
- monitoring can not only be applied to evaluate the current state of the disposal system, but might also be of use in supporting arguments for the future safety of the disposal concept, by essentially showing that perceived evolution of the system is in line with model expectations. Although first case studies have been performed to further analyse such an option [93], it is currently unclear what kind of statement could be based on such analyses and how these can be integrated in a safety case (see also [81]).

B.3. Analysis of monitoring objectives

Despite the recognized difficulties to group objectives, in this chapter, the most important monitoring objectives are shortly discussed, and therefore arranged in five groups with respect to the way these are related to decision-making:

- Regulatory requirements, including operational safety, nuclear safeguards, and performance confirmation or other monitoring activities that are part of a licence;
- Understanding of the baseline characteristics of the geological environment;
- Confirmation of safety performance and the adequacy of the repository's engineered measures;
- Providing information for decision-making;
- Confidence building.

B.3.1. Monitoring due to regulatory requirements

The first objective is mainly related to regulatory or legal requirements, that prescribe what should be monitored, either as part of a licence agreement, or as part of a licence application, e.g. in order to proceed to the next stage. The related monitoring activities are more or less compulsory activities that must be performed, and it is likely that the regulator also determines in which way monitoring has to be performed and reported. In this case it can be expected that monitoring requirements are based on existing methods, often accompanied by method descriptions. Generally, four main topics can be distinguished:

- performance confirmation
- operational safety
- safeguards
- Environmental Impact Assessment (EIA)

Monitoring for '*performance confirmation*' is related to *in-situ* monitoring of safety relevant components of the EBS and host rock as part of a license application. Here, the regulator may prescribe certain monitoring activities, more or less detailed, and define reference values that have to be complied to (see e.g. [73]). Currently, in the Netherlands no solid basis exists with respect to regulations (or expectations) on the performance of repository components. Any regulation would need more understanding on repository behaviour and the basis of safety - knowledge that has to be developed in e.g. programmes like OPERA – and should describe how support of safety performance and the adequacy of the repository's engineered measures can be collected, how information for decision-making can be provided, and how monitoring can be used for confidence building. '*Performance confirmation*' may also cover properties of the host rock that have to be met on a selected location, e.g. bandwidth of grain size distribution in case of disposal in an argillaceous host rock.

Monitoring for *operational safety* includes measures for radiation protection of employees, as applied in e.g. nuclear facilities or hospitals, monitoring of the state of constructional elements or features (e.g. displacement), and environmental conditions in the facility (e.g. air composition) as performed in mining operations. The safety and well-being of employees of a disposal facility is an important topic that has to be addressed in a further update of the safety case[30], but is of lesser relevance in the current discussion on radioactive waste disposal in the Netherlands, based on the assumption that sufficient experience on operational safety and occupational hygiene related aspects and accompanying regulations, guidelines and monitoring technologies is available, and that the necessary measures can be implemented in the existing disposal concept.

Monitoring of *safeguards* is related to the presence of fissile material in a disposal facility and regulated by IAEA [82]. Potential monitoring measures might involve access control during the operational phase and monitoring of the site in the post-closure phase. Due to the reprocessing of spent fuel of the Borssele Nuclear Power Plant (NPP), the amount of fissile material in The Netherlands is rather small. Besides, it is not expected that measures for safeguard monitoring interfere or interact with other monitoring activities. With respect to the main focus of the *RESTAC* project and the OPERA Safety Case in general, this topic is judged to be of minor importance in the current stage.

Monitoring as part of *EIA* regulations are defined as a separate monitoring objective in [81], and although some overlap may exists with other objectives, here monitoring activities are meant that are limited to surface monitoring that are sometimes part of EIA procedures, e.g. measuring of the presence of radionuclides in biosphere compartments as groundwater, soil, crops and plants, and air, or monitoring related to potential environmental effects of constructional works on site and in the subsurface (e.g. surface storage of excavated material, ground water level, land sinks). The latter aspect goes too much in detail for the current stage and will not be discussed further, but it is obvious that effects of constructional work on the surface environment should be minimized in agreement with existing regulations, and that this may involve monitoring activities of the operator and/or regulator. Any impact on the environment should be clearly communicated with the host community, and agreements on potential (counter)actions or compensating actions should be made. With respect to the first aspect, there are somewhat controversial views on the relevance of monitoring of radionuclides in surface compartments: while it does not increase confidence of experts - the absence of radionuclides in the biosphere in the first hundred years hardly tells them something on the correctness of assumptions and models behind relevant safety functions that should provide safety on long term - in general it seems to answer to concerns or demands of stakeholders and the general public. The latter will be discussed in more detail in Section B.3.5 on confidence building below.

B.3.2. The role of monitoring in understanding baseline characteristics

The second objective is related to an inventory of the characteristics of a site, which may also fit under '*monitoring*', when complemented by additional measurements of the same characteristics in course of time, e.g. to detect changes as result of disposal activities. '*Monitoring for understanding baseline characteristics*' is of importance for disposal in granite [83, 84, 81], although the general motivation - provide evidence of the suitability of a host rock and allow to identify disturbances as result of construction works - may fit to other disposal concepts, too. However, because monitoring involves the repeated measurement in time, '*understanding baseline characteristics*' goes further than only the qualification of site and host rock characteristics, that may be relevant in all cases.

[30] The OPERA reference concept already includes principal features in support of operational safety, e.g. the presence of two access shafts or the use of heavy shielding for HLW containers [1].

B.3.3. The role of monitoring in confirmation of the safety performance

The third objective is related to provide evidence for the safety of the disposal concept. This is a rather complex and much discussed monitoring objective, because of its technical complexity. '*Monitoring in confirmation of the safety performance*' could ideally be part of the first objective, i.e. 'performance monitoring' as prescribed by a regulator, but from the discussions performed in [81], it is obvious that there are ambitions to provide evidence in support of the safe future evolution of the disposal by combining monitoring with process models while it is currently not clear from what this could gain. In general, each disposal concept has a number of so-called '*safety functions*', that are testable claims on features or characteristics of barriers that contributes to the overall safety. Point here is that monitoring of safety performance often need to go beyond the simple examination of the current state of a barrier function (e.g. the absence of radionuclides outside a waste container). Monitoring of processes and features related to a safety function, is expected to provide meaningful support for relevant model assumptions used to argue long-term safety (e.g. compaction rate of a salt plug). This kind of monitoring is technically often very challenging, because it involves the monitoring of slow evolving processes over long time intervals, while the requirement that monitoring should not impair barrier functions [81, 85] obliges often the placement of sensors in locations that are inaccessible afterwards (see discussion on technical requirements and limitation in the next section). To overcome technical and practical limitations, some national contexts foresee the use of so-called 'pilot facilities' [68] or 'sacrificial cells' [86] which allows to monitor dedicated boreholes apart from the main disposal section, and with comparable properties as the 'real' facility, with less technical limitations.

Besides a number of complex technical aspects that accompany this objective, two underlying thoughts are of particular interest for the discussion in this report:

- the discussion challenges the question, what role *in-situ* monitoring should have in staged closure: while there are 'hard' criteria that must be met because it forms the basis of a licence (see '*performance confirmation*'), monitoring might provide much supportive information from which it is currently unclear how it can contribute to decision-making.
- while such data is expected to potentially contribute to confidence, the outcome of such monitoring activities are difficult to understand and interpret in their meaning for (lay) stakeholders, mainly because their meaning also relies on (understanding of) the underlying process models. It can be noted that the primary interest of stakeholders is often related to surface monitoring activities, i.e. reassurance that no harmful radionuclides are present in their surrounding environment, and therefore this type of monitoring need to be promoted by technical experts or expert stakeholders.

B.3.4. The role of monitoring for decision-making

The fourth objective is related to the use of monitoring results in decision-making during the staged closure of a disposal. As highlighted before, monitoring can have a role in providing evidence that can be used for decision-making. In the most obvious case, in a staged disposal process proceeding from one stage in disposal operation to the next is linked to a formal decision, for which monitoring may provide relevant input. Such a decision moment can be based on a well-defined procedure, e.g. by *a priori* definition of targets – as discussed in the previous section, or can kept more open, e.g. by bringing decisions (and all underlying analyses and evidences) into parliament. However, in all cases, quality and reliability of the monitoring data is essential (see for a more detailed discussion Section B.5).

B.3.5. The role of monitoring in confidence building

Although the general theme of '*monitoring in confidence building*' can be linked to all groups involved in waste disposal [87], when talking about '*confidence building*' in the context of monitoring, it mostly directs to the confidence of stakeholders and the general public. Limiting in this report the discussion of the role of monitoring in confidence building to the latter two groups, four different themes are distinguished:

- monitoring of parameters that address public and stakeholders concerns or requests
- involvement of stakeholders in implementing monitoring activities
- communication of monitoring results to stakeholders and the general public
- involvement of stakeholders in decision-making in case of deviating results

Certain parameters might be monitored in order to address concerns of stakeholders or the general public on potential radioactive contamination as result of the disposal operations. This monitoring is often related to radionuclides in the surface environment (e.g. groundwater, soil, crops and plants, air). An example here are the activities of the *Carlsbad Environmental Monitoring & Research Centre* (CEMRC), an environmental monitoring organization that performs independent health and environmental monitoring in the vicinity of the United States' underground *Waste Isolation Pilot Plant* (WIPP) [88]. The items to be monitored were based on a survey of the population around the site and include monitoring of air, drinking water, surface water and sediment, or radiation scans of the bodies of interested or concerned inhabitants. Another example is the environmental monitoring around the *Asse II* mine in Germany, involving the monitoring of air, aerosols, soil, grass, and water [89]. Other monitoring activities might be related to potential (physical) impacts of the disposal works on the environment, e.g. land sinks, water table, air quality, and noise, or to monitor health related indicators in the context of epidemiological studies.

With respect to the involvement of stakeholders in the implementation of monitoring activities, several options may exist, which however requires a certain expertise. Such expertise is most likely found by the regulator or government, see also Section B.3.3. For a broader group of 'lay' stakeholders, an approach as discussed in the previous paragraph may be more suitable.

An important aspect in relation to confidence building is the communication of monitoring outcomes. Technically speaking, several options exist, e.g. direct on-line presentations of actual monitoring values [90], or periodic summary reports, distributed on-line and/or as printed medium [89, 90]. Concerns here are related to general challenges in communicating complex scientific information about a controversial topic [9]:

- how to avoid misunderstanding or misinterpretation of outcomes;
- how to address existing frames on radioactive waste disposal, e.g. taking care that the outcomes are trusted;
- how to explain the meaning of a numerical monitoring outcome rather than 'expose' a lay public to 'naked' numbers.

The latter aspect is getting important when monitoring outcome deviates from expectations: due to the complexity and size of the overall monitoring infrastructure, the occurrence of deviating results can probably not be excluded, although it can be assumed that most deviating results are related to failures of monitoring components (see also Section B.5). However, even if a deviating result cannot unquestionably be attributed to a technical failure, it does not necessarily mean that the safety of a disposal is affected in any way, on short or long term. The mechanism for communicating monitoring results should thus be considered carefully: most likely, as part of predefined, internal QA procedures, primary monitoring results will be internally checked for quality and consistency prior to publication. As part of monitoring procedures, trigger values might be defined in order to distinguish between expected numerical uncertainties of a method and deviations that may point to processes or features that are significantly not in line with expectation. In case trigger values are exceeded, a mechanism should be defined that informs responsible experts, local partnerships and authorities. The question how to handle and communicating deviating results is further addressed in the next paragraph.

The last aspect of stakeholder involvement is closely related to the previous: when deviating results are registered that cannot be clearly attributed to a technical failure, than the results and the related risks or potential consequences or mitigating actions should be evaluated in a broader setting, i.e. including other people than the operators' organization that is involved in daily operational work in the disposal facility or is responsible for the monitoring. Currently, no clear agreement exists on the strategy that describes how such a process may look like, whom to involve, and how to communicate such results. However, it seems to be reasonable, that after some '*fact-finding*' that assesses potential explanations and their consequences, on a certain point stakeholders and representatives of the local partnership will be involved, either in order to communicate outcomes and their implication or, when risks cannot be excluded, to discuss whether actions have to be taken and what these actions might be.

B.4. Embedding of monitoring activities in the Safety Case

Although the relevance of monitoring for the safety case is generally recognized, currently insufficient understanding exists on how to embed monitoring activities in the Safety Case methodology. The benefits of such an embedding would be to get a clearer picture on the role of monitoring in the overall process, and how it can interact in a beneficial way with other elements of a safety case. It should be clear that this is highly dependent on a specific national context, and it should also be acknowledged that the *safety case* is more an ‘umbrella’ than a very specific, fixed methodology. However, several relevant links between monitoring activities and elements of a safety case can be identified:

- selection of parameters relevant to the long-term safety are based on the considered disposal concept and the related safety functions
- the break-down of safety functions to an actual list of parameters can be performed by using the safety cases’ so-called ‘*FEP-list*’ (list of features, events, and processes)
- uncertainty analysis as part of the safety cases’ performance assessment calculations should allow to rank potential parameters to be monitored with respect to their relevance for the long-term safety
- performance assessment calculations as part of the safety case should give insight to the range of values of a monitored parameter and the evolution in time that can be assumed as ‘safe evolution’, in line with the safety statement made and their underlying argumentations and assumptions
- monitored parameters might be linked to safety and performance indicators (SPIN) that are used to evaluate and communicate performance assessment results
- staged decisions as part of the safety case’ safety strategy may be supported by monitoring outcomes
- monitoring can contribute to the overall objective of confidence building

Most of the above mentioned links are in one or the other way part of the safety cases’ safety strategy, that defines on a high level how a safe disposal will be realized. Part of these aspects will be addressed in the recently started EU-Horizon2020 project *Modern2020* [37].

B.5. Implementation of monitoring plans

As discussed above, monitoring is expected to have a beneficial role for the implementation of the disposal process. While many monitoring activities can be based on well defined, often certified methods (e.g. for air, soil, and groundwater sampling and analysis), and can be based on long-time experiences from other fields of work (e.g. operational safety monitoring in mining or radiation monitoring in nuclear industry, military or health care), *in-situ* monitoring of safety relevant components of the EBS or the host rock has its specific technical challenges and limitations that need to be understood prior to the definition of a monitoring plan. These challenges and limitations are discussed in the remainder of this section.

B.5.1. Technical requirements

A larger number of technical requirements for *in-situ* monitoring in waste disposal facilities are identified in [85]. These can be arranged in three general, interrelated groups of requirements:

- requirements related to the preservation of safety functions
- requirements related to the specific environmental conditions present
- requirements related to the required performance of the monitoring equipment

The first group of requirements is mainly related to the fact that many sensors are expected to be located behind barriers, i.e. borehole seals or plugs, dams that isolate parts of a disposal facility, and - in case of post-closure monitoring - the shaft seal that isolates the overall repository from the environment. There is some general consensus, that monitoring should not impair the safety function of these barriers [85, 81]. In practice, this means that cables or wires through barriers should be avoided, and thus part of the monitoring system need to transfer their sensor readings wirelessly. Alternatively, the application of so-called 'non-intrusive' monitoring technologies can be considered, where properties are measured remotely from a safe distance that does not interfere with barrier functions (e.g. borehole tomography [91,92]).

The second group of requirements is related to the specific requirements due to the environmental conditions present in the repository: monitoring components must perform under harsh conditions (e.g. high lithostatic and hydrostatic pressure, radiation fields), that are often beyond specifications given for standard industrial components. Additionally, monitoring equipment has to operate over long periods (several decades), often without the option to access the sensor (or other parts of the monitoring equipment) in order to test, recalibrate or replace these. Requirements on reliability are thus greater than in other fields of application.

The third group of requirements is related to the performance of the monitoring components: the monitoring equipment and its set-up should be sensitive and accurate in order to allow distinguishing between 'safe' and 'unsafe' evolutions of the disposal. A proper description of the expected performance of a monitoring method is therefore necessary, including statements on sensitivity, accuracy, and precision under the given physico-chemical conditions, potential cross-sensitivities of a method and possible correction methods, potential artefacts by sensor placement in a particular environment/location, and sensor reliability in the projected time interval. With respect to the latter, a relevant part of methods descriptions are related to technical options to identify erroneous readings as results of failures of (parts) of the monitoring components (discussed in more depth in the next section). Furthermore, due to the long intervals of monitoring, a clear statement on the influence of time on accuracy and precision of a method must be given, that addresses potential (long-term) drifts by disintegration or 'aging' of sensors. The latter is marked as one of the technological key challenges, because many monitored processes evolve very slowly in time, and biased results due to drift effects must be avoided/excluded. Finally, as discussed in the previous paragraph, the method descriptions must account for the fact that in many cases, sensors or other parts of the monitoring system are not accessible after placement and cannot be tested, recalibrated or replaced.

In conclusion, *in-situ* monitoring can be marked as challenging, and the different requirements should be evaluated and quantified and documented in monitoring methods and procedure description that allows to get a clear picture on what can be expected from a certain monitoring set-up. This will be discussed in the next section.

B.5.2. Methodological aspects

Discussions in the MoDeRn project pointed towards the relevance of a proper methodical description of the technology used for monitoring. When using monitoring results for decision-making, the reliability of monitoring result is essential. In the next paragraphs, a number of methodological aspects with respect to *in-situ* monitoring are discussed.

Method performance definitions

The performance of a monitoring set-up must be defined in advance. Based on consideration used in analytical chemistry, in [93] it is distinguished between technical, methodological and procedural level. The technical level involves the combination of certain monitoring components, e.g. sensors, wires and connectors, signal amplifiers, and analogue-digital converters. On a methodological level, e.g. the placement and testing of sensor, potential influences of the sensor on its environment, potential correction methods for cross-sensitivities, or drift correction methods must be defined. On the highest, procedural level, overall aspect of the whole monitoring set-up are defined, e.g. aspect of redundancy of components, QA of data acquisition, processing and reporting or responsibilities and qualification of responsible employees.

Although currently limited experience is available on equipment behaviour under the harsh environmental conditions given in a disposal situation on the long term, there are some features that may be beneficial for the practical implementation of methods and procedures in a waste disposal:

- for most parameters, a slow evolution can be assumed, making it easy to identify single deviating sensor readings
- objects of interest can often be monitored simultaneously by several sensors (of same or different kind), allowing for redundancy
- objects of interest are often present in manifold (e.g. borehole seals), allowing repeated measurement of the same parameter at different locations
- parameters of interest have often physical relations to each other, allowing to check overall consistency of the results
- diurnal and seasonal variations of environmental conditions are rather small

Failure detection

When performing monitoring, results may deviate from the expected evolution. That may be due to a certain degree of numerical uncertainty as part of the used technology as described as part of a methods' performance description, or due the uncertainty of the process models that are used. As discussed in the previous section, when deviations are larger than can be explained by the known uncertainties and will point towards a possible impairment of the safety, it is important to be able to exclude a failure of (parts of) the monitoring system as cause, before corrective action are considered.

One challenge in repository monitoring is that often sensors (or other components) are located behind barriers and cannot be assessed to directly check whether a sensor is malfunctioning. Methods and systems for failure detection are therefore essential part of a monitoring system that can be projected and planned in advance, making part of monitoring methods and/or procedures. In [93], a first set-up for a structural approach for failure detection is discussed. First, a number of potential failures modes are distinguished here:

Technical failures:

- total or partial sensor failures
- failures of signal transmission
- failures of signal conversion

Methodological failures:

- failure of sensor installation and placement
- distortion of sample environment
- unidentified cross-sensitivity
- failure of correction methods (drift, cross-sensitivities)

Procedural failures:

- loss of redundancy (i.e. simultaneous failure of several sensors)
- failure of any error detection and error correction procedures

In a second step, a list of potential failure detection methods has been identified:

- Redundancy
- Diversity (or distinct functional redundancy)
- Electrical stimulation
- Reliability indicators
- Local Sensor Validation (LSV)
- Correlation

In a third step, it was evaluated which of the identified failures modes can be detected by which failure detection methods (e.g. a failure of a single sensor can easily be detected by redundancy). It was also recognized, that the number of basic measuring principles are limited, and if failure detection methods are linked to these basic measuring principles, the outcome of such an analysis can be applied to a large number of sensor technologies. It was concluded that a systematic approach to sensor failure is possible, and failure detection methods should be considered when designing a monitoring system, because in case monitoring results are used for decision-making, the ability to detect failures is essential. It should also be clear that inexplicable deviating results, independent of their potential significance for the long-term safety, will not contribute to confidence building.

Availability of technology

Once potential parameters to be monitored *in-situ* are identified, and technical and performance requirements for candidate technologies are defined, it must be assessed which technologies are available in order to monitor a certain parameter. Careful screening of potential technologies must be performed in order to evaluate the performance of a monitoring technology in a specific setting. In case no monitoring technology of suitable maturity exists for the specific purpose, additional R&D is necessary, and several options may need to be considered ranging from improving existing technology (e.g. improving accuracy or long-term performance) to the development of new candidate technologies. From [35], three key challenges with respect to the current state-of-art of monitoring technology can be derived:

- availability of suitable wireless and non-intrusive monitoring technologies
- long-term energy supply for the monitoring infrastructures behind barriers
- durability of the used monitoring components on the long term

Appendix C: Lessons learned from monitoring during the final stages of the CO_2 storage lifetime

This appendix contributes to RESTAC Subtask B *The role of monitoring in the staged closure*. *Insights from geological storage of CO_2* may be helpful in developing views on the role of monitoring in retrievability and staged closure of a repository for radioactive waste disposal and procedures for the staged closure of radioactive waste disposal sites. OPERA Report IR7.3.1.3 [94], which deals with the 'monitorability' of safety indicators briefly described some lessons learned from CO_2 storage (Chapter 4).

C.1 CO_2 storage as a greenhouse gas mitigation measure

Geological storage of CO_2 captured from fossil fuel combustion at power plants and industrial sources is a mitigation measure for the emission of greenhouse gases to the atmosphere. After the capture of CO_2 at the source, the gas is compressed and transported by ship or pipeline to the storage site (Figure C.1-1). The whole process from capture to storage of CO_2 is referred to with the acronym CCS, which stands for CO_2 Capture and Storage. The storage media are permeable reservoir rocks in depleted gas and oil fields or in deep saline aquifers ([95], p.2). The CO_2 with a purity of 95% or more is injected in porous layers at a depth of 800 m or more where the CO_2 reaches an optimum density.

Different mechanisms keep the injected CO_2 in place in the intended storage reservoir: the main short-term containment mechanism is by structural trapping where overlying permeable layers act as a barrier for the buoyant gas. Over longer time scales other trapping mechanisms occur, which increase the storage security in time: residual trapping after migration through porous media, dissolution trapping and mineral trapping ([95], p.2).

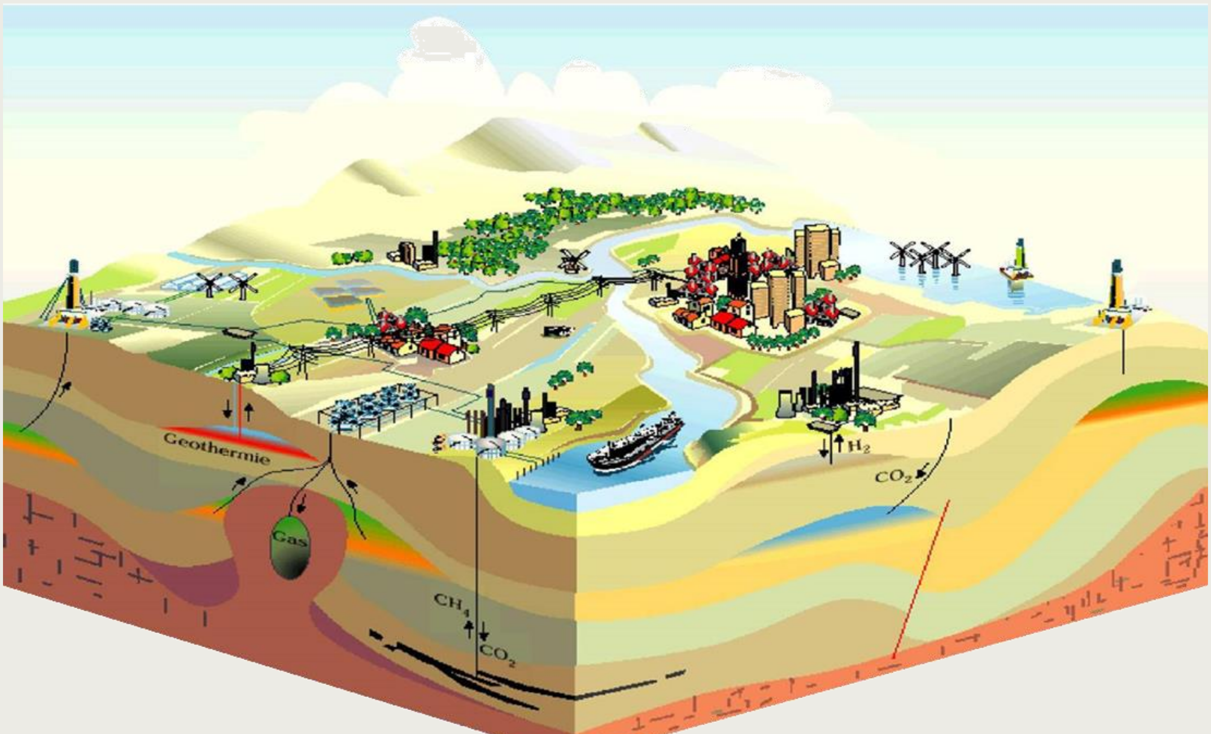

Figure C.1-1: Artist impression of infrastructure at the earth's surface and subsurface for capture, transport and storage of CO_2 (courtesy TNO, 2015)

Currently, 22 large-scale installations are operating or under construction with a total annual capture capacity of 40 Mt CO_2 ([96], p.29) worldwide. 1.7 Mt is stored annually in two Norwegian offshore storage projects, named “Sleipner” and “Snøhvit” (see Section C.7). A large part of the large-scale storage projects is connected with the so-called “Enhanced Oil Recovery”[31] in North America. In addition to the large-scale projects a large number of pilot projects exist; in the Netherlands offshore several kt of CO_2 are injected in an almost depleted gas reservoir in the deep subsurface (*K12-B* project; see Section C.7). In the UK and the Netherlands a number of integrated large-scale CCS projects are being prepared. The *Peterhead* and *White Rose* projects in the UK are now in the FEED phase (Front End Engineering Design). In the Netherlands the *ROAD* project [97] has a license to operate, the first license which was approved under the regime of the EU Storage Directive.

CCS is facing problems in creating a sound business case. Finding investors in the recent years of low or negative economic growth appeared to be difficult. The price of *European Emission Allowance* (EUA) of about 7 euro per tonne of CO_2 avoided [98] is too low to make CCS commercially viable at the moment. Furthermore, geological storage onshore is confronted with public resistance like has been seen in Germany and the Netherlands.

Environmental and safety risk management of CO_2 storage look in particular to the unintended leakage of CO_2 into groundwater, surface water, soil and the atmosphere. A potential storage site must be thoroughly investigated so that these sites have an acceptably low risk level. Particular attention is directed to the integrity of the wells, the seal on top of the reservoir and the properties of any faults dissecting the seal. Pressure build-up in the reservoir can lead to induced seismicity; the magnitude of this risk must be assessed in the characterisation phase and necessary measures, e.g. limitation of the injection and reservoir pressures are to be taken.

[31] *EOR* stands for Enhanced Oil Recovery by injection of fluids, e.g. CO_2 or steam, in the oil reservoir. CO_2 sweeps the oil reservoir and lowers the viscosity of the oil when dissolved in it and thus increases the oil productivity.

C.2 Stakeholder engagement

The central stakeholders in the process of licensing a storage site are the competent authorities and the site operator. The organisation of the licensing procedure is very similar to the existing procedures for oil and gas exploitation and storage.

In the Dutch *ROAD* project, stakeholder management played an important role in developing the CCS project [99]. The parties in the *ROAD* partnership are two electricity producers, i.e. E.ON Benelux and Electrabel Nederland with two partners, which are Taqa Energy and GdF SUEZ E&P Nederland. The latter two are active in the upstream gas production and storage in the territories of the Netherlands. The following activities demanded the involvement of stakeholders according to the *ROAD* partnership ([99], p.9):

- Project funding
- Licensing
- Regulatory framework
- Communication and public engagement
- Knowledge dissemination

The *ROAD* project is co-financed by the European Commission in the *European Energy Programme for Recovery*, the Government of the Netherlands and the Global CCS Institute. Licensing involves the *Environmental Impact Assessment* and the application for all permits to operate the CCS project. The relevant authorities are the Ministry of Economic Affairs, the DCMR Rijnmond Environmental Agency, the Department of Construction and Transport of the City of Rotterdam, Province of Zuid-Holland, State Water Authority of Zuid-Holland, State Water Authority of the North Sea and the Dutch Commission for Environmental Assessment ([99], p.13).

As CCS is an upcoming new technology, also new regulatory frameworks, e.g. the EU Storage Directive emerge, which need particular attention. Stakeholders are the European Commission, Dutch government officials and members of Parliament.

In the public outreach process it is of prime importance to map the social-political context and issues and the stakeholders involved to successfully develop the project. The following groups of stakeholders were identified ([99], p.18):

- local communities and local civil groups;
- regional NGOs (e.g. environmental);
- local and regional governments and authorities;
- regional business platforms (port and industrial area);
- national government and parliament;
- local and national media;
- national NGOs; and
- knowledge institutes.

Communicating with and engaging local communities and local civil groups are crucial for the development of CCS projects in populated onshore areas. Ashworth et al. ([100], p.9) set up a framework for social interaction (Figure C.2-1) and came up with a number of recommendations to stakeholders.

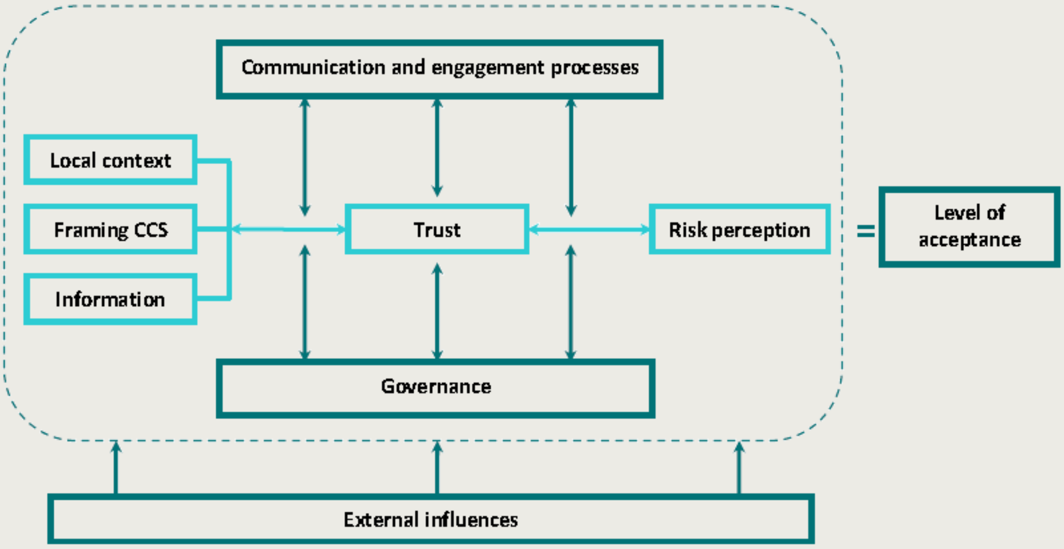

Figure C.2-1: Framework for interaction with the public (Ashworth *et al*., 2013: Fig. 1)

The framing of CCS should consider all opinions on climate change and its effects. CCS should be put in the context of climate change discussions, policies and energy debate in a balanced way. The local history and pre-existing concerns need to be mapped. The information provided should cover a wide range, needs to be balanced and of high quality.
Creating trust is of primary importance in engaging the local public. Ashworth et al. [100] recommend to identify trusted persons and entities in the local community and that the provided advice and information is seen to be trusted.

Gaps in the local knowledge of CCS and its context should be identified and the dialogue with the public is to start well before finalizing the plans and by making use of trusted advocates of CCS. The process of involving communities and stakeholders needs to be clearly defined and to work towards shared outcomes. The legal and regulatory framework must be well aligned across all levels.

Perceptions of risk may vary individually and should be addressed in a dedicated way. If the perceived risk is high, it is advised to have flexible plans so that people's concerns can be accommodated in dialogue.

C.3 European regulation for CO_2 storage and monitoring

'*Monitoring*' for the purpose of CO_2 storage can be defined as the continuous or discontinuous measurement of physical parameters of the storage site through the project lifetime to assure the safe and effective performance of the site, to initiate and to measure the effectiveness of corrective measures in case irregularities indicative of leakage occur. The baseline of the site, i.e. the situation before injection, needs to be monitored so that the effects of injection and storage can be properly interpreted.

In the context of the European Storage Directive, monitoring has one or more of the following objectives as was stated in [94]:

- To confirm predictions and test models for the geological and engineered system and environment, and accordingly updating of these models;
- To provide an early warning capability in case monitored behaviour does not match expectations;
- To assess the effectiveness of corrective measures that are initiated in case significant deviations from what is expected, occur.

The EU Storage Directive has been developed for the safe storage of CO_2. The Directive emphasizes the roles of monitoring and modelling in providing evidence for the permanent containment of storage of CO_2 in such a way that negative effects are prevented or can be sufficiently eliminated. An important aspect in the regulations is the eventual transfer of responsibilities from the site operator to governmental authorities after the definite cessation of injection and abandonment of the site. Specific conditions for the transfer of responsibility to governmental authorities have been included in the Directive and were tested on several sites in the EU *CO2CARE* project. These are discussed in Section C.4.

The EU Storage Directive ([102], Annex II]) defines a number of monitoring parameters which need to be monitored (see [101]):

1) Fugitive[32] emissions of CO_2 at the injection facility,
2) CO_2 volumetric flow at injection wellheads,
3) CO_2 pressure and temperature at injection wellheads (to determine mass flow),
4) Chemical composition of the injected substances,
5) Reservoir temperature and pressure (to determine CO_2 phase behaviour and state).

A central concept in the Storage Directive is '*significant irregularity*', which is defined as any irregularity during the injection, post-injection/pre-closure and even post-closure phase, which pose a risk of leakage or implies a risk to the environment or humans. Irregular site behaviour could be defined as a state or development of the storage site which is deviating from the predicted regular behaviour. The discrimination between acceptable deviations and irregularities need to be specified.

[32] Any release of gas from a (pressurized) system

C.4 Conditions for transferring responsibility of CO_2 storage sites

Article 18 of the EC Storage Directive outlines the requirements for transfer of responsibility of the operator of the CO_2 storage site to governmental authorities. Article 18(1) of the Directive says that the transfer can be approved when the following conditions are met [101, 103]:

1) all available evidence indicates that the stored CO_2 will be completely and permanently contained,
2) the financial obligations to manage any residual risk which emerges after the transfer of responsibility, have been fulfilled,
3) the site has been sealed and the injection facilities have been removed.

The operator has to demonstrate the following before the responsibility of a CO_2 storage site can be handed over to governmental authorities [102]:

- **The conformity of the actual behaviour of the injected CO_2 with the modelled behaviour:** Kronimus *et al*. [101] indicate that this requirement expresses the understanding of the storage behaviour at the site. To that end a choice of model types has to be made which are to be tested with monitoring data. It is considered of more importance that successive conformity tests show convergence of the modelled and monitored behaviour rather than observing absolute deviations. Tolerance to this type of deviations needs to be established upfront.

- **The absence of any detectable leakage:** In support of the absence of any detectable leakage the following elements have been put forward in the Directive [101]:
    - no detectable changes in the overburden above the storage reservoir,
    - no emissions detected to surface water or the atmosphere, and
    - no irregularities measured in the storage performance which are indicative of leakage.

  Monitoring of the reservoir pressure evolution is an important indicator for detecting irregularities in storing CO_2 in a permeable geological medium. Other recommended monitoring techniques for testing the absence of irregularities are [103]:
    - Mechanical well integrity tests by well logs,
    - Pressure, temperature and resistivity monitoring of the injection zone, and storage complex to monitor the plume position within the storage complex,
    - Pressure, temperature and resistivity monitoring of zones above the cap rocks to verify that no CO_2 is leaking outside the storage complex,
    - Periodic seismic surveys,
    - Groundwater, soil and air monitoring,
    - Geochemical tests.

- **The storage site is evolving towards a situation of long-term stability:** Guidance Document No 3 of the Storage Directive [103] identifies four indicators for long-term stability of the CO_2 storage site:
    - Models predict stabilisation of the CO_2 plume in the storage complex.
    - Key monitoring parameters are close to future stable values.

- The rate of change in the monitored parameters is small and declining.
- The backcasted modelling values are within the confidence intervals of the historical monitored parameters.

The following key monitoring parameters are mentioned in EC [103]:

- Pressure in the storage complex,
- Movement of the plume,
- Geochemical changes in in the storage complex and the wells,
- Material integrity of wells and abandonment plugs.

Convergence of the model predictions with the monitored behaviour is considered as a central element in proving long-term stabilisation. This strategy has its limitations as a number of storage processes become apparent only on the long term. In such cases the proof of stabilisation is based on well-founded and thoroughly calibrated models as approximations of long-term storage processes.

C.5 CO_2 storage end-of-lifetime stages and milestones

The CO_2 storage lifetime can be split in several consecutive stages according to Guidance Document No 3 of the EC Directive [103] from the Phase 1 '*Assessment*' to Phase 6 '*Post-transfer*' (Figure C.5-1). These phases are delimited in the following way ([104], p.8):

1. *Assessment:* Definition of the storage site and exploration requirements, evaluation of the storage potential and review of the exploration license application
2. *Characterisation:* Description of the storage site and the subsurface to comply with all requirements in the Directive and review of the storage license application
3. *Development:* Engineering design of the storage site and oversight of baseline monitoring and approval of any updates of the monitoring and corrective measures plan
4. *Operation:* Injection of CO_2 in the storage reservoir and inspections, oversight of monitoring and reporting and approval of any adjustments of the risk management plan
5. *Post-closure/pre-transfer:* Preparation for transfer of responsibility, continuation of inspections, oversight of monitoring and reporting and approval of any adjustments of the risk management plan after injection has definitely stopped.
6. *Post-transfer:* Long term stewardship by governmental authorities and risk management actions including monitoring as needed.

The phases and subphases around closure of the site and transfer of responsibility to governmental authorities are the most relevant for the purpose of this study. The duration of the operational phase (Phase 4) is around 10 to 30 years, the post-closure/pre-transfer phase (Phase 5) lasts for several years to a few decades and the post-transfer phase (Phase 6) can last for centuries to millennia.

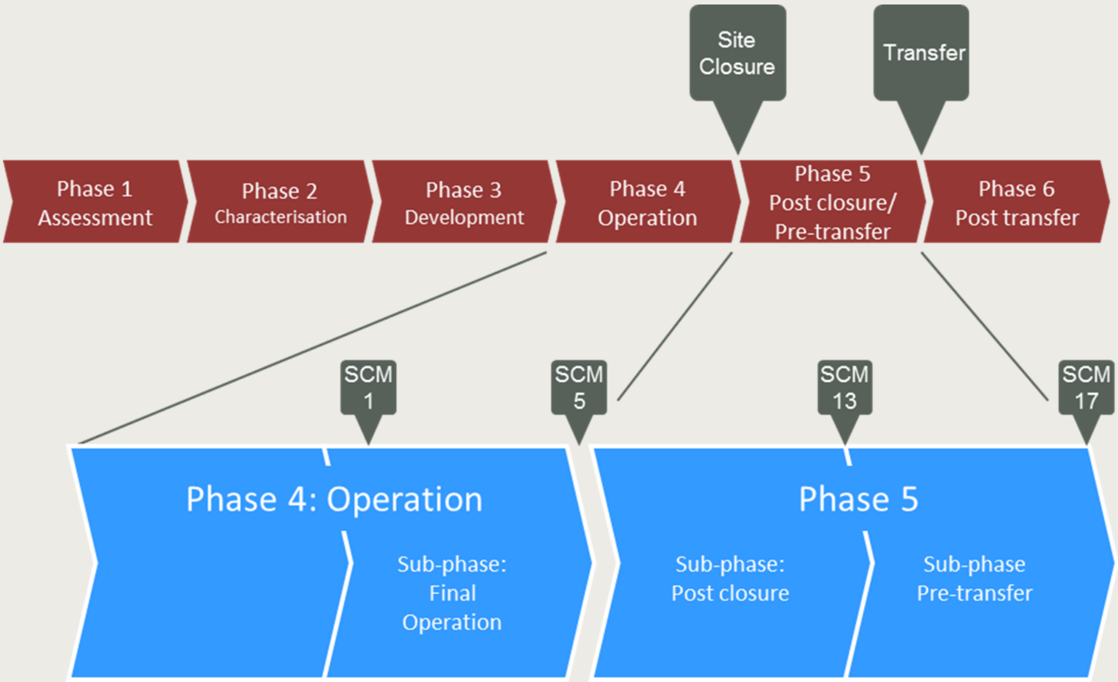

Figure C.5-1: Main phases of the CO_2 storage lifetime in red and main milestones [103] and subdivision in subphases in blue with selected Site Closure Milestones or SCMs [101]

Risk management activities, i.e. the cycle of risk assessment, monitoring and risk reducing measures, are continuously revolving during all phases of the CO_2 storage lifetime from the site assessment phase onwards. In the final operational phase a complete record of risk management activities including plans for closure, abandonment and responsibility transfer.

To structure the risk management activities in the final phases of CO_2 storage Kronimus *et al*. [101] introduced a number of *Site Closure Milestones* (SCM; see Table A3.1) which were already briefly introduced in [94]. A summary is provided in [105]. The SCMs are closely connected with the conditions for closing the injection, sealing the wells and dismantling surface facilities and transferring the responsibility. Following the milestones sequentially allows the site operator and competent authority to monitor the progress towards transfer of responsibility in a regular way.

The *Final Operation* subphase and *Site Closure* milestone (Figure C.5-1) includes six *Site Closure Milestones* (Table A3.1):

- *SCM0: Specify models and monitoring selected for conformity check:* To define the model and monitoring parameters which are key to proof the understanding of the storage concept and are needed to fulfil the conditions for responsibility transfer. Also the tolerance to deviations between modelled and monitored behaviour needs to be defined.
- *SCM1: Check model/monitoring conformity during final operational phase; if necessary update models:* The final operational stage can be used to test the pressure models with monitoring data and evaluate deviations between model and measurement. No large deviations are expected as the models are assumed to be well calibrated to the monitoring time series of the earlier operational stages.
- *SCM2: Provisional post-closure plan updated:* The provisional closure plan at the time of licensing the storage site needs to be updated. The main ingredients of the plan concern data availability, updated models and the specification of required monitoring or corrective measures for the post-closure phase. An update of the risk assessment is to be incorporated as well.
- *SCM3: Final (updated) post-closure plan submitted:* The plan is submitted for review to the competent authority.
- *SCM4: Final (updated) post-closure plan approved:* The review is directed to the following aspects: components of the provisional closure plan, all required monitoring and corrective measures and additional monitoring measures. It has to be explained if specific measures will be stopped.
- *SCM5: Site Closure:* After the approval of the post-closure plan the injection operations will have definitely ceased and the site has arrive in the post-operational phase.

The post-closure subphase comprises seven *Site Closure Milestones* which are principally dedicated to gathering and compiling evidence supporting the requirements for responsibility transfer.

- *SCM6: Optional update of risk management plan:* An update is necessary if risk-related requirements are included in the post-closure plan; otherwise this action can be passed without any action.
- *SCM7: Model check-update loop terminates:* This milestone, which is indicating a good understanding of the storage concept and absence of significant irregularities, is reached when the monitored behaviour is comparable to the modelled behaviour acknowledging reasonable tolerances for deviation.
- *SCM8: Models and monitoring data are within acceptable conformance after SCM7 has been reached without significant adjustment:* Guidance document number 3

proposes a minimum period of 5 years [101]. Kronimus *et al*. [106] recommend that this period is tailored to the specific needs for the site.

- SCM9: *Optional final update of risk management plan*: In case additional risks would have been identified in the post-closure subphase, the risk management plan needs to be updated. Otherwise this milestone can be passed without any action.
- *SCM10*: *Evidence of absence of leakage presented to the CA*: All relevant monitoring measures should confirm that there is no detectable leakage of CO_2 from the storage complex. The reservoir pressure is an important indicator. The CO_2 plume must remain in the storage complex which can be shown with the help of time-lapse seismic surveys or direct monitoring with a number of monitoring wells.
- *SCM11*: *Effectiveness of storage concept: Evolution to long-term stability demonstrated:* This milestone consists of three sub-milestones ([101], p.22):
    - The monitored pressure evolution matches the model pressure time series.
    - Observed movement of the plume matches the model predictions in an acceptable manner.
    - Optional model-monitoring verification of other parameters linked to the storage concept.
- *SCM12*: *Final wellbore check before abandonment (final well logging):* The integrity of the well materials is checked before plugging and abandoning the well. The most important aspects to be checked are mechanical deformation, casing corrosion, cement quality and bonding of cement and casing.

The *pre-transfer subphase* consists of five *Site Closure Milestones*:

- *SCM13*: *(Draft) Report for transfer of responsibility submitted:* The draft report provides the substantiation of the three requirements dealing with conformity of modelled and monitored behaviour (SCM8), the absence of detectable leakage (SCM10 and SCM12) and evolution to long-term stability (SCM11).
- *SCM14*: *(Draft) Closure report approved*: In case all milestones have been adequately fulfilled the CA will approve the closure report.
- *SCM15*: *Surface facilities removed:* After approval of the closure report the operator is to remove the surface installations unless the CA requests to leave some equipment for post-closure monitoring.
- *SCM16*: *Well abandonment accepted:* According to best industrial practices and existing regulations the wells will be abandoned as describes in the closure report.
- *SCM17*: *Transfer of responsibility approved and accomplished:* After completion of SCM 16 and SCM 17 the CA will approve the transfer of responsibility and the operator will be relieved from its responsibilities of the storage site.

A number of criteria have been developed which support decision-making in the risk management plan, in particular on meeting the criteria on the absence of detectable leakage, conformity of monitored and modelled behaviour and evolution to long-term stability ([106], Table 3).

Table C.5-1: Milestone Chart for CO_2 storage monitoring planning workflow [101]

Site Closure Milestone (SCM)	Description	Phase/ Moment	Sub-Phase
0	Specify models and monitoring selected for conformity check	Operation	Final Operation
1	Check model/monitoring conformity during final operational phase; if necessary update models		
2	Provisional post-closure plan updated		
3	Final (updated) post-closure plan submitted		
4	Final (updated) post-closure plan approved		
5	Site Closure	Site Closure	
6	Optional update of risk management plan	Post-Closure/Pre-Transfer	Post-Closure
7	Model check-update loop terminates		
8	Models and monitoring data are within acceptable conformance after M7 has been reached without significant adjustment (EC GD3 proposes a minimum period of five years)		
9	Optional final update of risk management plan		
10	Evidence of absence of leakage presented to CA		
11	Effectiveness of storage concept: Evolution to long-term stability demonstrated		
11a	Pressure evolution demonstrated to match model prediction		
11b	Plume movement is demonstrated to be an acceptable match to model predictions (within tolerances)		
11c	Optional verification of other parameters/features related to the storage concept		
12	Final wellbore check before abandonment (final well logging)		
13	(Draft) Report for transfer of responsibility submitted		Pre-Transfer
14	Report approved		
15	Surface facilities removed		
16	Well abandonment accepted		
17	Transfer of responsibility approved and accomplished	Site Transfer	

C.6 Workflow for managing occurring irregularities

If the modelled behaviour of the injected and stored CO_2 deviates from the monitored behaviour beyond the tolerance level (‘*Model-Monitoring Offset*’ or MMO) additional risk management actions have to be deployed. To this end a ‘traffic light’ system was developed ([106], Fig. 3). The traffic light system (Figure C.6-1) has three different states:

- *Status Green* implies that the site is in a regular condition as expected; all parameters are within their tolerance ranges
- *Status Orange* means that one or more parameters values is or are outside their tolerance range(s) which is leading to model recalibration or further risk management action
- *Status Red* indicates that the site is in an irregular mode which needs to be corrected by counter measures

The decision-making in case of offsets between modelled and monitored behaviour is supported by a set of technical parameters listed in Table C.6-1.

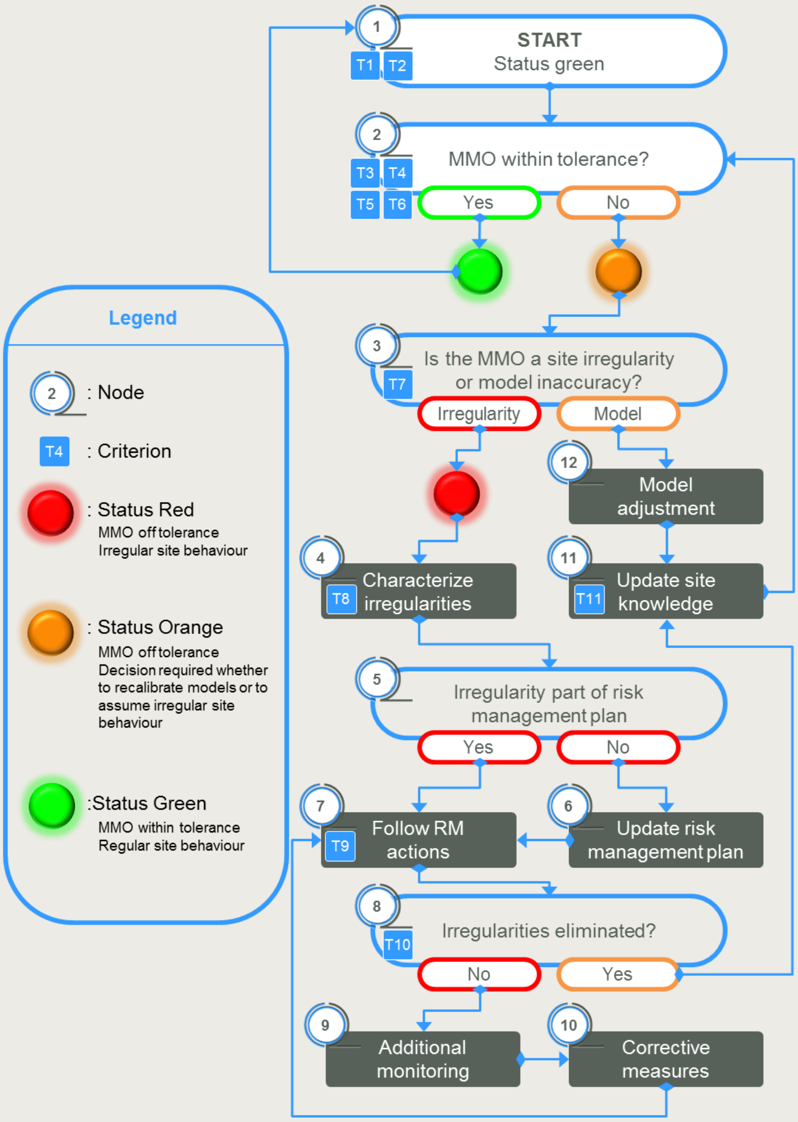

Figure C.6-1: Flow diagram of the traffic light system for managing deviations between modelled and monitored behaviour of the CO_2 storage site; MMO= Model-Monitoring Offset ([106], Fig.3)

Table C.6-1 List of technical criteria supporting the traffic light system; RM = Risk management [106]

Criteria	Description
T1	Models and monitoring of required site-specific monitoring parameters are implemented
T2	A list of prioritised models is in place and the mandatory models are implemented
T3	Duration of the time interval to check for MMO
T4	Relative amount of the tolerable MMO
T5	Accuracy/precision of monitoring technique
T6	Accuracy/precision of models
T7	Does a gathered MMO refer to site irregularity or is model recalibration required?
T8	In case of site failure: Are the primary and all connected irregularities identified?
T9	In case of site failure: are all required RM measures ready to be applied?
T10	Are the irregularities eliminated by the RM measures applied?
T11	Is there data to improve the site knowledge?

C.7 Case-specific evaluations of storage projects

The *CO2CARE* project has investigated the monitoring and modelling programmes of two CO_2 storage sites, the Sleipner site in the offshore waters of Norway and the *K12-B* pilot site in the Netherlands sector of the North Sea.

Sleipner CO_2 storage site

Since 1996 an average annual amount of 1 Mt CO_2 is injected in the *Utsira Formation*, a very permeable aquifer with a thickness of 200 m. The CO_2 is separated from the gas that is being produced from the deeper Sleipner gas reservoirs. The Utsira Formation has a lateral extension of 50 to 100 km from east to west and 400 km from north to south. The formation is covered by 700 m of sediments consisting mainly of mud- and siltstones.

The following conclusions on Sleipner are based on the hypothetic cessation[33] of injection in 2006. No evidence of anomalies were observed in the repeat seismic survey until 2008. In combination with the thorough characterisation of the site this is strong evidence for no leakage. In the course of injection since 1996 improved models show clear convergence to the monitored behaviour and uncertainties in the migration behaviour of the plume steadily decreased ([107], section 2.1). The migration of the CO_2 is distinctly controlled by the closed structures at the top of the Utsira Formation, also referred to as gravitation stabilisation. Flow simulations indicate that this process will lead to spatial stabilisation in decades. Models show that CO_2 dissolves in the surrounding formation water on a centennial to millennial time scale. The dissolution is sustained by the convection of the saturated formation water.

K12-B CO_2 storage pilot

Since 2004 several tens of kt CO_2 have been injected in a nearly depleted gas reservoir at more than 4 km depth below 500 m of Zechstein rock salt.

The modelled and monitored reservoir pressures do match well in most cases; deviations are often merely a couple of bars. Pressure anomalies observed during temporary shutdowns of the well could be well explained and are not pointing to a loss of containment of CO_2 in the reservoir. The Zechstein rock salt has an excellent sealing quality and no indications for gas migration along the wells have been observed. On the long term the underpressured reservoir is expected to gradually return to near hydrostatic pressure ([107], Section 2.2).

[33] Actually the injection of CO_2 at Sleipner is still ongoing.

Appendix D: Description of the Key Decision Steps

This appendix includes more detailed description regarding the key decision steps, as defined in the IAEA PRISM project [108, 109]. In general, the IAEA PRISM project recognised and recommended that

- The public and other interested parties should be involved as appropriate in each of the key decisions steps.
- The evolution of the safety case from one iteration to the next should be fully documented so that it is transparent to the interested parties (e.g. the safety case should provide clear records of changes and developments made at the disposal facility site, should provide clear explanations of new data, and should explain the reasons for any changes made, such as changes to conceptual or mathematical safety assessment models).
- The safety case should be reviewed and updated as necessary prior to each major decision step. The safety case should also be updated periodically according to national legislation and regulatory guidance. In practice, safety assessments may need to be updated more frequently than this to reflect actual experience and increasing knowledge of each component of the facility, and thereby support operational decision-making (e.g. relating to the acceptance or emplacement of specific wastes).
- At each step, alternative options should be presented and their pros and cons assessed.
- The relative importance of the arguments included in the safety case, and the level of scrutiny to which they are subjected by the regulator and other interested parties may change over time.

Decision Step 1: Need for Action

Based on the specific national context and the logistic boundary conditions (waste inventory, current policy on nuclear power, etc.), this decision step consists of the awareness for the need to find a safe solution for the long-term disposal of radioactive waste. According to IAEA policy, disposal of radioactive waste is considered the end point of the waste management process. At some stage in the development of a national waste management plan, a disposal option is proposed and implemented for each category of waste requiring disposal (see [110]). The rationale for action decision stems from the need to manage the hazard posed by the radioactive wastes. According to the specific national strategy, based on the characteristics of the waste inventory (current and anticipated in term of volume, activity and type of radionuclides, waste stream characteristics), the aim of this decision step is to launch a suitable disposal program that will ensure protection of the people and of the environment. Similar decisions may be required in relation to any potential remediation or upgrades to an existing facility.

In this step, a disposal programme will be initiated that ensures the implementation of a geological disposal. This may include the accumulation of scientific information and assessment of the necessary basis, the evaluation of possible sites and/or host rocks, the development of a disposal concept, the iterative performance of safety assessments which are supported by increasing experimental evidence, technical and regulatory reviews and public consultations [32]. An important part of a future safety case in this phase is called "safety strategy", which is a high-level approach that describes how a safe disposal should be achieved. In [3], three components of a safety strategy are distinguished:

- *"The overall management strategy of the various activities required for repository planning, implementation and closure, including siting and design, safety* *assessment, site and waste form characterisation and R&D. This management function keeps work focused on project goals, allocates resources to particular activities, and ensures that these activities are correctly carried out and co-ordinated;*

- *the siting and design strategy to select a site and to develop practicable engineering solutions, consistent with the characteristics of the selected site and the waste forms to be disposed; and*
- *The assessment strategy to perform safety assessments and define the approach to evaluate evidence, analyse the evolution of the system and thus develop or update the safety case."*

In the Netherlands, the safety strategy is still in development [111]. The process has led to a number of governmental and policy decisions [23, 24, 25, 112], and has resulted in initial disposal concepts [28, 113, 27, 1] and their safety evaluations [67, 114, 115]. The current OPERA programme can be considered as part of this on-going process, ultimately leading to a stepwise, iterative refinement of actions to develop and evaluate the stepwise implementation of a safe geological disposal.

Decision Step 2: Disposal Concept

In order to decide which disposal concept is the most appropriate for a given waste inventory, knowledge is needed on the volume and characteristics of the waste streams and on the different possible disposal options. This decision has to be undertaken in accordance with national strategy, priorities and regulatory framework.

The decision on which host rock/disposal concept is the most appropriate for a given waste inventory, and on which part of the waste is to be disposed in deep geological formations, depends on the existing and expected waste inventory and on the possible host rocks available. A decision on a particular disposal concept has to be undertaken in accordance with national policies, current practices and regulatory frameworks. In [42], a decision for a disposal concept in the Netherlands is foreseen for 2100. Prior to this (2080), a decision on whether or not aiming for a multinational disposal facility has to be made. With respect to the potential disposal concept to be decided for, one must be aware that if a multinational solution is chosen and it is decided that the repository will be situated in the Netherlands, a larger disposal facility is needed and the disposal concept might alter from a concept for the national waste inventory only.

A decision for a host rock, e.g. one of the two potential host rocks currently considered in OPERA - rock salt and Boom Clay, can be based on several criteria, including safety, economic, logistic, and socio-political aspects.

Decision Step 3: Site selection

The next step after choosing a disposal concept will be the selection of a disposal site, according to [42] foreseen in 2115. *Site selection* (or *siting decision*) can comprise several steps. As in the selection of the disposal concept, for such a decision several criteria should be taken into account: safety aspects, geo-scientific and technical aspects, economic and logistic aspects, and socio-political aspects. On basis of existing information, a first selection of regions can be made that fulfil general requirements of the repository design. Additional geotechnical characterisations can be performed in the candidate regions to support the suitability of these regions. Dependent on the disposal concept, the characteristics of the host rock can be more or less critical. Besides the use of remote techniques, boreholes can be drilled in order to acquire deep subsurface samples. Potential sites can then narrow down on community level. However, alternative approaches exist, e.g. where regions can mark their interest in hosting a disposal in an early stage, and after a pre-selection procedure, additional geotechnical work can be performed in order to support the suitability of a location [64].

Decision Step 4: Construction

Based on prior knowledge and collected information (repository design, safety case outcomes, site characterisation data, etc.), it can be decided to start up the construction process. With the construction of a disposal site, an operator of the disposal facility is needed, and a regulator should be implemented that supervises the operator's activities. Construction work should be performed on basis of predefined qualifications that are part of a licence application, and evidence that requirements are met should be provided by the operator. Of importance here are the (local) properties of the host rock, which must fulfil the technical requirements on which the safety assessment is based and the long-term safety relies on. Requirements may be defined on the extent the host rock is getting affected by construction works.

If necessary, during construction some modification of the facility layout may be performed in order to anticipate local circumstances. Also certain aspects of design and/or material selection may be accommodated to fulfil safety requirements. This may lead to re-assessment of license conditions. Another aspect of interest is to clarify the role of disposal monitoring or related activities such as the deployment of pilot or test facilities. These monitoring activities can be either part of the license application ("performance confirmation") or could be used to support a safety case in general. Monitoring activities are initiated in this phase (or even earlier), and will support decision-making, mainly in the later steps, as discussed below.

Decision Step 5: Operation

The decision for starting up the *operational phase* means, that now radioactive waste is disposed in the underground facility. It also includes all aspects of the transport, possible waste (re)packaging [34], and emplacing the waste packages. Such a decision can be supported by the submission of an updated safety case to the regulator that reflects the actual implementation of the disposal design and spatial properties of the host rock. The regulator takes the decision to approve or disapprove operation, dependent on whether tests performed and site characterisation data collected so far are satisfactory, and the construction meets (predefined) requirements. It should be noted, that construction and waste emplacement can be performed simultaneously by separating the radiological controlled zones - where the waste is handled - from the part of the facility where construction works are taking place. Although this makes this decision point more complex (partial decisions), it can shorten the operational period substantially and therefore may contribute to safety; for the OPERA reference concept, it is estimated that the waste emplacement process will proceed for more than a decade [1].

After waste emplacement, the underground access galleries can be kept open and (emplacement) equipment left in place for a certain period to facilitate retrievability of the waste packages.

Decision Step 6: Closure

The *closure* of a repository can be performed in a stepwise manner, i.e. after waste storage, disposal drifts are backfilled and sealed, and once a whole waste section has been completed, it can be backfilled and sealed by dams. Disposal galleries or sections of the repository can be backfilled and sealed while waste emplacement is still on-going in other

[34] Surface-based waste-conditioning facilities, where e.g. HLW is repacked in the so-called "OPERA-supercontainer" [1]

parts of the disposal facility. After completion of waste emplacement, the disposal drifts and access galleries can be backfilled and closed while still keeping the shafts open. The stepwise closure of the disposal facility increases the operational safety and may be beneficial in e.g. the case of flooding events.

To support monitoring and retrievability of the waste, however, it can also be decided to postpone the closure of the facility after waste emplacement is completed. The decision of the closure of (sections of) the facility may influence the ability to monitor the evolution of repository components, because the presence of seals implies that the monitoring equipment is not accessible anymore and that it relies on the presence of an autonomous energy supply and wireless data transmission techniques in order to avoid impairment of the seals by wires.

Decision Step 7: Post-closure

The *post-closure period* describes the situation when the facility is closed and the shafts are sealed and refilled. The repository will no longer need any maintenance or other human intervention, since all excavations have been backfilled and closed.

As long as the surface facilities are maintained and/or monitoring data from the disposal facility is acquired, it is referred to as the *institutional control period*. During that period the retrieval of the waste would still be possible, but unlike in the previous step, it would require costly drilling operations (e.g. cost estimation of shafts for a Dutch disposal concept: 150 - 675 million Euro [116]).

Decision Step 8: Post-Licensing

At selected points in time it can be decided to either prolong or withdraw any further institutional control. This may depend on the public interest in prolonged control, and may also be influenced by the state of the monitoring equipment in the disposal. Another important aspect is the presence (or absence) of the specific know-how that is needed to be able to understand the meaning of monitoring results or the (scientific) arguments behind the long-term safety of the disposal facility. This knowledge might be weakening in time, while it is necessary to judge the implications of monitoring results if these are not in line with expectations.

At some moment in time, however, further institutional control is expected to be withdrawn. This is called the *post-licencing phase*, where the responsibility of the operator and regulatory authority ends. The decision of withdrawing institutional control thus implies that no operator and regulator are needed. This also means that any financial reservations that may have been hold back to financing a potential retrieval of the waste[35] are not needed anymore.

[35] which includes the set-up of an interim storage, the development/search of a new disposal concept/site and the construction of it

Appendix E: Endpoints for radioactive waste disposal

Figure E-1 on the next page gives an overview of four groups of 'argumentations scenarios' based on [17]. In these argumentation scenarios, different 'endpoints' of radioactive waste disposal, are identified, namely

- '*no geological disposal*'[36]
- '*use time of interim storage, but eventually proceed to geological disposal*'
- '*retrievable geological disposal*'
- '*non-retrievable geological disposal*'[37]

Endpoints and argumentation scenarios are sorted and linked (marked in different colours). The index in square brackets refers to the original scheme. For a full description of the argumentation scenarios see [17].

[36] in some case 'no solution at all'
[37] or, in some cases, without explicit indication on the role of retrievability.

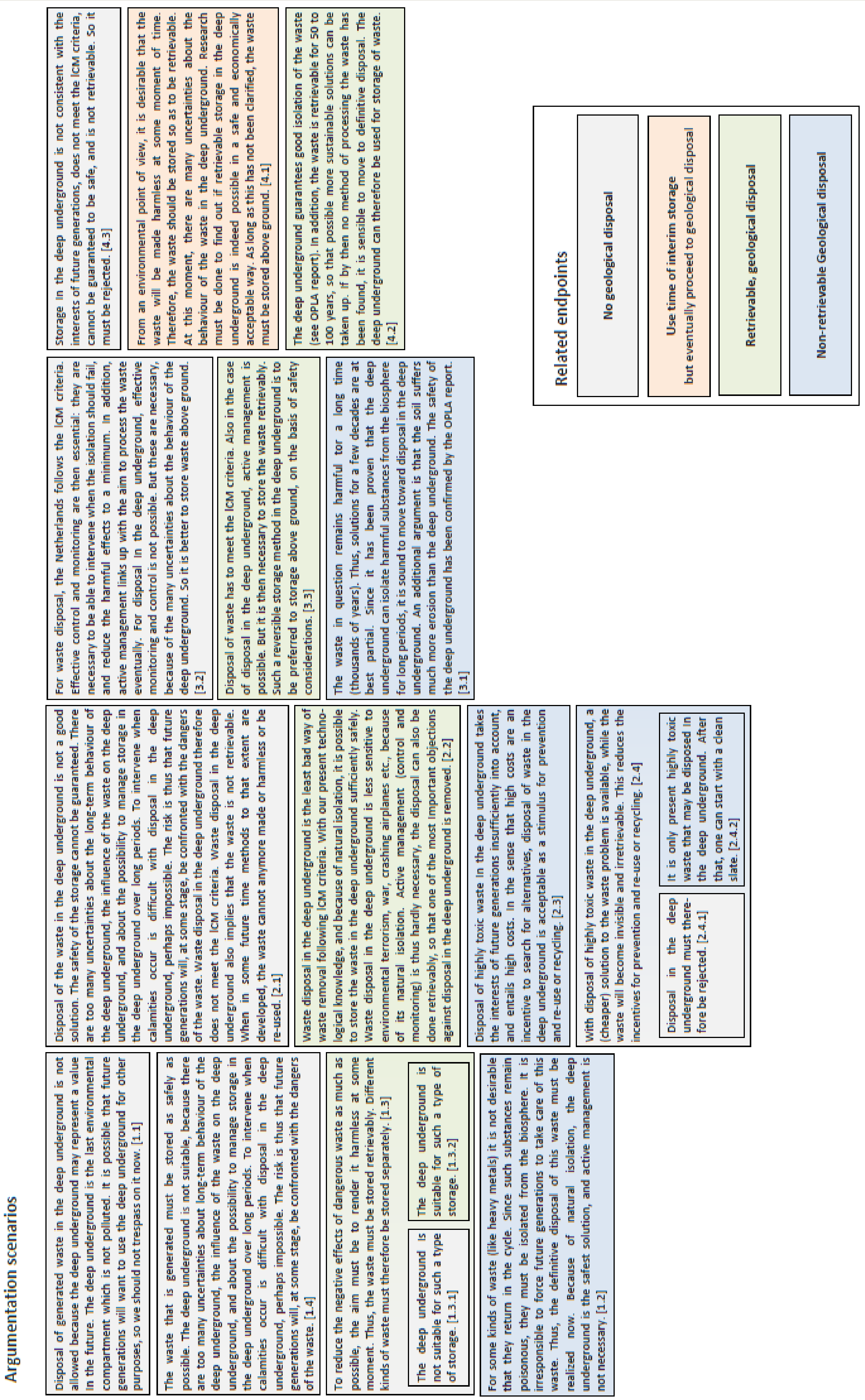

Figure E-1: Argumentations scenarios and endpoints of radioactive waste disposal

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OPERA

Meer informatie:

Postadres
Postbus 202
4380 AE Vlissingen

T 0113-616 666
F 0113-616 650
E info@covra.nl

www.covra.nl