Contract Number: 622177

Deliverable n°5.1

Monitoring the Underground: What role for repository monitoring in the governance of geological disposal for nuclear waste?

Work Package 5

Project Acronym	Modern2020
Project Title	Development and Demonstration of Monitoring Strategies and Technologies for Geological Disposal
Start date of project	01/06/2015
Duration	48 Months
Lead Beneficiary	*University of Gothenburg (UGOT) & University of Antwerp (UA)*
Contributor(s)	*Hannes Lagerlöf, Göran Sundqvist, Anna-Laura Liebenstund & Anne Bergmans*
Contractual Delivery Date	Month 18 (November 2016)
Actual Delivery Date	28/05/2017
Date of Issue	27/03/2018
Reporting period 1:	01/06/2015 – 31/12/2016
Version	Final

Project co-funded by the European Commission under the Euratom Research and Training Programme on Nuclear Energy within the Horizon 2020 Framework Programme

Dissemination Level		
PU	Public	X

History chart			
Type of revision	Document name	Partner	Date
First draft	Deliverable 5.1: Monitoring the Underground: Specific Challenges for Engaging Concerned Stakeholders	UGOT & UA	20161105
Full draft	Deliverable 5.1: Monitoring the Underground: Specific Challenges for Engaging Concerned Stakeholders	UGOT & UA	20161223
According to review comments	Deliverable 5.1: Monitoring the Underground: Specific Challenges for Engaging Concerned Stakeholders	UGOT & UA	20170117
Proof reading	Deliverable 5.1: Monitoring the Underground: Specific Challenges for Engaging Concerned Stakeholders	UGOT & UA	20170305
EB Review	Deliverable 5.1: Monitoring the Underground: Specific Challenges for Engaging Concerned Stakeholders	UGOT & UA	20170317
According to review comments	Deliverable 5.1: Monitoring the Underground: Specific Challenges for Engaging Concerned Stakeholders	UGOT & UA	20170404
According to secondary round of review comments	Deliverable 5.1: Monitoring the Underground: Specific Challenges for Engaging Concerned Stakeholders	UGOT & UA	20170515
Final Version	Deliverable 5.1: Monitoring the Underground: Specific Challenges for Engaging Concerned Stakeholders	UGOT & UA	20170528

Reviewed by

This report has been reviewed according to the Modern2020 Review Procedure and Quality Plan. Two formal reviewers were appointed accordingly; Michael Jobmann from DBE Tec and Assen Simeonov from SKB were assigned to read and comment this report. A formal review was performed by Michael Jobmann (DBE Tec) and written review statements were documented (January 2017). In a second stage, some members of the Executive Board provided additional feedback on the report and suggestions for improvement (March-April 2017).

Approved by

This report has been approved by Modern2020 Executive Board 2018 03 27

Abstract

This report is produced as a social sciences' contribution to the Horizon2020 EURATOM project Modern2020. It seeks to enable a better understanding of how monitoring the underground plays and can play a part in the governance of deep disposal facilities for nuclear waste. For this purpose, several aspects of repository monitoring technology development are addressed in two main parts. The first part focuses on how four nuclear waste management organizations (NWMO's) in the countries of Sweden, Finland, Belgium and France plan to monitor future repositories containing high-level long-lived nuclear waste. The report describes how the NWMO's frame the notion of monitoring, how they report on their plans to monitor future repositories, what role and weight is given to underground repository monitoring within the facility (as the development of such technology is the core focus of Modern2020), and what legislative demands there are in the respective countries. The second part looks at the role and framing of underground monitoring in the case of carbon capture and storage as another example of a technology designed for the perpetual safekeeping of a hazardous substance in deep geological formations. The report draws on document analysis and in-depth analysis of on the one hand legislative documents, and on the other hand a questionnaire created for NWMO's in Modern2020. By analysing the NWMO's in the four countries individually, it is shown that legislative demands vary significantly between the countries and that the respective NWMOs have divergent plans for underground monitoring. Moreover, it is shown that the notion of monitoring in nuclear waste management (NWM) is not uniform; the NWMOs all have divergent views on when, why (not) and how to monitor. A central conclusion regarding carbon capture and storage is that this technology has integrated underground repository monitoring, as well as post closure monitoring into its core concept. This is somewhat different from geological disposal of nuclear waste, where underground monitoring is not always of such central importance and post closure monitoring in most cases not considered (at least not in the near-field). To conclude, these results are discussed in relation to aspects that have been identified as central to Modern2020, that is, a 'contextual approach' to monitoring programme development and the role of public participation. The latter will be the focus of further Modern2020 research. As it is largely conditioned by pre-existing notions and technologies in NWM, this report has brought to the fore that waste management programmes are to a substantial degree 'locked-in' which limits the degree to which relatively recent views and developments regarding underground repository monitoring may permeate them.

Table of content

List of Abbreviations

Carbon Capture and Storage: CCS

Engineered Barrier System: EBS

Engineered Barrier System Monitoring: EBS monitoring

Environmental Impact Assessment: EIA

Geological Disposal: GD

Implementing Geological Disposal Technology Platform: IDG-TP

Nuclear Waste Management: NWM

Nuclear Waste Management Organization: NWMO

Science and Technology Studies: STS

Underground Research Laboratory: URL

Work Package: WP

Executive Summary

Background

The Development and Demonstration of Monitoring Strategies and Technologies for Geological Disposal (Modern2020) Project aims to provide the means for developing and implementing an effective and efficient repository operational monitoring programme, taking into account requirements of specific national programmes. An additional important aspect of Modern2020 is the explicit intention of addressing public participation and including (potentially) concerned local citizen stakeholders in the process of developing the monitoring programmes. It has been suggested, e.g. in the final report of the European Thematic Network on the role of monitoring in a phased approach to the geological disposal (GD) of nuclear waste (EC 2004), that monitoring might increase stakeholders' confidence in that the future repositories behave and function as intended. However, a previous project (MoDeRn), established that important divergences exist in the expectations regarding repository monitoring between nuclear waste management organisations (NWMO's) and their technical advisors on the one hand, and concerned inhabitants of (potential) disposal sites on the other hand. Thus, a social science Work Package (Work Package 5) in Modern2020 has the task to establish formats for integrating local public stakeholders' concerns and expectations into monitoring programmes, especially focusing on citizens from potential host communities. An important remark is, however, that public participation is a complex matter. Thus, in order to explore both possibilities and limitations of public participation in nuclear waste management (NWM), it has been deemed central to understand pre-existing legislation and differences between countries in which monitoring technology is being developed. The countries under study vary with regard to legislation, waste disposals technologies and much more. With this report, produced as a social sciences' contribution to this project, we seek to enable a better understanding of how monitoring the underground plays and can play a part in the governance of deep disposal facilities for nuclear waste. On the one hand, this report focuses on differences in the contexts of (national) situations regarding disposal plans and technologies. On the other hand it explores the role of monitoring and questions of governance in the case of a different type of deep underground disposal facility, namely carbon capture and storage. With this, we aim to develop a better understanding of the societal aspects that condition both the possibilities to monitor and the possibilities for local citizens to partake in the development of monitoring programmes and technology within Modern2020.

Introduction

This report starts with the observation that NWM since several decades has relied on the concept of a passively safe GD system in order to achieve long term safety. Passive safety is the central aim in nuclear waste disposal programmes; the centrepiece of NWM is the idea to eventually ‘walk away’ safely from the passive repositories after they have been closed, leaving them be for the hundreds of thousands of years it takes to render the nuclear waste harmless. However, demands for monitoring partly challenge passive safety. Conceptually, monitoring largely builds on a contrasting logic, namely that safety is to be upheld actively. It suggests that, instead of walking away, we should stay and observe (at least for some time). Taking into consideration that there is a potential tension, or even conflict, between passive safety and repository monitoring, a central question is to what extent the two can be combined. In technical documents, such as the IAEA safety guides on monitoring and surveillance of nuclear waste disposal facilities (IAEA 2014) it is explicitly stated that monitoring activity should not compromise the functions of the passive safety barriers. But what does that imply in practice, and what margin for interpretation is left?

The report then moves on to a critical reflection on what constitutes monitoring. Monitoring is explored in a wider context and its meanings and applications are researched far outside of NWM. It is acknowledged that monitoring is part of a general trend; monitoring is increasingly used in many areas, from everything between healthcare and migration. Monitoring is an important source of information used in policy-making. It is also noted that monitoring in NWM is not necessarily an all-new phenomenon. On the contrary, monitoring of the environment, of operations underground and so forth has been ongoing since the waste management programmes first saw the light of day. However, there are types of monitoring (in particular repository monitoring) that are more novel and controversial. As this report will come to show eventually, monitoring of the engineered barrier system (EBS monitoring) is the most contentious of monitoring technologies and a significant part of the tension between ‘passivity’ and ‘activity’ gathers around this type of monitoring.

Methodology

In this report we look in closer detail at four countries, namely Sweden, Finland, France and Belgium. The reason for this focus has first and foremost to do with the aim to engage local citizens from these countries in the project. Furthermore, they represent countries that are at different stages of developing a repository and repository monitoring programme. In order to grasp each country’s preconditions for developing monitoring technology, a data set that reflects their diversity is needed. The data material that is analysed in this report is derived from a range of documents. Firstly, we analyse a questionnaire produced by WP2 early in the project, reporting on differences between the various NWMOs partaking in Modern2020. Secondly, we analyse a range of legislative documents, government reports and scientific articles.

Results

The report starts its analysis with individual accounts of the NWMO's framing of monitoring in the four countries. Each individual account is reported together with a retrospective; we briefly sketch the history of nuclear power and NWM in each of the four countries. Thereafter, we study the NWMOs' plans for monitoring more in-depth, with a focus on plans regarding EBS monitoring or monitoring within the facility. Here, it is shown that the NWMOs have divergent plans, that repository monitoring demands in legislation reach from being concrete to vaguer or even non-existent at the present day. Moreover, the report shows that the concept of monitoring in NWM sometimes is surrounded by controversy. Even though NWMOs have engaged in producing 'glossaries' and standardized concepts, the notion of monitoring in NWM is not always clear as different actors ascribe different meanings to it, which is to some extent related to the early development stage of some GD programs. As such, what exactly constitutes monitoring is sometimes surrounded by disagreement, not least with regard to temporal aspects and the challenges it entails to monitor a repository for decades, or even centuries. In short, how long to monitor, who should do the monitoring, and how the monitoring is to be carried out, are questions without univocal answers. However, some monitoring is commonplace in all programs, for instance environmental monitoring, while some aspects of repository monitoring, and more specifically EBS monitoring is significantly more contentious. Some NWMO's recurrently point out that EBS monitoring is a potential threat to safety, while others seem to interpret the IAEA guidelines in a different manner and do propose EBS monitoring. A point subsequently made in this report with regard to this observation is that NWM significantly differs from carbon capture and storage (CCS) which has sought to integrate monitoring into its safety work. This technology is already being implemented since several decades, and the demand for monitoring is strongly embedded in European legislation. As the case of Barendrecht shows, this does not prohibit local public stakeholders to have specific demands regarding an underground monitoring system and to question the adequacy of a standard methodology designed to meet general safety requirements without addressing specific concerns relating to the particularity of a concrete situation.

Discussion

Lastly, the results are discussed in relation to a broader context. It is upheld that monitoring is far from a uniform concept, that it is not always clearly defined what aspects or types of monitoring are covered, when the term is used in policy documents or even in legislation, and that monitoring strategies and plans vary significantly between countries and NWMOs. The open character of monitoring may render it a good candidate for public participation – one might suggest that such an open concept could be explored and developed collectively. This report nonetheless concludes that the possibility of engaging concerned stakeholders in monitoring development is conditioned by the fact that NWM programmes have evolved over the course of several decades. Thus, monitoring technology development does not take place 'de novo', but relies heavily on pre-existing practices and technologies in NWM. Nevertheless we do observe evolutions in the approaches taken, even if this is not to the same extent (and for various reasons not to the same extent possible) in the different national contexts. The ideal of an inherently passive geological disposal remains of great importance in NWM, but in a good number of countries, the route to repository monitoring has also been set in, and the challenge to match those seemingly opposing approaches to safety is being taken up – most notably in France, but also in other countries.

What we have witnessed in the comparison between nations, and between NWM and the CCS case on monitoring issues, could be assessed as efforts to *exercise humility* as opposed to a strategy of *hubris*, as argued by Sheila Jasanoff (2003). The notion of passive safety, when expressed as the engineered barriers and geology guaranteeing safety or the safety case demonstrating guaranteed safety, has a strong connection to *hubris.* In that respect discussions and ambitions in relation to monitoring and monitoring strategies are explicitly about acknowledging remaining uncertainties, or should at least be about this, leading to a stronger focus on how to exercise *humility*. Monitoring in that regard can be considered as enabling a precautionary approach that moves '*from hubris to humility*' (Jasanoff, 2003). However, this does not mean that monitoring should be seen as the only route towards *humility*. Indeed, putting forward monitoring as a way to support safety could be just as much an expression of *hubris* as would be to ignore the possibility that a repository may not fully behave as expected in the safety case. But the notion of monitoring does help to emphasise that unexpected things – however unlikely – can never be fully excluded, resulting in a need to think about *technologies of humility* within a striving for passive safety. And as pointed out by Bijker et al. (2009: 161), in situations of uncertainty, a reflective discourse, including various stakeholders with various knowledge bases and interests, helps to provide "a satisficing approach to finding a proper balance between the possibilities of overprotection and under protection. Critical and reflexive consultation with all the stakeholders is therefore essential. Then, by definition, scientists do not know it all – and thus technologies of humility are called for". What role repository monitoring can play in this regard is what is being explored further in Modern2020, even if it is likely to differ between nations and between NW disposal concepts.

1. Chapter 1 – Background

1.1 Introduction

During the last decades we have witnessed increasing consensus on GD as the best way of taking care of nuclear waste. In 2006 and 2007, as an important sign of this consensus, a new European Commission 'Technology Platform' was initiated, stating that: "Deep geological disposal, may be arranged in many ways, but the preferred option is an excavated, engineered multiple-barrier geological repository…" (IGD-TP, 2016: 31). It was named the Implementing Geological Disposal Technology Platform (see e.g. IGD-TP, 2016) supported by a group of - European National - Nuclear Waste Management Organisations (NWMOs). According to the vision of this Platform, by the year 2025 the first repository for nuclear waste will be in operation in Europe. Such repositories would be the first of their kind in the world.

The IGD-TP acknowledges that GD is generally coupled with the notion of passive safety – the longstanding idea from NWM's early days that technological solutions for waste disposal should strive to evade any need for surveillance or monitoring during the waste's 100 000 year long life-span: "[a]t the international level, there is a consensus that the maximum level of passive safety can be obtained through geological disposal" (IGD-TP, 2011: 10). The basic idea, dating back from the 1950s, is that the attractiveness of GD lies in its ability to transport the dangerous nuclear waste to an environment beyond the biosphere, thereby protecting the life there. What is foreseen is a delegation to a more stable environment, i.e. to geological space and time.

GD has now become a 'technological fix' for what was earlier assessed as 'the Achilles' heel' of the nuclear industry (Sundqvist, 2002: 68; Shrader-Frechette, 1993: 11). Today, the IGD-TP after decades of research and development signals that it is time for implementation. However, there are still some remaining concerns to attend. Is passive safety, or walk-away safety, implying safe delegation to geology, really without any remaining uncertainties? Is it really just to calculate the safety a priori, construct the repository and forget about the waste?

Trying to govern something that has been assessed as impossible to govern due to time periods never before dealt with by technological measures, is close to what Sheila Jasanoff (2003: 238) has called a 'technology of hubris'. From this background it is reasonable to acknowledge technologies of monitoring as a response to remaining concerns and uncertainties in relation to GD of nuclear waste, or in the words of Jasanoff, to introduce more 'humility' in the further development and implementation of GD. While passive safety has played such a central role in NWM, the current demands for monitoring partly build on a different logic. Passive safety builds on the commitment not to take any active measures for maintaining the integrity of the repository, while monitoring stresses continuous vigilance. This tension becomes particularly explicit when considering repository monitoring, that is to say, monitoring within the GD facility itself, of the waste and of the engineered barrier system (EBS). Therefore the Swedish National Council for Nuclear Waste, for example, has pointed to a 'potential conflict of paradigms' (SOU, 2016: 152).

The Modern2020 project aims to provide the means to help develop and implement repository monitoring programmes as this is called for today in several national nuclear waste programmes. The project is connected to the IGD-TP and has the ambition to establish a common ground for monitoring activities to be deployed upon the realization of GD in the years to come. The basic idea behind the Modern2020 project is to "…provide the means for developing and implementing an effective and efficient repository operational monitoring programme, that will be driven by safety case needs, and that will take into account the requirements of specific national contexts" (Modern2020, 2016). Thus, an important idea in the project is to coordinate national variations, including legislation and governance processes, and not least expectations and concerns from various stakeholders, such as potentially concerned local citizens, in the development of means for constructing repository monitoring programmes. This is not necessarily a straightforward task, since many countries differ widely with regard to an array of aspects such as 'technological maturity', legislation, political culture, political opposition, nuclear power decommissioning, nuclear power new-build, and more. Establishing monitoring programmes in NWM is therefore a balancing act between standardization and flexibility, between supranational decision-making and nation state sovereignty, between passive safety and active vigilance.

This report *Monitoring the underground: specific challenges for engaging concerned stakeholders* is part of WP5 in the Modern2020 project. This WP is about establishing formats for integrating local public stakeholders' concerns and expectations into monitoring programmes, especially focusing on citizens from potential host communities. The start of the work in WP5 was connected to WP2, which is responsible for developing monitoring strategies, and its initiative to map the national differences concerning how monitoring and in particular repository monitoring (as there lies the technical focus of the project) is assessed and carried out in relation to the specific situation of a national programme. This means that we should be aware of, and take care of, national differences in the different national programmes concerning GD of nuclear waste, including existing formats of stakeholder involvement, not least local citizen involvement.

In essence, this report is a continuation of the work carried out previously in the MoDeRn project.[1] An early task for WP5, which we will come back to later, was to identify rough, but central, differences and similarities between those countries partaking in the project which are relevant for the local citizens groups involved in WP5. As such, divergent prerequisites for monitoring programme development in the various countries as well as how NWMOs intend to monitor their planned repositories to very varying degrees have been explored. Legislation in the countries with regard to monitoring and safety demands indeed vary significantly and, hence, NWMOs are prompted to work towards different monitoring ends. For instance, while some countries have explicit monitoring demands stipulated in legislation and guidelines, others do not. Even though monitoring in general has received attention previously in the field of NWM (see e.g. IAEA, 2014), and even though the general principles and central traits of repository monitoring have indeed been discussed (see e.g. MoDeRn, 2015), there is not necessarily always consistency amongst key actors with regard to what is considered as, and what could be the value of, monitoring the repository facility. NWMOs across Europe stress various actions of monitoring, and commonly divide the activity of monitoring into different strands, but not necessarily unanimously so. Environmental monitoring, near- and far-field, pre- and post-closure monitoring are just some designations that clearly display that there is no distinct demarcation between the different strands, or at least no consensual terminology. Thus, monitoring in the full sense of the word can indeed be confusing, since different answers will be received depending on who is asked the questions.

This report builds on these experiences, and as such, it is about *variations* in assessing the need for monitoring and how it should be performed, i.e. what should be monitored, how monitoring is related to ‘the safety case’ and how monitoring can be used to support GD decision making. Variation is an important topic since it will help us raise basic questions on why monitoring is needed, if at all, and how and why the assessments of these needs vary between nations and between national nuclear waste programmes. From such a background we can start asking questions about the possibilities to create a common ground, a common understanding, for developing a European monitoring strategy that suits all programmes. What is this common ground for such an ambition? Similarly, facilitating good public participation requires an understanding for the prerequisites of such participation in the respective country. Thus, first, we need to better understand these differences.

1.2 Monitoring as a general principle in Nuclear Waste Management

According to the Merriam-Webster Dictionary (2016) monitoring means *'to watch, keep track of, or check usually for a special purpose’*. Etymologically, the term monitoring stems from the Latin word *monere,* ‘to warn’. Still, the word is associated with the idea of not only taking

---

[1] Modern2020’s predecessor project MoDeRn ran from 2009 to 2013 and was funded through the European Atomic Energy Community’s Seventh Framework Programme (FP7/2007-2011) under grant agreement number 232598.

measurements, but to *'observe and check the progress or quality of (something) over a period of time; keep under systematic review'* (Oxford Dictionary, 2016). Furthermore, the noun 'monitor' may describe a device which produces pictures of things and words, which otherwise would not be visible, e.g. on a computer screen (Cambridge Dictionary, 2016). As such, the notion could also be linked to 'transparency' but also to governance, especially as monitoring results increasingly constitute the basis for political decision-making processes in society (Boswell et al., 2016).

Monitoring is deployed with various purposes, with an array of technical and political ambitions, in very diverse contexts. For instance, monitoring is increasingly used to improve healthcare, (Lupton, 2013; Oudshoorn, 2008; Petersson, 2016). Here, monitoring may promote caring for patients at a distance, in turn favouring both values such as cheaper healthcare as well as patient autonomy and independence. Simultaneously, monitoring can be used for bibliometric measuring (Nederhof, 2006), for instance by gathering data on publication rates among academic professionals, in turn used as an economic governance tool for (re)distributing and allocating funds on basis of academic performance. Monitoring is also deployed by citizens concerned for their environment (Narayan and Scandrett, 2014; Rodrigues, 2009; Engelbrecht and Schwaiger, 2008; Madruga, 2008). There are several examples of situations where distrust among citizens towards authorities has prompted these citizens to develop monitoring programmes of their own to supervise the integrity of their environment. Different kinds of monitoring activities that take place in relation to nuclear waste, nuclear accidents and so forth were researched in the previous MoDeRn project (Elam et al., 2012). Monitoring by citizens following the Three Mile Island accident is one example that was observed. There are also more contemporary examples; for instance when citizens set up a monitoring programme of their own in the face of the nuclear disaster in Fukushima following the great earthquake and subsequent tsunamis in 2011 (Hemmi and Graham, 2014; Normile, 2011). Using commercially accessible technology, the citizens attached sensors to cars that were driven through areas where nuclear fallout was suspected. The data retrieved through the sensors was communicated throughout the citizen network and presented online for anyone with an internet connection and a computer to review and interpret. The use of monitoring does not stop here for monitoring technologies are employed in areas from migration to employment, children's' school results and public health. Thus, it is obvious that the concept of monitoring is broad and that the word per se captures little specificity as it is deployed with various purposes, with an array of both technical and political ambitions. Monitoring systems' intrinsic political, democratic and social aspects render them especially relevant for analyses by social scientists.

So, when we speak of monitoring in this report, what do we mean? As we will see, monitoring in NWM is associated with a number of various applications. In fact, monitoring in the context of NWM is commonplace but also partly new. Monitoring is in some cases expected to play a more central role than before in assessing long-term safety and as monitoring technology has progressed, the ability to monitor has increased accordingly. Monitoring is commonplace in the sense that NWMO's have monitored the environment surrounding planned repositories, rock movements and much more for decades. They have also in various ways monitored the underground in underground research laboratories (URLs) and at potential disposal sites. Furthermore, there has been experience with monitoring inside underground disposal facilities (for radioactive waste types other than high-level waste or spent fuel) during the operational phase of the facility (e.g. in the Morsleben repository in Germany). However, what is relatively new, is the attention payed to underground 'repository monitoring, 'near-field monitoring', or 'in situ monitoring' in deep GD facilities for high-level waste or spent fuel, and this for the purpose of the long-term safety of such a facility.

In short, this type of monitoring is concerned with developments within the very repository itself and which could have an impact on its long-term integrity and safety. It is worth pointing out that repository monitoring is comprised of a range of possible monitoring technologies (with a strong emphasis on wireless technologies), measuring different parameters, and supervising not only the surroundings of a repository, but also the very waste barriers themselves. As previous insights into these divergent forms of monitoring already have shown, there are no definitive answers to the questions of their desirability and some do still question the technical feasibility to monitor. Modern2020's predecessor, MoDeRn (2015), concluded that there is for example no full consensus on how to monitor the very waste itself and that '… how to do this without breaching safety barriers and thus risking a reduction in the overall level of post-closure safety is a question that as yet has not been fully answered' (Bergmans et al., 2012: 24). As this report will come to show eventually, the monitoring of the EBS is the most contentious type of monitoring in NWM.

Many of the uncertainties about repository monitoring still stand. Previous studies about NWM have suggested that the purposes of monitoring vary depending on whom you ask. While implementers, regulators and citizens appear to agree that monitoring may contribute to building confidence in the repository (Bergmans et al., 2014: 56), public stakeholders and experts stress different aspects of the very concept of monitoring. Citizens emphasize that it is necessary to 'check' if the repository behaves as expected, while technical experts frame monitoring as an act of 'performance confirmation'. In this regard, citizens and experts sometimes have differing outlooks on what monitoring is able to offer. While some citizens might call for extensive monitoring to 'be on the safe side', some experts might call for restraint and point out that monitoring is not always altogether positive; misreading of monitoring data, for instance, could lead to - potentially harmful - disproportionate countermeasures.

The unique time-frames to which NWM inevitably must relate also entail questions regarding the operational periods during which the repository should, or should not, be monitored. Should monitoring be performed only before final closure of the facilities? Should monitoring be performed also after closure? Repository monitoring also creates questions relating to repository governance. What kind of monitoring results should be used to make decisions about future repositories? Who should review the monitoring data? How much should a repository monitoring programme cost?

As explained above, in contemporary NWM, it is the type of monitoring that is ‘near-field’ or ‘in situ’ and which aims at evaluating long-term safety that renders the most questions. It is this type of monitoring that has been the object of (technical) research and development in MoDeRn and which is now being further developed in Modern2020. By emphasizing vigilance, these forms of repository monitoring in some regards challenge longstanding ideas of passive safety. Even if repository monitoring constitutes a rather specific branch of monitoring compared to the vast areas of monitoring applications we discussed earlier, it is by no means characterized by simplicity. On the contrary, repository monitoring is not a mere question of technical feasibility, but closely tied to matters of democracy and values such as decision-making, transparency and accountability. The question of costs for example is one which is often implicitly present in evaluations of technical feasibility and merits being subject to a broader socio-political evaluation. Understanding the complexity of repository monitoring and where it could fit into the overall monitoring programme for a deep GD facility is crucial if the ambition is to strive for robust public participation. There can be no discussion and dialogue if the character of repository monitoring is not explicated, including the tensions it entails between the paradigms of passive safety and vigilant monitoring addressed earlier. Can these two paradigms be reconciled or do we need to choose between them?

1.3 Methods and Empirical Material

The data material that is analysed in this report is derived from a range of documents. Firstly, we analyse a questionnaire produced by WP2 early in the project, reporting on differences between the various NWMOs partaking in Modern2020. Furthermore, we analyse a range of legislative documents, government reports and scientific articles. In order to grasp each country’s preconditions for developing monitoring technology, a data set that reflects their diversity is needed. A broad range of documents such as the ones described above has therefore been deemed important in producing this report.

1.4 Structure

In this report, the country differences are described and dealt with in different respects. Firstly, in Chapter 2 we present a description of the importance of national contexts with regards to existing monitoring strategies in relation to GD of nuclear waste. We thereby focus on four countries, namely Belgium, Finland, France and Sweden. Even though a range of countries partake in Modern2020, the project clearly states that these four countries and their specific stakeholder settings are of extra analytical importance. In these four countries there is already an established link between local citizen stakeholders, Modern2020 and the local NWMO, hence our focus on them. The following questions are addressed in this chapter: How is the importance of monitoring assessed and taken care of in developing disposal concepts and the related 'safety case'? How could the differences between the nations be explained? What role do legislation, governance structures and technological trajectories play in this regard? As an important aim of this report is to focus on questions that we know are of interest to local citizen stakeholders in the communities where nuclear repositories are planned to be built, chapter two furthermore considers questions such as: Why monitor, and, if at all, how and when to monitor? Who should decide about monitoring? And why do nuclear nations assess monitoring differently? The ambition is to show similarities and differences between nations concerning GD. How important are these differences? Do we find any "essence" of monitoring strategies amidst all the differences? And what about an EU push for convergence, and best practice?

Secondly, in Chapter 3 we turn to the development of monitoring strategies and programmes in the area of carbon capture and storage. This technology is also about GD, and it is clearly conceived without the intention to retrieve. However, underground monitoring appears to play a more central role in the disposal concept and is furthermore explicitly called for in European legislation. Therefore we considered it worth the while to make the comparison with NWM.

Thirdly, and this will be carried out both in Chapters 2 and 3, we describe and discuss the formats of stakeholder involvement that could possibly be identified in the different national programmes for nuclear waste disposal and in carbon capture and storage. Finally, we draw some conclusions from the comparisons and turn back to the primary question of variations and a possible ground for developing a common monitoring strategy that could serve all programmes beyond identified differences.

2. Chapter 2 – Country Comparison

2.1 Background

This section addresses the differences between the countries partaking in Modern2020 and provides an insight into the work that has been done so far in the project. Just as in many other EU projects, a range of actors are involved (industry, technical expertise, social scientists, local citizen stakeholders etc.), representing a variety of countries. To accomplish a common view on the design of repository monitoring programmes means that the actors involved must overcome several potential challenges. One of these concerns the context in which the different actors operate. Modern2020, being a common arena for divergent NWM and actors, must regard the potential tension between the national and the supra-national. If the goal is a common understanding of either producing a generic monitoring programme, or at least providing a generic method for building multiple site-specific monitoring programmes, these potential tensions need highlighting.

Early work in the project consisted of mapping perceptions of monitoring among the participating NWMOs, i.e. taking a snapshot of the current status of monitoring in divergent contexts in order to identify already existing similarities and discrepancies. In a questionnaire, created by project partners, NWMOs from 10 countries answered questions regarding their national monitoring plans in relation to their already existing nuclear waste programmes. This material, produced within the project, was subsequently supplemented and analysed together with legislative documents, previous research, governmental bills etc. This inquiry provided important initial insights into the differences between the national contexts. For instance, we were reminded that legislative demands vary from country to country. While e.g. Finland is characterized by demands for EBS monitoring in legislation and regulator's guidelines, Swedish guidelines mention such monitoring only in negative terms, i.e. it can only be performed if not impairing passive safety. Furthermore, even if there are legislative demands in some of the countries, these demands vary in character. As such, it became apparent that the term monitoring was associated with both a range of activities, but also spatial and temporal aspects. Firstly, monitoring was shown to be associated with the supervision of the environment surrounding a future repository, as well as with supervision of repository material construction lines, with EBS, and 'social factors' such as public opinion. Thus, what the various project partners referred to when speaking of 'monitoring', was quite divergent and potentially confusing. The same pattern could be discerned with regard to matters of temporality; it was revealed that the complex timeframes in NWM rendered the notion of monitoring extra complex as different actors planned to carry out monitoring activities in different phases of the life span of a repository. Even if it was generally argued that monitoring is not needed after repository closure (circa 100 years after start of repository operation), there is still the view that monitoring, partly motivated by the respective national regulative framework, cannot be ruled out even after closure of the repository. A main conclusion that we can draw from these observations is that monitoring indeed is a complex notion. Very basic questions regarding the aims and purposes of monitoring repositories housing nuclear waste therefore remain: *What should be monitored? Why should we monitor? Can it be monitored? For how long should we monitor? Who is responsible for carrying out this monitoring? How are we to communicate the monitoring data? How can knowledge produced by monitoring equipment be used in the governance of repositories?* The need to study these aspects is reinforced by a recorded desire among local citizen stakeholders. First contacts with local citizen stakeholders in the context of Modern2020 showed that they sometimes perceive the discussions about monitoring in Modern2020 as unclear and at times confusing. Thus, it has been jointly agreed that a structured gathering of data illuminating the national contexts would potentially help in clarifying basic questions about monitoring and reveal differences between the various countries participating in the project. This, it is hoped, will aid in producing a clearer image of the possibilities and obstacles that Modern2020 may face in the time to come, as well as situating the local citizen stakeholders in relation to their respective contexts and local decision making structures. In turn, this would potentially facilitate further public engagement, both within the context of the Modern2020 project, as beyond.

In sum, monitoring is by no means a single universal tool or a panacea for the uncertainties of NWM, and as such, it entails a flora of questions that need answering. Currently, monitoring in NWM presents us with a range of challenges that cannot easily be overcome. Addressing all potential aspects of monitoring nevertheless opens for great complexity. This complexity we have briefly accounted for, and will now address more specifically throughout this chapter. There is a need for this, since the various monitoring activities in NWM are not so easily delineated and at times rather confusing, even for the more knowledgeable.

2.2 Structure

This chapter is structured as follows. Firstly (see section 2.3), we will provide a brief account of how the case of monitoring in Modern2020 can be conceptualized using basic concepts from the social sciences. Here, we explain in a concise manner how the chapter utilizes standard theoretical concepts such as ‘trajectories’ and ‘technological lock-ins’. Secondly, we argue that nuclear waste programmes are embedded in society. Here, we briefly account for the relevance of the history of NWM, the division of labour between implementer and auditor and many more aspects that differ between local NWM contexts. Thirdly, we account for the four countries of Sweden (section 2.4), Finland (section 2.5), Belgium (section 2.6) and France (section 2.7) individually. We first provide a brief historical outlook on each country and then proceed to account for legislative demands for monitoring. We also analyse how the different

NWMO's frame monitoring and how they intend to deploy it or not. Fifthly and finally (see section 2.8), we bring the accounts together in a discussion and conclusion about the main differences and similarities and elaborate on what we can learn from our observations.

2.2.1 Analysing Nuclear Waste Management and Repository Monitoring

Science and Technology Studies (STS) is an interdisciplinary field, to which all WP5 researchers adhere and have experience from. Making science and technology study objects for the social sciences for decades, STS is now an established field which provides a significant body of knowledge and a wide range of theoretical and empirical research. For instance, STS provides many useful accounts of how technology takes shape with regard to the society in which it is being developed. As we will see, and as we already have described, the essence of context is essential also in NWM. This is also acknowledged by the very description of Modern2020. Making use of some of this knowledge is important in Modern2020, since the project strives to: "take into account the requirements of specific national contexts (including inventory, host rocks, repository concepts and regulations, all of which differ between Member States)" (Modern2020, 2016). A deeper understanding of the impacts and significance of such national contexts is possible by adopting the viewpoints of STS.

In its most basic sense, STS provides accounts for how society impacts on science and technology, but also how science and technology impacts on society. In NWM, it is important to recognize that it is an area with longstanding concerns and rich history. Monitoring technology in Modern2020 is thus being developed with regard to many aspects that we will identify in this report. As the technical research and development in Modern2020 is focused on repository monitoring, the focus of this chapter will also be on this particular type of monitoring. Unless explicitly indicated, the term monitoring can as of here be read as referring specifically to repository monitoring.

Since a substantial portion of the work in WP5 is related to facilitating local citizen stakeholder participation, insights from the field of STS are crucial in understanding both possibilities and obstacles for enabling cooperation between laypeople and experts, between policy-makers and technicians. Before we analyse each country individually there is therefore a need to briefly account for how we will commence our analysis, from an STS point of view. Seeing the different nuclear waste programmes as embedded in wider society indeed entails a need to identify more specifically what constitutes this wider society.

Firstly, monitoring strategies in each of the countries will vary with regard to how close the countries are to implementing a NWM programme. This is important since a substantial amount of decisions may have already been taken that potentially restrict the possibilities for implementing repository monitoring technology to a significant degree. For instance, choice of disposal technology and siting processes are in some cases already considered completed tasks. This conditions the degree to which monitoring may or may not play a central role in the waste management programmes, which in turn is likely to affect local citizen stakeholders' opportunities to influence monitoring development. Secondly, it is of importance to understand the specific political contexts surrounding the respective nuclear waste programmes. For instance, are there plans for nuclear new-build? New, or the continuation of, nuclear power programmes will of course have an impact on the waste programmes and will produce additional uncertainty about the amounts of waste to be handled etc. Furthermore, other political factors such as local opposition and attempts at siting repositories will also have an impact on the programmes, and by extension on demands regarding monitoring. A government approval for siting a repository signals that implementation of a certain NWM programme is closer than if there is not. Thirdly, the legislation that the different NWM programmes relate to is of great importance. This is of course an aspect related to the politics of nuclear power and waste we mentioned earlier, but the legislation will also provide central insights into what the programmes are supposed to do. Even if they all rely on GD and passive safety, they do so to slightly different degrees. Legislators in different countries for example have different positions regarding issues such as reversibility, monitoring or surveillance; but also regarding how the waste management programme is reviewed. Since different legislative demands influence the very constitution of nuclear waste programmes, they will inevitably influence monitoring. Fourthly, it is of great importance to research how the individual NWMOs relate to their own context, how they interpret their own role in developing monitoring technology and what plans are already in place for developing monitoring technology, or not. To summarize; it is important to acknowledge the historical contingency of the aforementioned aspects of NWM. All countries that are analysed in this chapter are characterized by complex historical processes, which have shaped the constitution of their waste management concepts and nuclear (waste) policy. Thus, accounting for at least some main milestones in the respective NWM context is central for understanding the point at which we are today.

In this report, we will also refer to the phenomenon of 'technological lock-in' and 'technological path dependency'. These two concepts refer to technologies which are well established in society, but not necessarily through being technologically superior to other technologies (see e.g. Arthur, 1989). The main point of adopting this approach is acknowledging that technologies are intertwined with, and embedded in, society. When analysing a widespread technology, we therefore must not assume that it is widespread on account of its superiority. On the contrary, we must acknowledge the historical and societal aspects that have generated the lock-in. In order to do so, we must turn to areas outside of the technological specifics and study for instance political history through which the technology has emerged. Famous examples of technological lock-ins are for instance the “Betamax and VHS war” and the QWERTY keyboard. In the early days of home video’s systems, the two technologies of Betamax and VHS set out to conquer the market. Eventually, the VHS format prevailed whereas the Betamax format was defeated. This was achieved although Betamax was generally considered a rather superior technology. Likewise, the QWERTY keyboard is used almost exclusively in computers worldwide despite the fact that other concepts are evidently more effective and substantially faster. The concepts of technological lock-in and path dependency therefore makes us aware of, first, that technologies that have prevailed are not necessarily the ‘best’ ones and, second, that technologies are not easily replaced once they have gained a foothold. These concepts will be utilised in the following analysis of monitoring strategies in the four countries.

2.3 Sweden – Introduction

Sweden has long enjoyed the reputation of being a NWM pioneer state, being relatively far ahead on the road to real-life repository construction. The Swedish concept of Nuclear Fuel Safety (KBS-3) has been considered a role model technology for other countries (Elam and Sundqvist, 2011). Not least to Finland (Kojo and Oksa, 2014), where the KBS-3 technology appears soon to be realized in the municipality of Eurajoki. KBS-3 builds largely on the idea of passive safety; the nuclear waste is to be encapsulated in copper canisters surrounded by bentonite clay, buried deep in crystalline bedrock once and for all, avoiding the need for monitoring and surveillance to the extent possible. An application for building a deep GD facility in the municipality of Östhammar for final disposal of the waste was submitted in 2011 by the Swedish Nuclear Fuel and Waste Management Co (SKB). The application has been reviewed by the Swedish Radiation Safety Authority (SSM) and the Land and Environment Court. While SSM has approved of the application, the Land and Environmental Court has expressed that scientific uncertainties surrounding potential corrosion of the copper canisters raise issues with regard to safety. The Court could therefore not approve of the application in its current state, but has asked for more research from SKB which more elaborately analyses the long-term impacts of corrosion on repository safety. In order for the disposal facility to be finally approved, both governmental and municipal approval is required. KBS-3 is currently the only waste management solution on the table, and other technologies for waste management are largely considered redundant. Due to the inconsistency of the evaluations made by SSM and the Land and Environmental Court, a Governmental evaluation is still pending and it is in currently unknown when a Governmental response can be expected.

2.3.1 History and Context

The division of labour between implementer, regulator/auditor, and NWMO in Sweden is important for understanding the prerequisites for how nuclear waste is being managed. The delegation of responsibilities is stipulated by the Swedish Act on Nuclear Activities (SFS, 1984:3):

> 10 § Those authorized to engage in nuclear technological operations shall answer for that necessary action is taken in order to safely handle and finally dispose of the waste, generated as a result of the nuclear operations, or therefrom generated nuclear fuel which is not to be re-used… and all nuclear substances and nuclear waste are placed in a repository which is finally sealed… (translation by the authors)

In the 1970's, the legislative demand for nuclear enterprise responsibility for NWM, and the principle of 'polluter pays', led to the founding of SKB – a subsidiary to the entire Swedish nuclear industry operating with the purpose of fulfilling the requirements of Swedish legislation, striving for 'safety' and final storage of nuclear waste (Elam and Sundqvist, 2006: 14). Sometimes depicted as clear-cut and desirable, the Swedish model with a seemingly distinct division between implementer and auditor is sometimes highlighted as a key factor to the Swedish successful concept; the 'polluter pays' principle and the demand for nuclear industry responsibility for research and development (R&D) in combination with recurring authority audit is central (Sundqvist, 2002). In Sweden, a large amount of the tasks related to NWM is delegated to the nuclear industry and significant faith put in the ability of SKB to conduct independent research, develop state of the art technology, and bring solutions for final disposal of the waste to the table. The Swedish principle of 'polluter pays' is indeed important, but the duties of SKB and nuclear enterprise stretch beyond mere financial responsibilities. In Sweden, we may also speak of 'polluter develops' and 'polluter decides and implements'.

Final disposal of spent nuclear fuel has been planned for decades in Sweden. The KBS-3 technology for GD of such fuel has been the long withstanding concept on which the Swedish legislative demand for safety has relied. The call for 'absolute safety' of the final disposal of spent nuclear fuel was first used in the Swedish Nuclear Stipulation Act in 1977 (SFS, 1977:140). Nuclear power was at the time a highly politicized topic and the concept of 'absolute safety' was initially formulated by the 1976 bourgeois government. This coalition government – led by the Centre Party famous for its anti-nuclear power stance – was characterized by its disagreement regarding energy policy. The legislative demand meant to the Centre Party that nuclear new-build was off the table given the impossible task for nuclear power enterprise to guarantee 'absolute safety' before being allowed to commission additional nuclear reactors. Nevertheless, the Centre Party's fellow government parties disagreed and did not interpret 'absolute safety' as unattainable (Anshelm, 2006: 67). Subsequently, the issue led to governmental breakdown due to impassable controversy. To the other government parties, the demands for 'absolute safety' were interpreted as indeed tough to meat, but by no means impossible. In light of this development, the commissioning of nuclear power was once again deemed feasible in the light of the technology of KBS-3 which was considered the solution delivering the contestable 'absolute safety'. With the passing of the law, the issue of nuclear power and nuclear waste shifted from being a broad political issue to being more of a question of law and scientific evidence (Anshelm, 2000: 192). The Swedish Nuclear Stipulation Act was subsequently overthrown in 1984 and replaced by the more toned down Swedish Act on Nuclear Activities (SFS, 1984:3) where the word 'absolute' was omitted and replaced by requirements to 'safely handle and dispose of the radioactive waste'. Thanks to the strong legal requirements, Sweden became quickly world leading in NWM.

Passive safety has been essential in the Swedish case and KBS-3 relies heavily on the notion that the need for supervision, surveillance or monitoring should be avoided to the extent possible. Instead, risks and uncertainties should be calculated beforehand in order to pre-empt any unwanted circumstances. The principle of passive safety is imprinted in Swedish legislation which requires that the integrity of a future repository should rely on a system of passive barriers (SSMFS, 2008). Furthermore, the KBS-3 concept relies on the notion that all nuclear power plants will be decommissioned in due time. Due to the unclear future of nuclear power in Sweden which can be exemplified with the fact that plant closure and decommissioning has been postponed multiple times already, it is a difficult task to calculate the final amount of waste to be stored deep in bedrock. However, the KBS-3 concept is represented as being flexible with regard to such uncertainties, thereby claiming to cover the (unexpected) future needs for the Swedish nuclear programme.

The history of Swedish nuclear activity has, despite the advanced stages of KBS-3 implementation, been lined with additional controversy. SKB, which carried out test drillings in the 1980's in the quest for a suitable site for construction of a repository, encountered local opposition and was as a consequence forced to reconsider its repository siting strategy. The opposition was broad in the sense that a range of municipalities opposed any siting of nuclear waste repositories. The most notable opposition in the 1980's is perhaps Rädda Kynnefjäll (Save Kynnefjäll), where a local opposition group physically obstructed test drilling performed by the industry in order to find a suitable site for a repository (Anshelm, 2006: 103). When siting experiments were positioned elsewhere, opposition emerged also there. In the early 1990's, SKB was forced to deploy a new approach, and to develop so called 'feasibility studies' where municipalities were invited to volunteer for being candidates for the siting of a final repository (see e.g. Sundqvist, 2002; Bergmans et al., 2015). Few volunteered, but ultimately

Forsmark in the municipality of Östhammar became the designated site for final disposal of spent nuclear fuel. To this date, the SKB application for constructing a repository, submitted to SSM and the Land and Environmental Court in 2011, regards the KBS-3 concept and the location of Forsmark in the municipality of Östhammar.

Controversy has also taken place with regard to the technological properties of KBS-3, of for instance copper and bedrock. Whether copper corrodes in oxygen free water has been the major area for controversy. SKB has vouched for the non-corrosive nature of the copper while scientists at the Royal Institute of Technology (KTH) continuously have claimed the opposite, namely that copper does corrode in oxygen free water. Placing the copper canisters deep in crystalline bedrock, as intended by SKB, is safe in their eyes, while other scientists claim the opposite; the copper will start leaking radioactive substances within ‘only’ 1000 years. In June, 2016, and later in January 2018, SSM however chose to regard the SKB view as the most viable, thereby accepting the claim that copper does not corrode in oxygen free water. This prompted the KTH scientists to accuse Swedish authorities of severe professional misconduct. The controversy over copper corrosion has proven to be enduring. While SSM has approved of KBS-3, the Land and Environmental Court ruled in 2018 that it will not unless more scientific evidence can underpin the claims of copper’s non-corrosive nature. To date, the uncertainties surrounding the long-term safety of the copper canisters have proven to be an important factor in Swedish nuclear waste governance. The Land and Environmental Court’s decision to not accept SKB’s application stresses that uncertainties still remain. How these uncertainties will be governed in the future is still too early to tell, but it cannot be ruled out that monitoring of the EBS may be used as a tool for continuously observing the corrosive evolution of the canisters once emplaced in underground in the repository.

2.3.2 Monitoring in Legislation

An important feature of Swedish legislation is the absence of demands for EBS monitoring, and monitoring after closure of the repository. The guidelines of the Swedish Radiation Safety Authority heavily emphasize passive safety, while monitoring may be adopted if it improves passive safety but does not impair it (SSMFS, 2008:21). As passive safety for long has been the lodestar in Swedish NWM, EBS monitoring has been actively evaded and the current application submitted by SKB is concerned with the implementation of a passively safe GD facility not dependent upon monitoring. SKB’s development of KBS-3 largely relies on a priori safety assessments. Swedish authorities appear to have largely accepted the view that EBS monitoring is unnecessary in the face of KBS-3. As we will see, Sweden is a somewhat unique example since other countries are obliged to engage in some form of EBS monitoring of the future repositories housing nuclear waste.

2.3.3 SKB's Framing of Monitoring

So, the legislative demand for passive safety and the subsequent KBS-3 technology has explicitly, for decades, strived towards evading EBS monitoring. Even if SKB is not in principle against EBS monitoring, it is still argued that extensive monitoring of, for instance, the copper canisters themselves is in some instances associated with risk and potentially technologically unfeasible:

> Nuclear fuel repository safety rests on passive systems and the ability to make robust and scientifically well-founded assumptions about the processes affecting the different materials and components included in the barrier. Introducing surveillance equipment in a barrier means thus always a potential safety impact. (SKB, 2015: 8)

The demarcation between different kinds of monitoring is not necessarily clear-cut. One first remark is that SKB explicitly makes a distinction between the concept of monitoring and 'quality control'. This in an important distinction, since SKB appears to argue that necessary monitoring and control already is included, or aims at being included, in their already existing KBS-3 quality control programme. Some aspects of in situ and near-field monitoring are rendered superfluous in this logic. In short, quality control refers to "...the measures that need to be taken to provide assurance that the requirements made on the facilities during operation and after closure of the Spent Fuel Repository are satisfied. The goal is that the results obtained should conform to acceptable values for properties that contribute to safety and radiation protection." (SKB, 2013: 148). In other words, quality control serves the purpose of establishing safety *a priori* and during waste emplacement in order to secure post-closure safety.

With reference to the quality control, SKB argues not only that monitoring in many cases is unnecessary but in some cases, monitoring is even framed as a threat in itself, increasing risk instead of decreasing it. The threat, according to SKB, is mainly constituted by EBS monitoring, specifically. EBS monitoring technology, it is argued, might produce inaccurate signals which in turn might lead to misinformed decision-making:

> Inaccurate signals could, in the worst case, lead to unjustified decisions about various measures, such as to retrieve the canisters, which would be associated with high costs, and radiological hazards for workers involved in the process. (SKB, 2015: 9)

In addition to the argument that monitoring technology may jeopardize the integrity of the barrier system of KBS-3, SKB also emphasizes the risks of the malfunctioning of monitoring technology and the unfortunate turn of events such misreading could lead to. From the viewpoint of SKB, repository monitoring (other than that included in the quality control programme) therefore appears to have a possible twofold downside. The first being the danger of physical intrusion in the barrier system, the second being the danger of inaccurate and misleading monitoring data readings, which could have devastating consequences not just for the repository itself, but for personnel and for decision-making

Time aspects of monitoring are of course important in relation to the unforeseeably long periods of time during which the radioactivity of the waste deteriorates. In very rough terms, the existence of the repository is divided into two overarching periods: the period prior to closure, and the period after. In Sweden, the programme for governing the repository has developed since the 1970-s. Passive safety is indeed KBS-3's main function and as such, monitoring is not planned to play an important role, particularly not after repository closure. A recurring SKB argument is also many of all necessary safety measures are taken in their quality control programme. Whereas EBS monitoring is predominantly rejected by SKB, it should be noted that SKB occasionally states that monitoring may 'add confidence' in KBS-3's safety case (SKB, 2015: 24) and that "monitoring is important to handle the 'unknown unknowns'".

In sum, SKB offers a special outlook on monitoring and it is important to note that this outlook is broadly based on a differentiation between both different kinds of monitoring and the concept of quality control. SKB argues that most work relating to ensuring safety of the repository must take place *prior to* waste emplacement in order to accomplish passive post-closure safety. This safety is guaranteed through the quality control programme, it is argued, ensuring that a range of quality standards demanded by legislation and authority regulations are met. Bedrock conditions, welding quality of the copper canisters, drilling technologies, waste emplacement procedures are just a few examples of what constitutes this quality control programme. Certain types of monitoring do play a part in the quality programme and SKB's already undertaken work. Environmental monitoring, for instance, is an activity SKB has engaged in for quite some time. Nevertheless, as the strife for passive safety is emphasized in Sweden, repository monitoring in the way this concept is described and discussed in Modern2020, and as means for providing additional safety, is largely redundant in the words of SKB. It appears reasonable to conclude that SKB's arguments against repository monitoring regards primarily EBS monitoring, because this is considered potentially harmful to the a priori safety provided by the quality control programme. Hence, any monitoring that is deemed as interfering with passive safety will be dismissed with reference to the quality control programme.

2.4 Finland – Introduction

In the municipality of Eurajoki lies the nuclear power plant of Olkiluoto, which has been producing commercial nuclear power since 1979. In close vicinity of the power plant lies ONKALO – test site and laboratory for NWM research where experiments have been conducted since 2004 (Posiva, 2017). In 2016 the construction of a repository for nuclear waste was also started at the site, which currently has changed from an underground rock laboratory into a construction site of two new nuclear facilities: in addition to the underground repository also an encapsulation plant (ibid.). This is a contrast to, for example, Sweden where the hard rock laboratory in Äspö, close to the Oskarshamn reactor site, is an extensively excavated laboratory, but a laboratory that will not serve as a final repository. The final repository in Sweden is instead planned to be located much further north, in the bedrock of Forsmark. This makes the road to final disposal of nuclear waste (at least for a good part of that waste) relatively short for Finland since a substantial building effort has already been achieved.

Finland already disposes of its low-level and intermediate-level waste in the repository of Olkiluoto which has been operational since 1992 (STUK, 2016), as well as in the repository of Loviisa, operational since 1998. The waste disposal concept builds on burying the waste in the bedrock, at a depth of about 60-95 meters in Olkiluoto and about 110 meters in Loviisa. On the road towards deep geological repository construction for nuclear waste, Finland has come furthest. After submitting an application in 2008 for building the repository in the municipality of Eurajoki, Finnish authorities eventually responded positively. Due to the recommendations of the Finnish Nuclear Safety Authority (STUK), in November 2015 the government subsequently authorized the start of repository construction. The construction of nuclear facilities started in 2016 and in the early 2020-s, disposing of nuclear waste will commence at the ONKALO site. Finland is thereby one of the frontrunners in the race for starting GD. The Olkiluoto nuclear waste repository is expected to be closed sometime around the year 2120.

2.4.1 History and Context

Posiva, founded in 1995, is a rather small company owned by Fortum and Teollisuuden Voima Oyj (two large electricity providers in Finland). The nuclear companies are responsible for the waste while in interim storage. When the waste is transferred from storage to ONKALO, Posiva takes over the responsibilities of caring for it. During the ‘operational phase’, Posiva will gradually dispose of the waste until repository closure. According to current plans, after closure the state will take over all responsibilities over the repository, and Posiva will be relieved of its duties at the site.

STUK, founded in 1958, is the agency responsible for auditing nuclear waste issues. Since Posiva is responsible for developing and providing solutions to the waste problem, STUK has the function of overseeing this process. As previously mentioned, STUK has already approved the Finnish concept for waste disposal but will continue to audit also the remainder of the disposal process.

The Finnish disposal concept shares central properties with the Swedish. SKB has been working in close collaboration with Posiva, and the latter has widely embraced the Swedish GD concept – KBS-3 – as the main technology for waste disposal (Kojo and Oksa, 2014). Other solutions for handling the waste, such as deep boreholes or surveyed surface storage are not considered. Posiva has decided to utilize the KBS-3V-methodology, where the canisters will be emplaced in vertical holes bored from the tunnel floor. The spent nuclear fuel will be buried deep in crystalline bedrock, approximately 420-460 meters below the surface, emplaced in copper canisters surrounded by bentonite clay, all according to the KBS-3 concept. Surrounded by these engineered as well as geological barriers, the waste will be left untouched for more than 100 000 years until the level of radioactivity in the waste has reached the level of ambient background radiation. Passive safety is thereby the beacon also for Finland.

Finland is characterized by a low intensity of public discussion regarding the issue of nuclear waste disposal (Aufferman et al., 2015). Political debate over nuclear new-build is, however, more intense as power plants currently under construction have faced the obstacles of exceeding budgets and withdrawal of key investors. The consensus-driven character of Finnish politics applies also to the area of NWM which is sometimes portrayed as an arena of technocracy where few key actors drive the development of GD (Aufferman et al., 2015: 244).

In terms of formal legislative demands, Finland has decided that all waste accumulated in the country is the responsibility of those who have benefited from it. Hence, waste cannot be shipped across borders, but is regarded as a domestic issue. Finnish NWM is otherwise governed mainly by three types of legislative documents. The Government Decree 736/2008 – On the safety of disposal of nuclear waste (Ministry of Employment and the Economy, 736/2008), the Nuclear Energy Act (Ministry of Trade and Industry, 990/1987) and Regulatory Guidelines of Nuclear Safety (YVL guidelines) from STUK (2013). A central aspect and similarity with for instance Belgium and France, but in contrast to Sweden, is the legislative demand for repository monitoring, and more specifically EBS monitoring. To this we will soon return. However, similar to Sweden, Finnish legislation initially states that there can be no surveillance which impairs *long-term* safety, thereby putting an emphasis on 'passive safety':

> The disposal of nuclear waste in a manner intended as permanent shall be planned giving priority to safety and so that ensuring long-term safety does not require the surveillance of the final disposal site. (Nuclear Energy Act, Section 7h)

In Finnish NWM there is uncertainty in relation to the continued operation of nuclear power but also to nuclear new-build. It is required that a solution for the NWM has to be presented when applying to construct a new nuclear power plant. In addition to Posiva and the Olkiluoto site an additional nuclear power company, Fennovoima Oy, has started an environmental impact assessment procedure for selecting a site for its own nuclear waste repository, in order to fulfil the requirement which can enable them to construct their power plant which is currently in the process of applying for construction licence. Thus, there may be more than one nuclear waste repository site in Finland in the future.

2.4.2 Monitoring in Legislation

During the time in which the repository remains operational and the process of waste disposal is still on-going (up to 100 years), there are, as it seems, somewhat more concrete demands for monitoring. STUK has been delegated the task of defining the purpose and overarching constitution of such a repository monitoring programme, which is stipulated in the Government Decree (Ministry of Employment and the Economy, 736/2008). STUK is performing this task by establishing Regulatory Guides on nuclear safety (so-called YVL guidelines). For instance, in guideline D.5 § 506, (STUK, 2013), STUK establishes, among other things, that Posiva shall ‘monitor the performance of the engineered barriers’:

> **506.** During the construction and operation of the disposal facility, a research, testing and monitoring programme shall be executed to ensure that the site and the rock to be excavated are suitable for disposal and to collect supplementary information the safety-relevant characteristics of the host rock and the performance of the barriers. This programme shall at least include:

a. the characterisation of the rock volumes intended to be excavated;
b. the monitoring of rock stresses, movements and deformations in rock surrounding the emplacement rooms;
c. the hydrogeological monitoring of the host rock surrounding the emplacement rooms;
d. the monitoring of groundwater chemistry; and
e. the monitoring of the performance of engineered barriers.

Exactly what “monitoring the performance of the engineered barriers” entails is not specified in more detail, but the demands should be noted since they divert from some other countries’ legislative situation, most notably from Sweden’s, although the same technological concept is adopted in both countries. It also seems reasonable to assume that legislative demands such as these leave room for interpretation, not least by the NWMO subject to them. In light of this, it is of interest to study how the NWMO, in this case Posiva, interprets these demands.

2.4.3 Posiva's Framing of Monitoring

Posiva is expected to produce certain monitoring tasks upon the emplacement of waste in ONKALO. As mentioned above, STUK requires some specific areas to be monitored. Firstly, the purpose of monitoring is not necessarily encircled by consensus. Posiva argues that monitoring does not increase safety per se:

> But it has to be understood that monitoring will not bring us more safety, it just gives us more confidence on that safety level which we have gained with Safety Case work. Monitoring can be used also as a communication tool, to show that everything goes as expected. (Posiva, 2015: 19)

Possibly, there is discrepancy between how STUK and Posiva regard monitoring as a means for enhancing safety. STUK appears to be more vigilant, arguing that long-term safety indeed can be increased by monitoring:

> The planning of the construction, operation and closure of a disposal facility shall take into account the reduction of the activity of nuclear waste through interim storage, the utilisation of high-quality technology and scientific data, and the need to ensure long-term safety via investigations and monitoring. (STUK, 2013: § 401)

As we have seen in the Swedish case, EBS monitoring is often framed as a risk in itself as it might affect the integrity of the barriers. Monitoring, although often suggested to enhance safety, can on the contrary jeopardize safety in this line of reasoning. This argument has also been used in the Finnish case. In response to the Modern2020 questionnaire, Posiva expressed the view that there is no technology that can be adopted which does not impair the safety of the barriers:

> We don't have reliable monitoring technology, which we could use without endangering long term safety... (Posiva, 2015: 17)

It is sometimes upheld that monitoring is nothing new. This is also the case in Finland and Posiva refers to longstanding monitoring of the environment and, for instance, hydrogeological factors. Pre-existing monitoring will proceed also in the foreseeable future. However, repository monitoring appears to be treated as something different. But firstly, Posiva tells of 'old' monitoring programmes:

> ONKALO facilities will be part of actual disposal facilities. Posiva has been running multidisciplinary (Rock Mechanics, Hydrology and Hydrogeology, Hydrogeochemistry, Surface

> Environment, Foreign Materials) monitoring programme during the construction of ONKALO. (Posiva, 2015: 6)

While monitoring is presented as an integral part of Posiva's concept, repository monitoring is something partly new. One important aspect of repository monitoring is monitoring of the EBS. To what extent it is desirable and feasible to monitor the EBS remains an open question:

> Based on needs the open disposal facilities will be monitored (host rock monitoring). A monitoring programme of Engineered Barrier System (EBS) is not yet planned in details, thus it is not even sure will there be any monitoring equipment in EBS. (Posiva, 2015: 7)

The perhaps most interesting tension here is the demand for monitoring the EBS as we saw earlier. As we have also repeatedly seen, SKB's argument against EBS monitoring is the threat it poses to passive safety (Lagerlöf and Liebenstund, 2016). From this perspective, any violation of the passive integrity of the repository constitutes a danger and monitoring becomes a potential risk. Posiva and Finland have embraced the Swedish concept of KBS-3. In the SKB logic, STUK's demands for EBS monitoring are problematic to meet. Nevertheless, Posiva argues that even though EBS monitoring perhaps cannot be performed directly, it is more likely to be performed indirectly:

> Conventional monitoring methods can be used in tests where is not real nuclear waste. In real disposal facilities safety cannot be endangered, thus monitoring has to be limited to places where is possible to use proven monitoring methods so that any safety function does not alter. (Posiva, 2015: 20)

In sum, Posiva shares central views on monitoring with SKB. The concept of monitoring is framed as only partly 'new'; in fact, Posiva has engaged in various monitoring exercises in the past. These exercises are ongoing and are comprised of monitoring activities ranging from environmental monitoring, to monitoring of, as Posiva (2015: 6) puts it: 'Rock Mechanics, Hydrology and Hydrogeology, Hydrogeochemistry, Surface Environment, Foreign Materials'. Such monitoring tasks are not viewed as problematic, but rather as something that will strengthen the safety case. EBS monitoring, on the other hand, constitutes more uncertain terrain. While STUK's guidelines state that Posiva shall monitor 'the performance of the engineered barriers', such a statement is not specific and it remains to be seen how Posiva will relate to this demand in practice. While Posiva, like SKB, appears reluctant to monitor the

EBS directly, representatives in Modern2020 from the Finnish NWMO indicate a recent shift towards developing 'indirect' EBS monitoring.[2]

2.5 France – Introduction

Also in France, GD is now the lodestar in the quest for the safe keeping of high-level and intermediate-level long-lived waste. '*Centre industriel de stockage géologique*' (Cigéo) is the name of the waste disposal facility currently being developed in order to take care of the waste[3], in order to meet the requirements of the French law. The host rock of Cigéo is Callovo-Oxfordian clay at 500 meters depth, which has a low permeability and a high retention capacity for radionuclides dissolved in water . Since 2000 and under recurring review by the nuclear safety authority (Autorité de Sûreté Nucléaire), Andra has conducted research activities on this specific clay host rock as well as technological development of Cigéo, in particular in its underground research laboratory (URL) sited in Meuse and Haute-Marne departments . Andra has defined a ZIRA (Zone d'Intérêt pour la Reconnaissance Approfondie/ Zone of Interest for Detailed Reconnaissance) in the context of a license application for Cigéo. Since 1991 and formalized by the 2016 Act, the 'reversibility' has become a centrepiece of the governance of Cigéo. As we will discuss in more detail below, the French notion of reversibility is focused on governance with retrievability of waste as one of the tools of the reversibility.

2.5.1 History and Context

Andra was established by the December 1991 Waste Act as an autonomous public body in charge of the long-term management of all French radioactive waste, under the supervision of the Ministry of Ecology, Energy, Sustainable Development and the Sea (formerly the Ministry of Industry and the Ministry of Environment), and the Ministry of Research.

By passing the 1991 Act on R&D for radioactive waste management, the French Parliament placed France's high-level waste (HLW) and long-lived waste (LLW) management policy on the path to seeking long-term safe solutions.

After 25 years of research, in particular at the URL, and a feasibility study produced by Andra in 2005, in 2006 the French Parliament (2006 Planning Act) gave Andra the task of designing and building a reversible deep geological disposal repository, as the reference solution to ensure the long-term safe disposal of high-level and intermediate-level long-lived waste. This

---

[2] Tuomas Pere, personal communication 17/03/2017

[3] The French waste inventory of Cigéo comprises at present 75.000 m^3 of long-lived intermediate-level waste (ILW) and 10 000 m^3 of high-level waste (HLW).

decision was supported by the argument that deep geological disposal limits the burden placed on future generations. Its reversibility ensures opportunities for options and development with regard to the decisions taken by our generation, including the ability for future generations to reconsider earlier choices if desired.

The newly passed law from July 2016 (n°2016-1015 du 25 juillet 2016) defines reversibility as giving future generations the ability to either continue the construction and operation of geological repository or to reassess previously made choices in the management of nuclear waste and to evolve new management solutions.

It also prescribes that Cigéo should be able to adapt to changes in the energy policy, regardless of whether that implies emplaced waste to be taken out (and being redefined as a resource) or the facility to be redesigned to take in new categories of waste. The HLW dedicated to go into Cigéo today is mainly waste generated through the reprocessing spent nuclear fuel. The spent MOX fuel is currently not being considered as a waste, but could potentially become so in future.

The 2016 Act provides essential details for the continuation of Cigéo, allowing Andra amongst other purposes, to prepare the disposal authorization to be submitted in 2019. Firstly, it validates the proposed project evolutions by Andra at the end of the public debate in 2013, in particular the establishment of an industrial pilot phase for for full-scale in-situ tests. Secondly, it stipulates governance dynamics of time with i) the inscription of a new parliamentary appointment after the pilot phase, and - at least every five years – ii) the update of the Cigéo Operations Master Plan (Plan Directeur pour l'Exploitation de Cigéo) in consultation with all stakeholders including public and iii) the review of of reversibility principles in consistency with safety case reviews.

The new law requires that the operation of a repository needs to start with a pilot phase, to consolidate reversibility and demonstrate the safety of the facility. During this pilot phase, all waste packages must remain easily recoverable. Hence, the French programme makes an explicit distinction between the notions of 'reversibility', which puts an emphasis on the governance and *flexibility* of the process and that of 'retrievability', which implies the technical ability to *recover* the waste[4]. Therefore, the law also stipulates that the pilot phase should include retrieval trials.

---

[4] In that same line of reasoning, the OECD's NEA defines reversibility as "the ability in principle to reverse decisions taken during the progressive implementation of a disposal system" and retrievability as "the ability in principle to recover waste or entire waste packages once they have been emplaced" (OECD-NEA 2011).

Like other countries that are in an advanced stage of developing their GD concepts, France aims for passive safety in the long term (after closure), since the reversibility requirement only applies to the operational period of the repository which constitutes some 100 years before the repository is to be closed. Different from countries proposing that future generations should ideally never think about the waste again, and perhaps even forget it, French reversibility builds on the notion that future generations should have a potential say in waste management issues. Or in the words of Andra (2016): The reversibility of disposal is considered to be the ability to leave the next generation options concerning the long-term management of radioactive waste.

In France, more than in the outer countries discussed in this report, political opposition haunted waste management concepts as environmental organizations and local publics continually questioned the feasibility of geologically disposing of the nuclear waste (Barthe et al., 2014). In the 1990's, opposition emerged rather rapidly and French NWM, previously conducting much of its research in secluded forums, was suddenly in the public's headlights (Barthe, 2009). In light of this development, in 1991, generally perceived to be an important year in French nuclear politics, the Bataille Law was launched. Reversibility was gradually established, initially requested by local actors and endorsed by the 2006 Act.

Currently, the concept of deep GD is still facing some public resistance. With both local resistance groups and national/international anti-nuclear groups opposing both nuclear power and questioning the safety of nuclear waste repositories, there is no knowing what the outcome of their opposition will be.

In order to streamline and enable public consultation and increase public acceptance in the future, the law from July 2016, as previously described, includes a paragraph requiring the waste manager to update every five years the repository's master plan in consultation with the public and other stakeholders.

2.5.2 Monitoring in Legislation

An important observation to be made is the explicit demand from the French Agency for Nuclear Safety (ASN) for establishing a “surveillance” programme (i.e. monitoring programme) (ASN, 2008). In their so-called ‘safety-guide’ (2008), ASN requires monitoring in the phase before operation (monitoring of the baseline conditions). During the operational phase, monitoring of the repository is required as well. Such monitoring is described as including systematic measurements in order to control the construction, the operational safety, to provide inputs for retrievability and to assess that the repository evolves in accordance with post-closure safety requirements and that the defined monitoring parameters remain in the limits as defined in the safety case (ASN, 2008). However, since the law states that GD safety should be achieved by fully passive means, Andra (2015) does not expect additional legal requirement for long-term repository monitoring.

2.5.3 Andra's Framing of Monitoring

As we have seen, Andra is required to perform monitoring during the repository operational period until it is finally closed (as all nuclear facilities). For Andra, monitoring ("Surveillance") refers to making sure that that the GD repository evolves as expected and that post-closure safety is ensured. In addition to required monitoring (Surveillance) programme, Andra could develop a programme for "Observation" (not requested by the Regulator) in order notably to contribute to consolidate knowledge of processes occurring in the repository, leading to possible future optimation of the repository concept in a modular implementation approach.

The ambition to construct a reversible repository has some connection with monitoring. Yet this relation between monitoring and monitoring for retrievability is not a one-on-one relationship. According to Andra, even when there was no requirement for retrievability, in any case there would have been monitoring in the operational phase. Therefore, a range of monitoring requirements related to potential retrievability are covered by operational safety requirements and by post-closure safety requirements.

As such, there is different interpretation regarding the notional spectrum of terms like 'surveillance', 'observation', 'reversibility' and 'retrievability'. They clearly still mean different things to different actors in the field (NWMOs from different countries, public, etc.).

Contrarily to monitoring during the operational phase, there has been a debate about the necessity of monitoring for part of the post closure phase. This relates of being able from surface to obtain any significant measurements given that the law states that GD safety is achieved by fully passive means.

Potential post-closure monitoring devices will be limited and will not interfere with repository works or Callovo-Oxfordian host rock to ensure the maintenance of passive safety. Both during and beyond these phases, Andra will also be conducting environmental monitoring; the basis for this type of monitoring is already in place today in the area around the underground research laboratory (Observatoire pérenne de l'environnement) (Andra, 2016).

2.6 Belgium – Introduction

Belgium has not gone as far down the waste disposal road as Sweden, Finland and France. While Belgium has quite an advanced programme for low- and intermediate-level nuclear waste, there is no formal policy decision regarding the adoption of any specific method for disposing of the country’s high-level, long-lived waste (Schröder et al., 2015). Nevertheless, there is a long tradition of research into GD and Belgium hosts one of the oldest underground research laboratories (URL) in the world - HADES, constructed in 1980. As a consequence, research is specific to (Boom) clay as a host rock. HADES is nevertheless a generic URL, and the Belgian national programme (ONDRAF-NIRAS’s Waste Plan) also remains at a generic level and is not site-specific. More recently, in 2014 the EC’s nuclear waste directive 2011/70/EURATOM (European Council, 2011) was transposed into Belgian law.[5] The directive as such does not name GD as the obligatory end stage of NWM, but can be interpreted as such, since in its introductory part, explicit reference is made to GD as the ‘safest and most sustainable option’ for the management of high level waste and spent nuclear fuel. This implicit recognition of GD is also echoed in the Belgian law of 03/06/2014.

2.6.1 History and Context

ONDRAF-NIRAS, the Belgian NWMO founded in 1981, is responsible for both the short and long-term management of all nuclear waste in Belgium. It is a public agency, subordinated to the Federal Minister of Energy and Economy. However, ONDRAF-NIRAS is not publicly funded, but based on the polluter-pays-principle receives contributions from the private entities producing the waste, including the Belgian State where all legacy waste (e.g. from past research activity) is concerned (Schröder and Bergmans, 2012). In 2011, ONDRAF-NIRAS developed a national ‘Waste Plan’ that serves as a strategy document to move towards GD in one collective facility for the so called category B&C waste, which comprises today of long lived intermediate level waste (ILW) and high level waste (HLW). The ILW comes mainly from (past) R&D activity, dismantling activities, production of nuclear fuel and reprocessing of spent fuel, while the HLW consists today only of vitrified waste, originating from the reprocessing of spent fuel. However, as there exists a moratorium on reprocessing since 1993, the spent fuel from the Belgian nuclear reactors as of that date constitutes a category that is somewhat ‘in limbo’. Legally, it is not considered as waste and at the present day it is still owned and taken care of by the electricity producers. Nevertheless ONDRAF-NIRAS has been obliged by law since 2003[6] to take into account the possibility of having to manage and dispose of spent fuel as an

---

[5] Law of June 3, 2014 regarding ... the transposition of into internal law of Council Directive 2011/70/Euratom of July 19, 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste (Moniteur Belge 27/06/2014).

[6] Law of April 11, 2003 regarding the provisions for the decommissioning of the nuclear power plants and the management of spent fuel (Moniteur Belge 15/04/2003).

additional waste category. Another important public actor is AFCN-FANC, the Belgian regulator, responsible for granting the license, supervising the work of ONDRAF-NIRAS related to safety issues, while the government and the parliament develop the legal framework.

The Belgian legislator follows the international standard in aiming for passive safety, although there is no explicit decision to reach this through GD. Art.4 of the Belgian Law 03/06/14 does state that:

> HLW and spent fuel have to be managed safely in such a way that the long-term safety of a disposal facility is provided among others by safety measurements that are able to evolve over the long term to a situation of passive safety. (Translation by the authors).

In Belgium, the political organization is an important factor influencing the management of nuclear waste. Consisting of three regions, the Flemish, Walloon and Brussels Capital Region, there is potential conflict between regional and national policies. For instance, nuclear technology and development is governed at a national level, while environmental legislation and other related, intersecting policy domains are governed at a regional level (Schröder et al., 2015: 147). So far this has not led to any clashes between authorities, but a different ruling regarding the environmental impact assessment for nuclear and non-nuclear issues is thus possible. While environmental impact assessment is a competence that generally falls under the regional competences (the EU directives being transposed by regional legislation), in 2006 a specific federal EIA-law was developed to address the evaluation of plans and programmes of issues remaining a Federal competence, such as electricity production and supply, supply and transport of natural gas, the exploitation of the territorial seabed and the management of radioactive waste.[7] However, when such plans and programmes eventually lead to concrete projects (such as a nuclear waste disposal facility), the overall environmental impact assessment of that particular project will be the competence of the concerned region, whereas its radiological safety will be assessed by AFCN-FANC.

In Belgium, the siting process for a GD has not started yet. However, in terms of repository siting strategies, ONDRAF-NIRAS has deployed similar participatory approaches as Sweden for the siting of a low- and intermediate-level waste facility. In this case, 90 municipalities deemed as suitable for hosting such a facility, all refused to cooperate. ONDRAF-NIRAS resorted to a voluntary approach and successfully enrolled four municipalities in the siting process. Besides the lack of political commitment to GD and the subsequently lacking siting process, already in 2003 the Belgian programme for the disposal of long-lived and high-level waste was

---

[7] Law of February 3, 2006 on the assessment of the effects of certain plans and programmes on the environment and on the participation of the public in elaborating such plans and programmes (Moniteur Belge 10/03/2006).

evaluated as scientifically mature with regard to research on GD and “well developed and sufficiently advanced to address the siting issue” by an international review committee organized by the OECD’s NEA (NEA-OECD, 2003: 11). For this conclusion, the reviewers referred to both the level of technical experience and the information available, as to the attention paid to the stakeholder issue (Bergmans et al., 2006).

2.6.2 Monitoring in legislation

There is little statement neither in the Waste Plan, nor from the authorities on the specifics of monitoring, in terms of its design and purpose. The absence of political clarity with regard to a future repository impacts monitoring. A general statement that can be made is that Belgium appears to be more open towards monitoring than Sweden and Finland, despite the lack of formal legislation demanding it. However, the Law from 03/06/14 does specify:

> Reversibility, Retrievability and Monitoring are modalities that have to be considered in the design of a GD facility for a certain, still to be defined, period of time. However, these modalities have to take into account the necessity of not jeopardizing the safety of the facility (Translation by the authors).

These demands are not precise and open to interpretation. It becomes clear, even though the notions are not further specified, that ‘reversibility’ and ‘retrievability’ will be relevant aspects of the Belgian disposal concept. As a monitoring programme needs to be developed site-specifically in relation to an existing waste management concept, in the Belgian case it is currently difficult - or even impossible - to develop a detailed monitoring programme.

2.6.3 ONDRAF/NIRAS’ Framing of Monitoring

ONDRAF-NIRAS expects monitoring to become more important as the repository programme moves towards operation (ONDRAF-NIRAS, 2015: 10). Therefore, the development of a monitoring strategy is considered to:

> … evolve as the repository design concept and the regulations mature, and therefore, the strategy was designed with flexibility in mind (ONDRAF-NIRAS, 2015: 22-23)

It is still unclear what exactly is going to be monitored. Next to the physical and chemical indicators of repository behaviour and of its surroundings, the Belgian waste management agency assumes that social science indicators of public beliefs, concerns, and attitudes about the repository project might be monitored as well. It is assumed that the frequency of monitoring will be influenced by stakeholder requests. Especially regarding environmental monitoring, ONDRAF-NIRAS expects an intensification of demands to survey the repository area (ONDRAF-NIRAS, 2015: 5, 22-23).

With regard to repository monitoring more specifically, it can be deduced that ONDRAF-NIRAS anticipates that requirements will be set which are similar to the situation in France, that is to say, some underground monitoring to establish that the system behaves as expected and to assess the safety in case retrieval of a waste package would be considered:

> A distinction should be made between the retrievability during the operational phase including the construction of the repository and the institutional control period during which a retrieval of the waste is always possible for societal reasons. During the operational phase per se, the monitoring will play a role of performance confirmation and if the retrieval of a waste package is required it will be decided by the operator. During the institutional control period, retrieval might be required by the Government under the request of stakeholders. The decision will be then taken by the supervising authority. The environmental monitoring could be the trigger but more probably the retrieval will be the result of an independent societal decision. Such a latter decision would need a specific licence application (ONDRAF-NIRAS, 2015: 18)

The absence of formal decisions regarding a future repository for B&C waste and potentially spent fuel means that Belgium is further away from waste emplacement than the other countries accounted for in this report. Reviewing the words of ONDRAF-NIRAS, monitoring appears to play a greater role than is the case in Sweden and Finland. The technological lock-in represented by KBS-3 makes repository monitoring, and more specifically EBS monitoring, much harder to incorporate, whereas Belgium has a disposal concept which is still being refined and thus more open for monitoring. As the notions ‘reversibility’ and ‘retrivability’ are included in legislation as relevant aspects of the Belgian disposal concept, it is to be expected that a Belgian monitoring programme will relate to these requirements. However, it is not very likely that this will be specified more in detail before a specific site has been chosen.

2.7 Conclusions and Summary

This chapter has shown the impact of context on plans for repository monitoring in the four countries of Sweden, Finland, France and Belgium. With context, we understand the diversity in disposal technology (e.g. technical concept and host rock), in each programme’s progression towards implementation, in political context and in relation to legislative demands.

We thus observed very different historical processes that have shaped the different waste management concepts. Whereas Sweden was guided early on by legislative demands for ‘absolute safety’ and ‘final disposal’, and the second still essential in the Swedish case, France developed the contrasting principle of reversibility in light of political controversy over the nuclear waste issue. In Finland, the repository implementation process has been characterized by low levels of both controversy and public debate. Lastly, Belgium has come far in the technological development of concepts for GD but since these concepts are not politically anchored, they have not yet advanced in formal policy. Evidently, these very different contexts have great impact on the waste management concepts.

As a result of the historical processes mentioned above, the countries vary significantly with regard to how close they are to implementing their respective NWM programmes. In Sweden and Finland, implementation appears to be close, as siting procedures essentially have been completed. For instance, emplacing real nuclear waste is planned in ONKALO already in 2021. In France, the 2016 Act provides essential details for the continuation of Cigéo, allowing Andra to prepare the disposal authorization to be submitted in 2019 while the concept of deep GD is still facing some public resistance. It is an even bigger contrast to Belgium, where siting attempts have not yet led to the formal selection of a repository host community. The conditions under which each country relates to monitoring are therefore rather divergent.

Furthermore rather divergent legislative demands for monitoring future repositories exist. These appear to be largely related to the diversity in disposal concepts (including host rock availability) and to the advancement of the disposal programmes. Sweden has stood out as the clearest advocate for passive, non-monitored safety, as legislative demands here clearly state that monitoring should not interfere with passive safety (although a range of other monitoring tasks are required to be performed). In the three remaining countries, there are indeed more explicit legislative demands for monitoring. However, these demands are set apart by their somewhat different aims. It should be stressed, however, that passive safety and final disposal of the waste is still a central part of all four countries plans, regardless of monitoring demands in legislation. Nevertheless, using different terminology, it is not always clear what the demands in the different countries actually entail. There is a tendency for the demands of not being extensively explicit, which means that there is likely to be room for interpretation when monitoring programmes are developed and made more concrete. What the demands often do not explicate is to what extent the repositories should be monitored, exactly what should be monitored, for how long and by whom. Hence, a lot of questions that should be asked about the functions of monitoring in NWM cannot be answered simply by reading legislative demands. In light of this, it is important to study how the NWMO's interpret monitoring, legislation and their own role in developing the programmes since they constitute important actors in the quest for repository monitoring.

Identifying the NWMO's monitoring strategies was the last step in this chapter. As we showed, a series of both similarities and discrepancies could be discerned between them. The overarching ambition of the NWMO's to monitor their future repositories generally corresponds but is not restricted to the demands of legislation and the host-rock conditions. Some NWMO's for instance might consider performing monitoring which is not explicitly demanded on the premise that it may improve safety. This can be discerned in the case of Belgium. Nevertheless, the lack of demands for (EBS) monitoring in Sweden has left this specific type of monitoring out of the KBS-3 concept, whereas France and Finland are preparing more elaborately to answering the monitoring demands by developing specific monitoring strategies. The legislative context of the countries is not the only explanatory aspect, but evidently very important in understanding the prerequisites for how monitoring programmes emerge.

Even though monitoring activities can be very divergent, and even though an array of parameters can be surveyed in a repository, one certain type of monitoring stands out. In the beginning of this report, we stated that repository monitoring was partly a new kind of monitoring. Still repository monitoring is also a NWM commonplace, as various monitoring activities have been ongoing for decades, both around and in close vicinity to repositories. As chapter 2 has suggested, the newness of repository monitoring largely lies in the monitoring of the EBS. A conclusion that we can draw from reviewing the different countries and their NWMO's statements is that EBS monitoring is the most controversial type of monitoring in NWM. The controversy of EBS monitoring is constituted by its potential intervention in passive safety. A recurring argument made by both SKB and Posiva is that repository monitoring is feasible as long as it does not interfere with passive safety. A range of repository monitoring activities are not problematic from this point of view, but EBS monitoring is portrayed as being intrusive and encroaching on the very concept of passivity. Thus, EBS monitoring is controversial as it threatens the 'integrity of the barriers' and the longstanding concept of passive safety. To put it simply, monitoring equipment in NWM tends to be more controversial the closer it is placed to the canisters containing the nuclear waste.

3. Chapter 3 – Monitoring in Carbon Capture and Storage

3.1 Introduction

As shown in Chapter 2 monitoring of nuclear waste is not (yet) a straightforward matter of which all actors involved have the same interpretation. Countries, most often due to national legal requirements, frame monitoring in their waste management programmes differently. Some actors in the field consider monitoring to be irrelevant, since safety of a repository is achieved by passive means. For this reason and also for giving an example where lay people have expressed their views on monitoring we would like to call in Carbon Capture and Storage (CCS) as a comparative case. Drawing on the case of a planned CO2 storage facility in Barendrecht, the Netherlands, enables us to take a closer look at a case in which a local population was confronted with a specific strategy for repository monitoring. Making the comparison between nuclear waste (repository) monitoring and CCS monitoring may help to evaluate what monitoring could be in relation to safety, and more importantly, how to bridge the gap between expert and lay stakeholders and what role monitoring can play in this endeavour. In a nutshell, the aim of this chapter is to contribute to enlighten the concept of 'repository monitoring' by presenting CCS monitoring as a particular case and contrast it with the case of repository monitoring of GD of nuclear waste. In the following sections, we first undertake a closer examination of monitoring strategies concerning CCS on a generic level and then in relation to a planned facility in Barendrecht.

3.2 CCS as a comparative Case

3.2.1 'Technological Architecture' as an analytical Perspective

Just as much as in the case of NWM, previous research has stated that CCS can be perceived as a socio-technical system, as many actors from different fields of expertise – technical experts and local publics, government and industry, just to name a few – are involved (Russell, Markusson & Scott, 2011). As this might in itself not be enough commonality to qualify CCS as a comparative case, it has been argued that CCS is a technology that resembles in its main features GD of nuclear waste, as both CCS and nuclear waste disposal deal with an unwanted, pollutive waste that has to be isolated over long timespans in geological facilities (Spreng et al., 2007). Furthermore, both are about risk issues, oriented towards future risks concerning possible leakage. They are also localized risk issues, involving the challenge to find a proper place for a repository, which often is generating protests from publics who do not want to live in the vicinity of such a facility. In what follows we present CCS as a comparative case to GD of nuclear waste. This will be done by focusing on the two functions of 'waste isolation' and 'monitoring'. We present these with the aim to contrast the different performances of these functions (Parthasarathy, 2005).

3.2.2 Waste Isolation: How to safely contain hazardous waste

In this section we present how the *function of waste isolation* is performed in both cases. We explain in detail how a CCS storage facility works and contrast this mode of operation with the task of disposing of nuclear waste in a GD facility.

CCS is a technology that is used by energy intensive industries or fossil fuel power plants. From this perspective it can be described as a transitional technology to diminish CO2 emissions until the establishment of less polluting industries is finally achieved. For example, the German federal government supports research on CCS as it recognizes the technology as an option to reduce greenhouse gas emissions (BGR, 2016; BMWi, 2016). The EU commission's directives 2009/29 and 2009/31 make a direct connection between CCS and the option to save emissions and to trade the related certificates by means of the EU's emission trading scheme. However, both directives warn that CCS should not be an incentive for extending the share of fossil fuel power plants and thus leading to a reduction of efforts to develop and promote sustainable, renewable forms of energy production.

CCS suggests that pollutive amounts of CO2 gas do not have to be emitted into the atmosphere but can be split off (Carbon Capture) and stored in secluded spaces (Carbon Storage). In contrast to GD of nuclear waste, CCS is a technology that is already operationalized since 1996. The Norwegian Sleipner installations perform the removal of CO2 from produced gas and re-inject and store it in the host rock formation (Statoil, 2016a). Typically, such reservoirs lie at least 1000 meters under the earth's surface and can contain tens to hundreds of million tons of carbon dioxide. For example, depleted oil or gas fields can serve as geological reservoirs. Geological CO2 storage has the aim to retain the gas without any occurring leakage. Thus the gas is aimed to remain shielded from the environment with no intention to recover it. Different storage sites have different CO2 retention times, depending on the atmospheric concentrations. Studies have shown that some sites are capable to trap the gas for several thousands of years. In principle, it is expected that a properly designed storage facility is able to contain the gas into eternity. However, due to the natural circumstances, it is acknowledged that leakage may happen at some point (Chadwick et al., 2009). CO2 gas considered as a geologically stored 'waste' is not as dangerous as nuclear waste, even though it does not decay. CO2 is a regular component of the air we breathe and is safely used in the industry, for example to preserve food (Spreng, Marland &Weinberg, 2007). However, higher doses of leaking CO2 from a storage into the ground can pollute drinking water in the aquifer (van Eijs et al.,2011; Spreng et al., 2007). High amounts of CO2 in the atmosphere can be fatal and lead to asphyxiation, as the case of the gas disaster at Lake Nyos in Cameroon has shown. In 1986, 1746 people were killed by a sudden eruption of large amounts of CO2 gas from the lake (Butt et al., 2012).

Similarly, the concept of GD of nuclear waste has the aim to dispose of a pollutive (radioactive) and hazardous substance in a secluded environment. However, as the notion 'disposal' suggests, GD facilities have to be constructed in such a way that nuclear waste does not leak for a vast amount of years, as nuclear waste is highly radioactive over thousands of years and small doses of it can already be lethal. Geological repositories are built as the final destination for the waste. Any repository, being located in salt, clay or crystalline rock, has to guarantee that passive safety is achieved. In each repository's safety case it has to be proven that the hazardous waste remains contained to not endanger humans and the environment. Thus, the geological and the geotechnical barriers have to maintain their performance targets for this period of time. However, the migration of radionuclides is considered to be inevitable after a certain amount of years. Canister-leakage may not be happening under any circumstances during this time period, since the crystalline rock is unsuitable as a hydraulic barrier. The main function of the crystalline rock is to mechanically protect the waste, to avoid easy access to the waste by human intrusions. Disposal concepts in clay and salt take large credit of the hydraulic barrier function of the host rock. In these concepts leakage may not occur at the boundary of the host rocks (in the Swedish case: leakage of the canisters). It has to be proven that the favourable host rock properties are preserved (e.g. France) and that the leakage at the host rock boundary is below a defined value (e.g. Germany). Canister failures are expected and assumed in the safety assessment of clay and salt concepts. Thus a migration of radionuclides after a period of 100.000 years through the rock (and the drift and shaft/ramp system) is an expected, normal evolution scenario.

Waste isolation is a strong focus for both NWM and CCS. However, the requirements for isolation are stricter in the nuclear case, since leakage could have more dangerous consequences. In the next section we will further specify the difference between the two cases concerning leakage, and see that some leakage is accepted in the CCS case.

3.3 Monitoring

3.3.1 Surveying the Behaviour of the Storage/Repository

Monitoring, both in the case of CCS and nuclear waste, is motivated by certain objectives. In this section, we outline how the *function of monitoring* is performed in the case of CCS to contrast this with the case of nuclear waste repository monitoring, to understand the respective monitoring objectives and relevant monitoring technologies chosen to meet them.

CCS monitoring can be compared to nuclear waste repository monitoring, as in both cases the aim is to observe the behaviour of a substance stored in the underground. As Chadwick et al. (2009) state for the case of CCS:

> The principal requirements of a site monitoring program are to establish current storage site performance and to assist in the prediction of future performance, with the ultimate aim of enabling site closure.

EU directive 2009/31 states that *'Monitoring is essential to assess whether injected CO2 is behaving as expected, whether any migration or leakage occurs, and whether any identified leakage is damaging the environment or human health'.* Thereby, monitoring has a twofold motivation. On the one hand, monitoring serves to confirm the safety of the facility to not endanger humans and/or the environment. On the other hand, the aim of monitoring is to demonstrate the integrity of a storage related to the goal of emissions reduction. These two objectives have to be adjusted as they provoke different quantities that would represent 'alarming' monitoring values: a storage that leaks small amounts of CO2 spread over a broad area would be entirely safe, but not meeting the goal of emissions savings. Conversely, a leakage emitting a hazardous amount of CO2 from a small leak would endanger the population, but the emission goals would still be met (Chadwick et al., 2009).

Another aspect specific to the *function of CCS monitoring* relates to the fact that in CO2 storage a difference is made between *migration* and *leakage* of CO2. The notion migration defines the movement of the gas within the storage facility and the surrounding subsurface. The notion means that CO2 escaped the reservoir, but remains trapped in the subsurface. Leakage of CO2 has to be prevented, and it is assumed that a storage in principle is able to function without any leakage occurring. However, it is acknowledged that leakage might be happening in due time. Leakage describes the dissemination of migrated CO2 from the geosphere into the atmosphere, surrounding seawater or potable shallow aquifers, depending on an onshore or offshore location of the reservoir (Van Eijs et al., 2011; Chadwick et al., 2009).

Similarly, in NWM it is acknowledged that migration of the radionuclides will happen at a certain point in time – although, as earlier mentioned, the containment period covers several thousands of years and as a consequence safety requirements are more long-term. In nuclear waste repository monitoring, in somewhat similar terms, a difference is made between 'monitoring migration' and 'monitoring leakage': monitoring leakage in repository monitoring means to conduct 'environmental monitoring', meaning to monitor whether radionuclides escaped within the geosphere and atmosphere.

In the case of CCS, EU directives 2009/31EC and 2009/29EC mandate that the monitoring programme, developed by the operator, needs to be site-specific and risk based. Based on site-specific risk assessment, a CCS monitoring programme needs to address both migration and leakage scenarios. Thus, monitoring tools can be categorized broadly into ‘monitoring CO2 migration in the subsurface’ and ‘monitoring CO2 leakage on the surface’. Monitoring technologies to measure CO2 migration in the subsurface (such as seismic, gravimetric or electromagnetic methods) are already known from the oil and gas industry. Suitable underground monitoring areas include the reservoir itself and the wells. As these technologies do not measure surface leakage, they cannot provide information whether emission goals are met. Although, taking measurements underground to track and/or quantify the CO2 in the reservoir is crucial to provide important information about the current and future containment processes and verify indirectly that the reservoir is behaving as expected (Chadwick et al., 2009; CATO2, 2013).

Monitoring to measure CO2 leakage has the aim to detect CO2 in the atmosphere. At onshore locations, such measurements can be taken directly. However, leakage is not expected ‘in the foreseeable future’. As the paths of migrating CO2 might be long, surface leakage may not occur for hundreds of years. Even though these time spans are way shorter than those dealt with in the case of nuclear waste repository monitoring, they still pose challenges for monitoring to prove that no leakage occurs. Current surface monitoring measurements of CO2 fluxes, which are compared against measurements of the baseline conditions, serve to indicate the future behaviour of the storage site (Chadwick et al., 2009; Van Eijs et al., 2011). Chadwick et al. (2009) suggest that surface monitoring might even only be required in case subsurface monitoring measurements give indications that a leakage might be occurring at the surface. Chadwick et al. (2009: 16) describe this approach to develop a risk-based monitoring programme as ‘pragmatic rather than prescriptive’. The approach to monitoring CCS is insofar ‘pragmatic’, as only the most likely (most ‘risky’) leakage pathways, individual to each site, are monitored. This is a feature of CCS monitoring that should be treated with care – only measuring ‘most risky paths’ does not seem to applicable in the nuclear waste case, as we will discuss later.

In the case of nuclear waste repository monitoring, at first, it has to be noticed that the generic notion ‘monitoring’ comprises several sub-aspects, relating to different monitoring locations and time phases of the repository. Repository monitoring in its entirety aims at informing the evaluation of the overall development of the repository. Geophysical techniques similar to the ones used in CCS can be used for repository monitoring, including monitoring of the engineered barriers, e.g. canisters.

Similar to the CCS case, the migration of fluids that can transport radionuclides is monitored in the nuclear waste case. However, the pragmatic approach applied in the CCS case is not followed in nuclear waste repository monitoring. In repository monitoring, the ‘normal development scenario' of a GD has to be defined by the operator and submitted during the license application process to the regulator. Deviating scenarios, so-called alternative scenarios, have to be developed, too. In this context, monitoring may provide information that allows evaluating whether the repository system behaves as defined in the normal scenario or if it is moving into an alternative scenario. Subsequently, nuclear waste repository monitoring has the aim to picture the overall condition of the repository; monitoring leakage paths of radionuclides is only a partial aspect of repository monitoring. It becomes clear that conversely to the CCS case, monitoring has not the aim to follow up on individual risk scenarios (such as leakage paths), but its aim is to survey in representative areas the entire development of the repository. As we have pointed out earlier, for some actors in NWM, this goal to monitor the overall behaviour of the repository is a contradictive demand. As repository safety is aimed to be guaranteed by fully *passive* means based on the engineered and geological barriers, in principle no human maintenance is required. In this way of thinking, *active* surveillance in the form of repository monitoring is considered to be unnecessary and even potentially counterproductive.

3.3.2 **Time Aspects**

Similar to the case of nuclear waste repository monitoring, CCS monitoring technology includes instruments that can operate in the long term without maintenance, as a CCS storage site has to be leak-proof for several decades (Gibbins and Chalmers, 2008). In line with the EU directives 2009/31EC and 2009/29EC, the monitoring programme for a CCS facility has to cover the phases of baseline monitoring, operational monitoring and post-closure monitoring. The duration of monitoring is highly site specific (Chadwick et al., 2009). To give a reference value of the Barendrecht case (see below), the operational phase (injection phase) of the storage was expected to take around 25 years. The operation time depends on the size of the storage. For example, the Sleipner CCS started the injection of CO2 gas in 1996 and is still operating. It currently captures and stores up to one million tons of CO2 annually (Statoil, 2016b).

After the closure of the storage facility, which is considered to happen *'When all available evidence indicates that the stored CO2 will be completely and permanently contained'* (Directive 2009/31, Article 18), EU legislation demands continuous monitoring. For this purpose the responsibility for the facility, including the duty to monitor, at that point should be transferred to the competent national regulatory body. After the transfer of responsibility, the national authorities have to bear the costs for all post-closure monitoring. The former operator has to provide a financial contribution to the regulator that covers the costs for a monitoring period of at least 30 years. During the post-closure phase, monitoring activities shall be reduced to a minimum at which leakage can still be identified, and, in case of appearing leakage, intensified again (Directive 2009/31/EC). The directive does not give information on the total duration of the monitoring period.

In the case of nuclear waste repository monitoring, the time spans in which sensors should be able to deliver data are required to be much longer than those required in the case of CCS monitoring. Currently, wireless monitoring equipment with autonomous power supply is being developed that can be placed behind the engineered barriers in a GD. Commercial batteries available today only offer a limited lifetime of maximal 30 years, which is considered to be too short, as the mere operational phase of a GD is expected to take approximately 100 years. Following this number, for example in France, the Planning Act 2006-739 requires that the possibility to 'reverse' past steps and technological choices must be given for a period of at least hundred years. As a consequence, the French NWMO Andra describes that it plans to carry out monitoring for a period of hundred years during the operational phase, as monitoring provides information on the behaviour of the repository that is necessary for reversibility management. For this and similar cases, batteries that provide electrical power supply over more than 30 years are currently under development (Modern2020).

3.3.3 Deviation of Measurements

The EU directive 2009/31 advises that a CCS concept and its risks have to be reassessed in case of deviations from the planned storage behaviour. In case new leakage paths are identified, which had not yet been identified during the development of the monitoring programme, the monitoring programme has to be updated accordingly. Furthermore, the directive requires that the operator needs to feedback monitoring results periodically to the responsible regulative authority. In addition, the directive advises that regulative authorities should establish 'a system of inspections' to make sure that the requirements of the directive are fulfilled. The operator has to make provisions concerning his liability for potential damage to humans and/or the environment. In case of 'significant irregularities' or leakage of CO2 from the storage complex, the operator has the obligation to take corrective measures and provide a 'corrective measures plan' upfront.

This is a similarity between CCS and GD. At least in the German case (a current practice in the German Morsleben storage facility), 'corrective measures plans' exist which have been developed by the implementer. These plans have already been approved by the authorities. The idea behind such plans is that once approved they can be applied by the operator if needed without delay.

Corrective measures are described as 'any measures taken to correct significant irregularities or to close leakages in order to prevent or stop the release of CO2 from the storage complex'. What such a corrective measure plan concretely entails is not further specified in the directive.

In case the operator fails to take these corrections, the competent authority should step in and recover the costs from the operator. A periodical updating of the monitoring plan is a standard procedure in the quantitative risk assessment approach, for example this policy is applied in the case of CCS in Barendrecht (Van Eijs et al., 2011). The approach to update the disposal concept and consequently monitoring is also to be found in NWM, for example in France and Germany. These updates shall enable the questioning and reviewing of the current disposal concept on a regular basis.

3.4 CCS Monitoring – The Barendrecht Case

3.4.1 Introduction and Background Information

As CCS monitoring programmes have to be designed site-specifically (Chadwick et al., 2009), at this point we would like to turn to the case study of a planned CO2 storage facility in Barendrecht, the Netherlands. We would like to elucidate a case in which a concrete monitoring strategy was developed and a local population was confronted with this plan. We think, given the long history in many countries of public resistance towards nuclear energy and nuclear waste and its disposal, it is of interest to examine a case, in which monitoring has been a major point of criticism from the local population, even though a monitoring demand is strongly embedded in European legislation. In the Barendrecht case, public resistance has even caused the cancellation of the project. In this section, we first give some background information on the case. Then, we turn to presenting the monitoring strategy that was proposed by the operator and point out the local public's perspective on monitoring.

CCS is recognized in the Netherlands as supporting the reduction of CO2 emissions and thus generating financial benefit via the EU Emissions Trading System (MER, 2008). In 2007, the Dutch government issued a tendering procedure for a CO2 storage demonstration project. The company Shell, in cooperation with NAM (Nederlandse Aardolie Maatschappij BV) and OCAP (Organic Carbon Dioxide for Assimilation of Plants), initiated the development of a project to store CO2 gas in depleted gas fields under the community of Barendrecht. The project plan suggested to conduct segregated CO2 from Shell's 17km distanced oil refinery Pernis into two depleted gas fields below Barendrecht. It was planned to inject compressed CO2 into the two empty reservoirs through already existing wells, which finally should also be used for monitoring (Seeberger and Hugonet, 2011). The smaller field was planned to be filled starting in 2011 and the second, bigger one in 2015, in which injection would be lasting over a period of approximately 25 years. Being a demonstration project, the aim was to lay the foundation for further CCS projects in the rest of the country and thereby placing the Netherlands in a forerunner position in terms of knowledge and innovation in the field of CCS (Feenstra et al., 2010). For the realization of this project, the Dutch government provided a funding sum of 30 million Euros. However the newly appointed government in November 2010 stopped the project before its implementation (Terwelm et al., 2012; Feenstra et al., 2010). In a letter to the parliament, the Dutch Minister of Economic Affairs, Agriculture, and Innovation (2010) declared that the project was stopped due to considerable time delay, resulting from a complete lack of societal support from the local community. Several studies suggest (for example Feenstra et al., 2010; Brunsting et al., 2011; Cuppen et al., 2015; Desbarats et al., 2010) that the local opposition towards the CCS project in Barendrecht had risen so high that it could finally topple the project due to lack of adequate and timely stakeholder interaction in the project development. Communication between the project implementers, the national government and the opposing local community only took place when the project plan was already entirely developed. Furthermore, within the moments of interaction, all stakeholders remained firm in their opinion so that no agreement was found that would have enabled the realization of the project.

3.4.2 The Operator's Monitoring Strategy

Even though CO2 storage had not yet been implemented in 2008 in the Netherlands (and still to date has not), Shell and its associated project developers state that CCS technology was mature enough to safely store CO2 in the gas fields below the densely populated Barendrecht region. However, as the CCS Barendrecht was aimed to serve as a demonstration project, the project developers remark that learning effects would result from non-technical aspects, and monitoring. Non-technical learning objectives referred to the economic, managerial, judicial and societal effects of the project. As typically in the case of CCS, also in the Barendrecht monitoring strategy, measurements serve a double purpose: they are used to control the CO2 gas injection process, but also to account for the total quantity of non-emitted CO2. Regarding the latter, it is stated that a monitoring programme represents an important learning objective, in so far as it should be proved via monitoring that no CO2 would leave the reservoir in order to show that CCS is a valuable technology to reduce Dutch greenhouse gas emissions. This is considered crucial since the financial compensation for the non-emitted CO2 via the EU Emissions Trading System is considered to be an important learning effect for the project.

The technologies relevant to monitor the pressure, temperature and behaviour of the CO2 within the reservoir are well known from experiences in the oil and gas industry. Monitoring would serve to control whether the quantity and quality of the injected gas is maintained during the storage process (MER, 2008).

Monitoring is framed by the operator as a 'risk-based mitigation measure' in the monitoring concept. This approach starts from the assumption that the risk that CO2 leaks can be 'assessed and managed':

> Also a monitoring plan is an example of a mitigation measure because it will allow you to take preventive actions to prevent migration or leakage and limit possible effects. Mitigation measures have to be taken for all medium and high leakage risk scenarios and might be needed for low risk scenarios. It has also to be shown that for those scenarios the effect of mitigation will reduce the risk to a negligible or low ranking and that the risks are ALARP (As Low As Reasonably Practicable) (Van Eijs et al., 2011)

It becomes clear that monitoring in the case of CCS is motivated by the attempt to diminish the risk of CO2 migration. Risk-based monitoring means to map out all possible leakage paths, identify and rank the risks, and measure the risks that are ranked high, and disregard those considered low enough. This risk-based approach in Barendrecht can be attributed to the relevant EU directives (see above). Only based on these defined risks, the suitable monitoring technologies can be selected. It is acknowledged in the monitoring plan that the risk perception associated with CO2 storage differs very much between technical experts and other stakeholders, such as the local population. Consequently, the monitoring plan suggests to discuss, define and redefine 'the quantitative definition of the word 'reasonably' in ALARP – even though it is stated that the facility is 'designed for no leakage at any quantity' (van Eijs et al., 2011). In interviews with responsible engineers for the project, it was stated that it is crucial to discuss the public's concerns towards a CCS facility. It was suggested that it would be productive to adapt the monitoring strategy where possible according to the public's wishes. The example of 'earthquake monitoring' was given: even though engineers would not consider it necessary to measure earthquake risks around a CO2 storage, publics would consider it important. It was stated that 'going on with the clash of interests' would not be constructive (Van Eijs Interview). Furthermore, it is acknowledged that even if Shell adopted a 'conservative approach in order to always err on the safe side' (Kuijpers, 2011), publics tend to have less trust in standards set up by the operator than in those defined by a governmental authority.

Similar to CCS, monitoring in the nuclear waste case represents a learning objective due to the reason that repositories are nowhere in operation yet. A monitoring programme lasting for such long time spans has never existed until the present day. As well, in both cases, monitoring strategies need to be developed site-specifically.

3.4.3 The Municipality of Barendrecht: A Different Understanding of Monitoring?

The local population of Barendrecht had many doubts about the reliability of the project plans, both towards the operator and the government. Together with input from external experts the municipality clustered its questions, concerns and requirements in a 'checklist' containing 100 questions. This checklist was finalized in December 2008 and discussed among all stakeholders before the Environmental Impact Assessment Report (EIA) was published. The council of Barendrecht required that all questions had to be answered before an approval of the project could be given. Monitoring was one of the checklist's seven themes, which furthermore entailed the general topics of *safety, risk analysis, geological research, changes in property values* and *legal issues* (Feenstra et al., 2010).

The public's major concern regarding monitoring was that the operator and the Dutch government would not properly organize their responsibilities to carry out monitoring. (Brunsting et al., 2011). Citizens wondered how the responsibility to monitor would be organized in practice after the required monitoring period of 30 years (EU directive 2009/31) had ended. It was doubted whether the operator would provide sufficient resources to continue monitoring. It was argued that monitoring after the operator was released from his monitoring duty, would be needed to continue into eternity, paid for by the government. Two main reasons were given to support this assumption. First, to make sure that the CO2 does not escape the reservoir, as a leakage of CO2 was considered to be harmful to health. Second, with regard to CCS serving to save emissions relevant for the EU's emission trading system, citizens argued that monitoring needs to continue forever. However, they opposed this shift in responsibility, as they argued this infinite continuation of monitoring payed for by public funding, would violate the 'polluter pays principle' (Desbarats, 2010; Feenstra et al., 2010).

3.5 Conclusions

In the comparison between NWM and CCS performed in this chapter we have focused on the two functions of *isolation* and *monitoring*. Both are technologies with the aim to isolate dangerous substances in the underground and apply monitoring, this is a basic similarity, which then differs in some important respects.

In CCS the purpose of monitoring is made very concrete, and is regulated through supranational legislation. Monitoring serves to prove both safety and the emission containment capacity of the storage facility. This double purpose seems to be clear and agreed within the technical literature, in the relevant EU directives and as well in the investigated case study of the Barendrecht CCS storage. As such, the necessity for monitoring seems agreed not only from a societal-regulatory perspective, but also from a technical point of view. In contrast, nuclear waste repository monitoring is still at the stage of research and development. Some actors from the field of NWM doubt the necessity of active monitoring, arguing that GD safety is to be guaranteed through a passive system. Other actors, instead, are very much in favour of monitoring and think that monitoring could provide added value, for example to demonstrate reversibility, to evaluate the proper functioning of an engineered barrier, or to increase the understanding of host rock behaviour in response to the emplacement of the waste.

It is often discussed at which location and during which phases monitoring is needed. Questions like *'Is EBS monitoring necessary?'*, *'Do we want/need monitoring in the post-closure phase?'* and '*How can monitoring during the operational phase contribute to post-closure safety?'* repeatedly appear in discussions among technical experts in the realm of Modern2020 research. It becomes clear that there are different facets of the *function of monitoring*, as monitoring can be carried out during different phases and in different locations. These facets all belong to the same generic term 'monitoring', but in the end relate to different 'parts of the problem'. Thus, giving the argument that monitoring is in principle not needed anyway since safety is provided by passive means is a debatable argument that still exists in the case of NWM. In the case of CCS, at least among the technical community, monitoring is not a controversial issue, but considered an important part of technology development.

A further important aspect typical for the CCS case is the 'risk-based' approach to monitoring. As already explained, this approach seems to apply not so much to repository monitoring, since this type of monitoring has the aim to map out the overall development of a repository and not only the most risky paths for radionuclide leakage. For this reason, the approach aimed for in Barendrecht, to discuss the meaning of 'reasonably' in ALARP, cannot be transferred directly to nuclear waste repository monitoring. The question 'when and how nuclear waste repository monitoring will become pragmatic', and, at least to some extent, 'risk-based' is relevant to ask, since there will certainly be a point in time when factors such as financing or the technology readiness level (not to mention the site as such) will become relevant and constrain monitoring programmes.

One last lesson learned from CCS could be the need for timely involvement of citizens and other public stakeholders. For GD this could for example start during the period of baseline monitoring, that is before repository construction. Based on their experiences with those first monitoring activities, public (and other) stakeholders could get an understanding of what kind of results can be achieved with monitoring and how these can be evaluated. Input could at the same time be given for the development of a monitoring concept for the repository to be constructed.

4. Chapter 4 – Conclusions and Discussion

In this concluding chapter we summarize some of the most important topics discussed earlier: what monitoring is and how the definitions and roles of monitoring vary between nations, and between NWM and the CCS technology. We also try to make clear the possibilities and consequences for public participation (involvement of citizen stakeholders) in relation to different understandings of monitoring in connection to existing NWM practices.

Today monitoring is a general trend in society and is increasingly used in many areas. In the field of NWM environmental monitoring has been in practice for long time, while underground repository monitoring, and in particular EBS monitoring, is of more recent date. The latter is also more technically challenging, particularly in view of informing the evaluation of the repository's long-term safety behaviour. It is this aspect of monitoring which is under research in Modern2020, and on which the views on its needs and what it can achieve remain the most diverging. In this report, we have suggested that monitoring in several regards is commonplace in NWM, and that controversy arises mostly with regard to EBS monitoring. But also other forms of (repository) monitoring are surrounded by ambiguity and sometimes even confusion, as different actors in NWM use the notion differently. Therefore monitoring remains a somewhat open concept, which can be ascribed different meanings. This open character also implies a possibility for different actors, or stakeholders (including citizen stakeholders), to influence discussions and definitions on what monitoring means. However, it is also important to acknowledge the limitations to this openness. Passive safety, or delegation of safety to geology, is the aim for GD of nuclear waste. The European Technology Platform 'Implementing Geological Disposal' (IGD-TP) argues that 'there is a consensus that the maximum level of passive safety can be obtained through geological disposal' (IGD-TP, 2011: 10). Since the 1970s this ambition has been the default mode in the planning process in practically all nuclear nations. Therefore, monitoring ambitions are part of a secondary strategy that comes up in relation to issues such as retrievability and reversibility, i.e. uncertainties in safety calculations in relation to different scenarios. Repository monitoring has become more important during the last decades, not least because it has been pushed by the French requirements of reversibility and the rapid development in the field of monitoring technology. It is still an open question whether reversibility opposes the ambition of passive safety. It depends on the time perspective, when to stop monitoring, but what is clear is that the distinction between passive safety and active safety, between storage (with the intention to retrieve) and disposal (without the intention to retrieve) has become blurred. However, the commitment to reversibility stresses a logic that is not always emphasized. Sweden, for instance, leans strongly on passive safety and holds the view that the burdens of nuclear waste should not be put on the shoulders of future generations. French reversibility instead builds on the notion that future generations should have a potential say in waste management issues. It is also important to recognize the difference between NWM and CCS in this respect. CCS is a younger technology and has incorporated monitoring as something important already from the beginning, while in NWM, it has not played an as central role, but is more a kind of 'add on-technology'.What is often portrayed in NWM as 'technological maturity', of which Sweden and Finland are often uplifted as examples of, can also be problematized. The closer to implementation a certain NWM programme comes, fewer of that programme's components and elements are up for public discussion. Hence, a 'technologically mature' country can be characterized by a technological lock-in, path dependency or a predetermined trajectory. Since NWM programmes are generally characterized by a longstanding history of many concerns, they are deemed to be partly shaped with regard to these. Of this we see several examples in this report. Sweden and Finland, for instance, generally coupled with the identity of NWM frontrunners, have no extensive plans for monitoring. This is especially true in the case of Sweden. In both countries, the technological lock-in may be perceived as more significant than in for instance Belgium. The degree of technological maturity is important for participation arrangements, as a technological lock-in may render any participation beyond technical implementation less meaningful; the trajectory of a certain NWM programme might already have been established and is not easily redirected. The openness gradually diminishes and also the group of actors having possibilities to influence and modify the technological concept. When new topics arrive, due to for instance technological development, such as monitoring technologies, mature programmes usually have more problems to include these compared to less mature programmes. In this situation, a range of aspects that a monitoring programme inevitably will have to relate to are currently not being addressed, significantly impacting potentially concerned local stakeholders' opportunity to influence NWM and monitoring technology development. The slightly less mature Belgian NWM concept may in fact render monitoring and public engagement more feasible. As we have seen, the implications and possibilities of developing monitoring programmes must be understood in light of 'a bigger picture' (including the relationship between the disposal concept and the host rock), and knowledge that transcends the boundaries of the Modern2020 project.

The maturity of technological concepts has consequences for public participation and citizen involvement. It is difficult to unconditionally discuss the importance of monitoring and what monitoring can achieve when many decisions concerning technology and safety already have been taken. Previous referenda, disposal technology choices and completed siting procedures are examples of aspects that condition the prospects for public participation and developing monitoring programmes. However, an important ambition of this report has been to identify differences between development processes in some of the most important and mature NWM nations, and between NWM and the CCS technology.

Due to the development in time, and underground repository monitoring being depended on quite recent technologies, the differences between CCS and NWM become understandable, including why the former has monitoring integrated into its ‘safety case’, while in the latter monitoring seems to be rather an add on-solution. This is also a reason for citizen involvement and citizen influence being less self-evident in NWM.

In this report we have highlighted some important differences between nations on how to assess monitoring, and also some controversial topics on what to monitor. The Swedish Nuclear Waste Council, adviser to the Swedish Government, puts forward a possible conflict between nations and concludes that the Swedish NWMO SKB, contrary to the country’s Nuclear Waste Council and NWMO’s in other nations, is reluctant to develop EBS monitoring:

> The Council’s conclusion is that there are important international actors which contrary to SKB believe in both the importance and the possibilities of developing systems for measuring condition values in sealed parts of the repository to a reasonable cost. These actors have already started developing such systems and their focus is largely consistent with that of the Council (SOU, 2015:11: 109) (translation by the authors).

The status of repository monitoring is quite unclear in many nations. When putting together monitoring assessments and ambitions from different nations, and also adding the differences to be found in a comparison with CCS, we can conclude that there is a remaining lack of clarity. This situation will further influence the contacts with local communities potentially affected by GD and the discussions with them about monitoring. In this communication it is important to clearly indicate *what* can be achieved with monitoring (and what it cannot achieve), and *why* which form of monitoring is applied, including what is made in other nations and for what reasons. The existing variation between the NWM programmes described in this report could be presented to local citizen stakeholders as a resource for further discussions and a possibility to clearly motivate the reasons for suggested plans and programmes concerning monitoring. The ambition of the Modern2020 project of coordinating national variations, e.g. in relation to national legislation and regulation, could in this respect be extended to include also the views of national citizen stakeholder-groups. However, there are reasons to be less hopeful about these prospects of including citizen stakeholders in developing monitoring programmes. The path dependency and lock-in situation for the most mature programmes is evident, and when passive safety is a crucial part of the trajectory there is not much room for new perspectives on monitoring.

In this report, we have also suggested that monitoring programmes are by no means a guarantee for establishing ‘confidence’ in future repositories. As the Barendecht case showed, local citizens and publics might still oppose controversial facilities despite extensive monitoring efforts on part of the implementer. Understanding on what grounds local citizens do so comes with the need to address and analyse a broad range of potential reasons for their actions and opinions. Their reasons may be both technical and political, which stresses even more the importance of situating the controversial technologies in their societal context. A general advice to those seeking to create ‘good public participation’ is to include concerned actors from an early stage in the implementation process. However, there are no guarantees for the success of such endeavours. Thus, even if it can be expected to increase the chances of successful participation and implementation of contentious facilities to seek broad public support early on in the process, there can be a conundrum of reasons for public dismissal of a controversial facility; it is not a question of mere technical feasibility. The time-frames and technological lock-in characterising NWM, which we have addressed earlier, speak against also the notion of ‘early public participation’; monitoring development in NWM is rather a ‘late public participation’ effort since repositories are expected to be operational in the years to come and have already developed over the course of decades. For Modern2020, this implies that expectations on facilitating good and extensive public participation in the development of monitoring technologies must be weighed against the obstacles we have addressed in this report.

Naming what monitoring in NWM means and what it can offer, also defines who can finally be involved in discussing monitoring, and also triggers a discussion about monitoring of a repository in the long-run. This ‘issue articulation’ is an important aspect of developing monitoring (see also Bijker et al. 2009: 155). The fact that the local population in Barendrecht was only involved at a late stage in the process and doubted the responsibilities for monitoring and eventually toppled the CCS project entirely supports the endeavour to involve local stakeholders in the development of a monitoring strategy. To focus on ‘issue articulation’ and the still open character of what monitoring actually is and what it can do, including national variations and variations between technologies such as GD and CCS, could also be used as a resource in communication between stakeholders.

We would like to stress that the nuclear waste case offers a possibility to discuss the selection process of the monitoring parameters (such as presented in the Modern ‘Screening Workflow’ – Modern20202 Deliverable 2.1) together with interested stakeholders. We consider this as an opportunity to create a productive discussion basis for the topic of monitoring, since we assume that the risk perceptions associated with nuclear waste disposal, which are after all, decisive for defining monitoring will vary between technical and public stakeholders (compare findings in MoDeRn 2015).

In sum, what we have witnessed in the comparison between nations and between NWM and the CCS case on monitoring issues could be assessed as efforts to *exercise humility.* As Sheila Jasanoff (2003) has argued it is easy to find technologies of *hubris* in the nuclear field, and the promises set up by GD and passive safety, that our grandchildren can just forget about it, is an obvious example. The discussions and ambitions in relation to monitoring and monitoring strategies are explicitly about acknowledging remaining *uncertainties* in GD projects or should at least be about this, i.e. on how to exercise *humility*.

Even though it is well known what consequences the leakage of radionuclides has, it is uncertain when and under which conditions migration and subsequently leakage will happen. It cannot be predicted with absolute guarantee that the barriers will remain stable for a sufficient period of time to not endanger humans and the environment. As such, monitoring can be considered as a necessary tool for a *precautionary approach* that moves 'from hubris to humility' (Jasanoff, 2003). In such a situation of uncertainty, a reflective discourse, including various stakeholders with various knowledge bases and interests, helps to, as Bijker et al. (2009: 161) put it, 'providing a satisficing approach to finding a proper balance between the possibilities of overprotection and underprotection. Critical and reflexive consultation with all the stakeholders is therefore essential. Then, by definition, scientists do not know it all – and thus technologies of humility are called for'.

References

ANDRA (2013) *Projet CIGÉO - Centre industriel de stockage réversible profond des déchets radioactifs en Meuse/Haute-Marne. Le dossier de maître d'ouvrage débat public du 15 mai au 15 octobre 2013*. ANDRA 504 - DCOM/13-0028 – Février 2013.

ANDRA (2015) *Work Package 2 Questionnaire 'Monitoring Programme Design Basis, Decision Making and Monitoring Strategies'*. Unpublished Modern2020 project material.

ANDRA (2016) *Andra - French national radioactive waste management agency*. Available at: http://www.andra.fr/international/. [20170324]

ANDRA (2016) *Position Paper on Reversibility.* Available at: https://www.andra.fr/download/andra-international-en/document/577va.pdf. [20180222]

Anshelm J. (2000) *Mellan frälsning och domedag: Om kärnkraftens politiska idéhistoria i Sverige 1945-1999.* Eslöv: B. Östlings bokförlag Symposion

Anshelm J. (2006) *Bergsäkert eller våghalsigt?: Frågan om kärnavfallets hantering i det offentliga samtalet i Sverige 1950-2002.* Lund: Arkiv.

Arthur WB. (1989) Competing technologies, increasing returns, and lock-in by historical events. *The economic journal* 99: 116-131.

ASN (2006) *Annual Report 2006. The law on sustainable management of radioactive materials and waste*. Available at: http://www.asn.fr/annual_report/2006/radioactive-waste-management-act.html [20161024]

ASN (2008) *Guide de sûreté relatif au stockage définitif des déchets radioactifs en formation géologique profonde*. Available at: https://professionnels.asn.fr/content/download/50883/352509/version/2/file/guide_surete_2008.pdf [20161125]

Aufferman B, Suomela P, Kaivo-oja J, Vehmas J & Luukanen J. (2015) A Final Solution for a Big Challenge - The Governance of Nuclear Waste Disposal in Finland. In: Brunnengräber A, Di Nucci MR, Losada AMI, et al. (eds) *Nuclear Waste Governance: An International Comparison.* Springer.

Barthe Y. (2009) Framing nuclear waste as a political issue in France. *Journal of Risk Research* 12: 941-954.

Barthe, Y. & Meyer, M. (2012) *Identifying remaining socio-technical challenges at the national level: France*. European Commission, Insotec Working Paper.

Barthe Y, Elam M & Sundqvist G. (2014) *Divisible and Non-Divisible Matters of Technological Concern: Negotiating Nuclear Waste Solutions in Sweden and France*. European Commission, Insotec Working Paper.

Barthe Y and Meyer M. (2012) *Identifying remaining socio-technical challenges at the national level: France*. Available at: http://econpapers.repec.org/paper/halwpaper/hal-00704559.htm [20161023]

Bergmans, A., Van Steenberge, A., & Verjans, G. (2006) CARL Country Report–Belgium. Antwerp: University of Antwerp. Available at: http://webhost.ua.ac.be/carlresearch/ [20171004]

Bergmans A, Elam M, Simmons P & Sundqvist G. (2012) *Monitoring the Safe Disposal of Radioactive Waste: a Combined Technical and Socio-Political Activity* Available at: http://cordis.europa.eu/pub/fp7/euratom-fission/docs/07-modern-d1-3-1-basis-for-stakeholder-communication_en.pdf [20170415]

Bergmans A, Elam M, Simmons P & Sundqvist G. (2014) *Monitoring and the Risk Governance of Repository Development and Staged Closure: Exploratory Engagement Activity in Three European Countries.* European Commission. Available at: https://ueaeprints.uea.ac.uk/49379/1/MoDeRn_D1.4.1_Engagement_Report_final.pdf [20180221]

Bergmans A, Sundqvist G, Kos D & Simmons P. (2015) The participatory turn in radioactive waste management: deliberation and the social–technical divide. *Journal of Risk Research* 18.

BGR (2016) *CO2 Speicherung*. Available at: http://www.bgr.bund.de/DE/Themen/Nutzung_tieferer_Untergrund_CO2Speicherung/CO2Speicherung/co2speicherung_node.html [20160920]

BMWi Bundesministerium fuer Wirtschaft und Energie (2016) *Die weitere Entwicklung von CCS Technologien. Bedeutung und Anwendungsfelder von CCS.* Available at: http://www.bmwi.de/DE/Themen/Industrie/Industrie-undUmwelt/ccs,did=747282.html [20160920]

Boswell C, Fleming C, Spinardi G & Yearley S. (2016) *The Politics of Monitoring: Information, Indicators and Targets in Climate Change, Defence and Immigration Policy*. Available at: http://www.pol.ed.ac.uk/__data/assets/pdf_file/0020/133832/Monitoring_-_Case_for_Support.pdf. [20171014]

Brunsting, S., de Best-Waldhober, M., Feenstra, C. Y., & Mikunda, T. (2011) Stakeholder participation practices and onshore CCS: lessons from the Dutch CCS case Barendrecht. *Energy Procedia*, *4*, 6376-6383.

Butt, T. E., Giddings, R. D., & Jones, K. G. (2012) Environmental sustainability and climate change mitigation—CCS technology, better having it than not having it at all!. *Environmental Progress & Sustainable Energy*, *31*(4), 642-649

CATO2 (2013) *Technical report describing the design of monitoring systems.* CATO2-WP4.5-D05. Available at: https://www.co2-cato.org/publications/library1/technical-report-describing-the-design-of-monitoring-systems-and-remediation [20160923]

Cambridge Dictionary (2016) *Cambridge Dictionary - Make your words beautiful*. Available at: http://dictionary.cambridge.org/ [20160923]

Chadwick, R.A.; Arts, R.; Bentham, M., Eiken, O., Holloway, S., Kirby, G.A., Pearce, J.M., Williamson, J.P. & Zweigel, P. (2009) *Review of monitoring issues and technologies associated with the long-term underground storage of carbon dioxide*. In: Evans, D.J.; Chadwick, R.A., (eds.) *Underground gas storage : worldwide experiences and future development in the UK and Europe.* London, UK, Geological Society of London, 257-275. (Geological Society Special Publications, 313).

Cuppen, E., Brunsting, S., Pesch, U., & Feenstra, Y. (2015) How stakeholder interactions can reduce space for moral considerations in decision making: A contested CCS project in the Netherlands. *Environment and Planning A*, *47*(9), 1963-1978.

Desbarats, J., Upham, P., Riesch, H., Reiner, D., Brunsting, S., de Best-Waldhober, M. & McLachlan, C. (2010) Review of the public participation practices for CCS and non-CCS projects in Europe. *Report of the FP7 project "NearCO2, 11*.

DIRECTIVE 2009/29/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL (2009) *amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community*. Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0063:0087:en:PDF [20160924]

DIRECTIVE 2009/31/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL (2009) *on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006*. Available at: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32009L0031 [20160924]

EC (2004) *Thematic Network on the role of monitoring in a phased approach to geological disposal of radioactive waste – Final report.* European Commission project report EUR 21025 EN.

van Eijs, R., Kuijper, M., & Bisschop, R. (2011) Containment demonstration for the Barendrecht CO 2 storage project. *Energy Procedia*, *4*, 4092-4099.

Elam M. & Sundqvist G. (2006) *Stakeholder involvement in Swedish nuclear waste management*. SKI Report 2007:2. Stockholm: The Swedish Nuclear Power Inspectorate.

Elam M. & Sundqvist G. (2011) Meddling in Swedish success in nuclear waste management. *Environmental Politics* 20: 246-263.

Elam M., Sundqvist G., Simmons P. & Bergmans A. (2012) *Monitoring the Safe Disposal of Radioactive Waste: A Combined Technical and Socio-Political Activity*. European Commission Community Research, Brussels U6 Report.

Engelbrecht R & Schwaiger M. (2008) State of the art of standard methods used for environmental radioactivity monitoring. *Applied Radiation and Isotopes* 66: 1604-1610.

European Council (2004) *Thematic Network on the role of monitoring a phased approach to geological disposal of radioactive waste Final report*. European Commission project report EUR 21025 EN.

European Council (2011) COUNCIL DIRECTIVE 2011/70/EURATOM of 19 July 2011 - establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste.

Feenstra, C. F. J., Mikunda, T., & Brunsting, S. (2010) *What happened in Barendrecht. Case study on the planned onshore carbon dioxide storage in Barendrecht, the Netherlands.* Prepared by the Energy research Centre of the Netherlands (ECN) Project, 6.

Gibbins, J., & Chalmers, H. (2008) Carbon capture and storage. *Energy Policy*, *36*(12), 4317-4322.)

GNS Gesellschaft für Nuklear-Service mbH (2016) *Internationaler Vergleich: Frankreich.* Available at: http://www.endlagerung.de/language=de/7135/frankreich [20160427]

Hemmi A & Graham I. (2014) Hacker science versus closed science: building environmental monitoring infrastructure. *Information, Communication & Society* 17: 830-842.

IAEA (2014) *Monitoring and Surveillance of Radioactive Waste Disposal Facilities - Specific Safety Guide*. Available at: http://www.pub.iaea.org/MTCD/publications/PDF/Pub1640_web.pdf [20160427]

IGD-TP (2011) *IGD-TP Implementing Geological Disposal of Radioactive Waste Technology Platform Strategic Research Agenda*. Available at: https://igdtp.eu/wp-content/uploads/2017/09/SRA-Complete-web-version_July-14_2011.pdf [20180221]

IGD-TP (2016) *Implementing Geological Disposal Technology Platform Vision Document*. Available at: https://igdtp.eu/wp-content/uploads/2017/09/VisionDoc_Final_Oct24-1.pdf [20180221]

Jasanoff S. (2003) Technologies of humility: citizen participation in governing science. *Minerva* 41: 223-244.

Kojo M & Oksa A. (2014) *Adaption of the Swedish KBS disposal concept to Finland: A technology transfer case study.* Insotech Working Paper, European Commission.

Kuijper, I. M. (2011) Public acceptance challenges for onshore CO 2 storage in Barendrecht. *Energy Procedia*, *4*, 6226-6233.

Lagerlöf H & Liebenstund A-L. (2016) *The Framing of Monitoring - Case Comparison of Belgium and Sweden*. Unpublished draft report. University of Antwerp and University of Gothenburg.

Landström, C. & Bergmans, A. (2015) Long-term repository governance: a socio-technical challenge. *Journal of Risk Research,* 18**,** 378-391.

Lupton D. (2013) Quantifying the body: monitoring and measuring health in the age of mHealth technologies. *Critical Public Health* 23: 393-403.

Madruga, M.J. (2008) Environmental radioactivity monitoring in Portugal. *Applied Radiation and Isotopes* 66: 1639-1643.

MER Ondergrondse opslag van CO2 in Barendrecht (2008) *Deelrapport 1: Samenvattend hoofdrapport.* Available at: http://api.commissiemer.nl/docs/mer/p20/p2047/2047-93mer_sam.pdf [20180221]

Merriam-Webster Dictionary (2016) *Merriam-Webster Dictionary*. Available at: http://www.merriam-webster.com/ [20180221]

Minister of Economic Affairs, Agriculture, and Innovation (2010) *Uitwerking van de afspraken voor de individuele CO2 opslagprojecten die momenteel in voorbereiding zijn*. Available at: https://www.rijksoverheid.nl/documenten/kamerstukken/2010/11/04/uitwerking-van-de-afspraken-voor-de-individuele-co2-opslagprojecten-die-momenteel-in-voorbereiding-zijn [20180221]

Ministry of Employment and the Economy (736/2008) *Government Decree - On the safety of disposal of nuclear waste.* Helsinki: Ministry of Employment and the Economy.

Ministry of Trade and Industry (990/1987) *Nuclear Energy Act*. Helsinki: Ministry of Employment and the Economy.

MoDeRn (2015) *Monitoring Developments for Safe Repository Operation and Staged Closure*. Available at: http://www.modern-fp7.eu/ [20180221]

Modern2020 (2015) *Modern2020*. Available at: http://www.modern2020.eu/ [20160923]

Modern2020 (2016) *About Modern2020*. Available at: http://www.modern2020.eu/about-us/about-modern2020.html [20180221]

Narayan S & Scandrett E. (2014) Science in community environmental struggles: lessons from community environmental monitors, Cuddalore, Tamil Nadu. *Community Development Journal* 49: 557-572.

NEA (2003) *SAFIR 2: Belgian R&D Programme on the Disposal of High-level and Longlived Radioactive Waste. An International Peer Review. Paris: OECD.* Available at: https://www.oecd-nea.org/rwm/reports/2003/nea4431-safir2.pdf [20180221]

NEA (2011) *Reversibility and Retrievability (R&R) for the Deep Disposal of High-Level Radioactive Waste and Spent Fuel. Final Report of the NEA R&R Project (2007-2011).* Paris: OECD.

Nederhof, A.J. (2006) Bibliometric monitoring of research performance in the social sciences and the humanities: A review. *Scientometrics* 66: 81-100.

Normile, D. (2011) Citizens Find Radiation Far From Fukushima. *Science* 332: 1368-1368.

Ondraf-Niras (2015) *Work Package 2 Questionnaire 'Monitoring Programme Design Basis, Decision Making and Monitoring Strategies'.* Unpublished Modern2020 project material.

Oudshoorn, N. (2008) Diagnosis at a distance: the invisible work of patients and healthcare professionals in cardiac telemonitoring technology. *Sociology of health & illness* 30: 272-288.

Oxford Dictionary (2016) *Monitor*. Available at: https://en.oxforddictionaries.com/definition/monitor [20180221]

Parthasarathy, S. (2005) Architectures of Genetic Medicine Comparing Genetic Testing for Breast Cancer in the USA and the UK. *Social Studies of Science*, *35*(1), 5-40.

Petersson, J. (2016) Technospatialities and telehealthcare: unfolding new spaces of visibility. *Information, Communication & Society* 19: 824-842.

Posiva (2015) *Work Package 2 Questionnaire 'Monitoring Programme Design Basis, Decision Making and Monitoring Strategies'.* Unpublished Modern2020 project material.

Posiva (2017) *ONKALO.* Available at: http://www.posiva.fi/en/final_disposal/onkalo#.Wovyn3xG2po [20180221]

Rodrigues, M.E. (2009) *Modes of Lay Environmental Monitoring: Towards a Sociology of Environmental Monitoring.* Dissertation. The University of York: Department of Sociology.

Russell, S., Markusson, N. & Scott, V. (2012) What will CCS demonstrations demonstrate? *Mitigation and Adaptation Strategies for Global Change*, *17*(6), 651-668.

Seeberger, F. & Hugonet, V. (2011) Barriers and consequence analysis for subsurface containment in Barendrecht CO 2 storage. *Energy Procedia*, *4*, 4100-4108.

Schröder, J. & Bergmans, A. (2012) *Identifying remaining challenges at the national level: Belgium.* Insotech Working Paper, European Commission.

Schröder J, Bergmans A & Laes E. (2015) *Advanced Research, Lagging Policy - Nuclear Waste Governance in Belgium.* In: Brunnengräber A, Di Nucci MR, Losada AMI, et al. (eds)

Nuclear Waste Governance: An International Comparison. Wiesbaden: Springer Fachmedien Wiesbaden.

SFS (1977:140) *Lag om särskilt tillstånd att tillföra kärnreaktor kärnbränsle, m.m. (Villkorslagen).* Stockholm: Miljö- och energidepartementet.

SFS (1984:3) *Lag om kärnteknisk verksamhet.* Stockholm: Miljö- och energidepartementet.

Shrader-Frechette KS. (1993) *Burying uncertainty: Risk and the case against geological disposal of nuclear waste*. Berkely: University of California Press.

SKB (2013) *Fud-program 2013 - Program för forskning, utveckling och demonstration av metoder för hantering och slutförvaring av kärnavfall*. Stockholm: Svensk Kärnbränslehantering AB.

SKB (2015) *Work Package 2 Questionnaire 'Monitoring Programme Design Basis, Decision Making and Monitoring Strategies'*. Unpublished Modern2020 project material.

SOU (2015) *Kunskapsläget på kärnavfallsområdet 2015 - Kontroll, dokumentation och finansiering för ökad säkerhet (SOU 2015:11)*. Stockholm: Miljö- och energideparementet.

SOU (2016) *Kunskapsläget på kärnavfallsområdet 2016 : risker, osäkerheter och framtidsutmaningar (SOU 2016:16)*. Stockholm: Miljö- och energideparementet.

Spreng, D., Marland, G., & Weinberg, A. M. (2007) CO 2 capture and storage: Another Faustian Bargain?. *Energy Policy*, *35*(2), 850-854.

SSM (2015) *Långsiktig säkerhet - konsekvensanalys.* Preliminary Report. Stockholm: Strålsäkerhetsmyndigheten.

SSMFS (2008) *The Swedish Radiation Safety Authority's regulations and general advice concerning safety in connection with the disposal of nuclear material and nuclear waste. (Report number 2008:21).* Stockholm: Strålsäkerhetsmyndigheten.

Statoil (2016a) *The Sleipner Area*. Available at: http://www.statoil.com/en/OurOperations/ExplorationProd/ncs/sleipner/Pages/default.aspx [20160923]

Statoil (2016b) *Our CCS projects*. Available at:
http://www.statoil.com/AnnualReport2010/en/sustainability/Health,Safety,ClimateAndTheEnvironment/Climate/CarbonCaptureAndStorage/Pages/OurCCSProjects.aspx [20161212]

STUK (2013) *YVL D.5 - Disposal of nuclear waste*. Helsinki: Säteilyturvakeskus.

STUK (2016) *Disposal of low and intermediate-level waste in Finland*. Available at: http://www.stuk.fi/web/en/topics/nuclear-waste/disposal-of-low-and-intermediate-level-waste-in-finland [20180221]

Sundqvist, G. (2002) *The bedrock of opinion: science, technology and society in the siting of high-level nuclear waste.* Dordrecht: Kluwer Academic Publishers.

Terwel, B. W., ter Mors, E., & Daamen, D. D. (2012) It's not only about safety: Beliefs and attitudes of 811 local residents regarding a CCS project in Barendrecht. *International Journal of Greenhouse Gas Control*, *9*, 41-51.