European Joint Programme on Radioactive Waste Management

Deliverable 10.8: Views of the different actors on the identification, characterization and potential significance of uncertainties related to human aspects

Work Package WP10 UMAN, Subtask 3.4

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Executive Summary

This report provides information about the work of UMAN Subtask n°3.4 – Characterization and significance of uncertainties for different categories of actors – Uncertainties related to human aspects. It builds directly on the earlier draft documents associated with milestone report MS23 Preliminary list of uncertainties from UMAN and milestone report MS101 Views of the different actors on the identification, characterization and potential significance of uncertainties related to human aspects.

The report presents the description of the human-related uncertainties, synthetizing the results from the various inputs with a focus on the ten main uncertainties associated with the following topics and considered as of high-priority for further investigation, i.e.:

- A: Process for the identification of a workable set of repository requirements
- B: Continuity of the waste management policy along political changes
- C: Robustness of the presently considered safety requirements with regard to the long term
- D: Public acceptance of the repository at potentially suitable or projected location
- E: Schedule to be considered for implementing the different phases of the disposal programme
- F: Robustness of the safety case vis-à-vis sociotechnical factors
- G: New knowledge
- H: Adequacy of safety-related activities (in siting, design, construction, operation and closure) for the implementation of (operational and long-term) safety provisions
- I: Robustness of safety vis-à-vis possible cyber-attacks or programming errors
- J: Availability of well-educated human resources, and relevant experts in radioactive waste management along the repository lifetime until closure

It should be noted that the description of uncertainties D, E, J and H has been enriched compared to the initial milestone reports through the inputs from UMAN Tasks 4 and 5.

The last chapter gives recommendations for potential future actions to address human related issues within the radioactive waste management programmes that still have the greatest uncertainties.

The process used in this subtask was that in order to characterize the main uncertainties related to human aspects, a preliminary list of uncertainties related to human aspects was established, starting from a seed list, and enriched through brainstorming within an expert group and through workshops. A summary table was then developed for the characterization process consisting of 4 main columns related to: (i) detailed characterization, (ii) the potential consequences of the uncertainty, as contribution to risk assessment, (iii) challenges and potential options for risk management and (iv) significance for the actors.

Ten uncertainties deemed of high priority for further investigation were selected from the preliminary list. They have been used as a basis for a more detailed questionnaire sent to UMAN participants. Outputs from the questionnaire have been synthetized and captured and analysed. Finally, the four uncertainties selected for further discussions within UMAN Tasks 4 and 5 during 2022, have been D, E, G and H.

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Glossary

CSO	Civil Society Organisation
DGR	Deep Geological Repository
EC	European Commission
EJP	European Joint Programme
EU	European Union
EURAD	European Joint Programme on Radioactive Waste Management
GDF	Geological Disposal Facility
HLW	High Level Waste
IAEA	International Atomic Energy Agency
ICS	Interaction with Civil Society
IGD	Implementing Geological Disposal
LILW	Low and Intermediate Level Waste
LIMS	Large Inventory Member States
LLW	Low Level Waste
MS	Member State(s)
NGO	Non-Governmental Organisation
NPP	Nuclear Power Plant
NRA	Nuclear Regulatory Authority
OECD	Organisation for Economic Co-operation and Development
PMO	Programme Management Office (EURAD Work Package)
R&D	Research & Development
RE(s)	Research Entitie(s)
RW	Radioactive Waste
RWM	Radioactive Waste Management
SEA	Strategic Environmental Assessment
SIMS	Small Inventory Member States
SNF	Spent Nuclear Fuel
TSO(s)	Technical Safety Organisation(s)
UMAN	Uncertainty Management multi-Actor Network
VLLW	Very Low-Level Waste
WMO(s)	Waste Management Organisation(s)
WP	Work Package

1. Introduction

This report presents the views of the different actors on uncertainties **related to social, economic and other human aspects** relevant to safety of radioactive waste and spent fuel storage and disposal facilities. It constitutes an important input to the work performed in Subtasks 4.2[1] and 4.3[2] on possible uncertainty management options and preferences of actors, as well as to Task 5[3] dedicated to interactions within a broader group of actors including Civil Society (CS).

As defined in the work plan, the objectives of the UMAN Subtask 3.4 on uncertainties in human aspects which are addressed in this report are to: identify relevant uncertainties, characterize the uncertainties, assess the evolution of such uncertainties and describe the significance of such uncertainties. It is important to also consider the relation between these uncertainties and strategic choices within a radioactive waste (RW) and spent fuel (SF) disposal programme, such as the choices on reversibility and retrievability.

The report is based on:

- the preliminary results of the work performed by the expert group of Subtask 3.4, presented in milestone report MS23 (Dumont 2020) and milestone report MS101 (Dumont 2021),
- the inputs from Subtasks 2.1[4] and 4.2 on the classification schemes,
- the answers to the questionnaire launched in the framework of Task 3[5], on the various types of uncertainties, including those related to human aspects,
- continued work by the expert group of Subtask 3.4 on the characterization of the 10 uncertainties selected as of highest priority for further investigation in report MS23 (Dumont 2020).
- feedback from Task 4[6] (primarily the 2nd workshop[7], June 2021 (Mikšová, J., 2022)) and Task 5 (primarily third seminar[8], June 2022 (Dumont, 2023)).

It is organized in three parts:

- Description of the uncertainties (results of the identification and characterization process),
- Description of the uncertainties selected to be investigated in more detail,
- Reflections for future work.

The report contains also appendices that describe the rating of the various uncertainties identified in the preliminary stage, leading to the selection of the 10 uncertainties that have been investigated in more detail.

2. Methodology: the identification and characterization process

The methodology developed is based on an iterative approach to establish the various views of the actors, combining various exercises:

- a structured brainstorming within the expert group (representatives from 2 waste management organizations (WMOs), 1 research entity (RE) and 1 representative of civil society (CS), to identify as completely as possible the relevant uncertainties, characterize them and select the uncertainties most relevant (high priority) for more detailed characterization and for studies or research on how to deal with them. It combines work

[1] UMAN Subtask 4.2: Compilation and review of available information on possible uncertainty management options
[2] UMAN Subtask 4.3: Preferences of the different actors on uncertainty management options
[3] UMAN Task 5: Interactions between all categories of actors, including Civil Society
[4] UMAN Subtask 2.1: Generic strategies for managing uncertainties
[5] UMAN Task 3: Characterization and significance of uncertainties for different categories of actors
[6] UMAN Task 4: Uncertainty management options and preferences of different actors across the various programme phases
[7] UMAN Task 4.3 Workshop 2: Management options and preferences of different actors regarding uncertainties related to human aspects, June
[8] UMAN Seminar 3: Uncertainties related to human aspects

performed during meetings and individual work of each of the experts, with cross-checking from the other experts involved in the subtask;

- A presentation followed by discussions in a subgroup at the first UMAN work package (WP) meeting, at Bel V premises in Brussels, in November 2019;
- integration of the results of the questionnaire distributed to EURAD participants, which addressed the 10 uncertainties with the highest priority for further investigation
- integration of results from other tasks and subtasks, namely from Subtasks 2.1 and 4.2 about classification schemes, from the Task 4 second workshop (Mikšová, 2022) and from the Task 5 third seminar (Dumont 2023), both dedicated to human aspects.

The result of the process is a two-level description:

- A comprehensive description of a section of uncertainties, integrating the inputs from the various exercises.
- A less detailed description for a large list of uncertainties identified by the expert group, as presented in the Appendices A and B.

In the course of the work, the team tried to capture all primary uncertainties mentioned by respondents and are represented by the summary points of this report. It is noted that there were a few additional uncertainties identified by the respondents individually (just few) to the questionnaire that were not identified as priority by a significant number of multiple respondents (see section 2.5).

2.1 Broad description of the methodology for synthetizing the information collected

Following preliminary work of commenting a seed list of uncertainties that had been established by the subtask leader, a methodology was developed, based on an Excel table, in order to manage the very large amount of information to be processed, and to enable the structuring of interactions from within the expert group as well as with other subtasks. This excel table has been enriched by the subtask expert group throughout the development of the subtask and is used as the database supporting this report.

2.2 Tools for identification

2.2.1 Identification number

The identification number has been introduced to facilitate discussions, within the subtask expert group and outside. It allows their follow-up, namely when the wording of their description is amended. It is made of two blocks:

- As a prefix, the number of the phase that was used to identify the uncertainty (see Chapter 2.2.2);
- As a suffix, a number allocated to the uncertainty within the identification phase.

NB: This should be considered only as an identification number, not more: it does not mean that the uncertainty refers only to the phase that is mentioned in its ID number[9].

2.2.2 Time phases

In order to help identification, the Subtask 3.4 group decided to follow a path based on the lifecycle of the repository, from the observation of a need (“Need for action”) to the passive behaviour of the repository after closure and at an end of oversight (“Post closure – passive control”). Eight phases, or

[9] For example, uncertainty n°3.1, on costs prediction and funding availability, is hanged to phase 3 (construction), but concerns all phases.

"stages", have been identified. They are similar, but not completely identical, to the EURAD phases as presented in EURAD basic documents (like, Strategic Research Agenda[10], Roadmap[11], Deployment plan[12]). A reason for the discrepancies is that they have been established with categories of human activities in mind (design, siting, construction…), whereas the EURAD phases are defined as successive periods of time, even if their labelling refers to the main activity within each period. In fact, our stages correspond to a combination of the 5 EURAD phases (as in Roadmap: 1. Initiation: Policy, framework and programme establishment, 2. Site Selection: Site(s) identification and selection, 3. Site characterisation: Underground investigations and site confirmation, 4. Construction: Facility construction, 5. Operations and Closure: Facility operation and closure) and of the 7 EURAD transverse themes. Therefore, in order to allow common understanding within EURAD, a table of correspondence with the EURAD phases and themes has been established (see Table 1) which is linked to the EURAD Roadmap[13].

It should be stressed that the phases/stages are only a tool to help identifying the various uncertainties.

Table 1. Correspondence between identification stages and EURAD phases/themes.

Stage of the repository used for uncertainties identification	Stage Identification number	EURAD phase number	EURAD phase and theme
Need for action	0	Phase 1	Initiation: Policy, framework and programme establishment Theme 1: National Programme Management
Disposal concept development	1a	Phase 2	Site Selection: Site(s) identification and selection, Generic assessment of options Site Requirements and waste inventory Themes 2 (Pre-Disposal), 3 (EBS), 4 (Geoscience), 5 (Disposal facility design and optimisation), 7 (Safety case)
Site evaluation and detailed design	1b-2	Phase 2 Phase 3	Site Selection: Site(s) identification and selection, Site characterisation: Underground investigations and site confirmation, Site Requirements, Evaluation Theme 6 (siting and licensing) Site Characterization & Selection
Construction	3	Phase 4 Phase 5	Construction: Facility construction, Operations and Closure: Facility operation and closure (facility construction and construction work carried out during operation and closure) Theme 3 (EBS), 5 (Disposal facility design and optimisation) and 7 (Safety case)
Operation	4a	Phase 5	Operations and Closure

[10] https://www.ejp-eurad.eu/sites/default/files/2019-11/eurad_sra.pdf
[11] https://www.ejp-eurad.eu/roadmap
[12] https://www.ejp-eurad.eu/sites/default/files/2020-01/4.%20EURAD%20Deployment%20Plan.pdf
[13] https://www.ejp-eurad.eu/roadmap

Stage of the repository used for uncertainties identification	Stage Identification number	EURAD phase number	EURAD phase and theme
			(except final closure) Theme 1 (National Programme Management), 5 (Disposal facility design and optimisation) and 7 (Safety case)
Closure	4b	Phase 5	Operations and closure (subphase related to final closure) Theme 1 (National Programme Management), 5 (Disposal facility design and optimisation) and 7 (Safety case)
Post-closure – Indirect oversight	5a	Phase 5	Post-closure phase (first subphase)
Post-closure – No oversight	5b	Phase 5	Post-closure phase (second subphase)

2.2.3 Uncertainty origin and corresponding typology

The factors at the origin of the uncertainty are described and categorised with regard to the various types of human aspects. This helps, firstly to describe the uncertainty, secondly to check that the various categories of human aspects are addressed.

We created 7 categories, which are relevant in identification of human related uncertainties. These categories are the following: Societal, Political, Technological systems, Financial, Governance and risk governance, Socio-technical and Organizational.

We will next provide definitions of the core categories and provide also examples of some of them.

- ***Societal*** relates to or involves society. Societal concerns /problems/values (Cambridge Advanced Learner's Dictionary & Thesaurus, Cambridge University Press). Examples of societal questions relevant for the nuclear waste management context would include social acceptance of nuclear waste management, social media, and societal support for education of experts in the nuclear waste management. Other examples for societal problems that could affect nuclear waste management are wars, distrust in institutions, and increase of right and left wing extremists. Aspects of societal issues also cover issues of human behaviour, including human habits like water consumption and inadvertent intrusion of future generations.
- ***Political*** means the way power is achieved and used in a country or society. Synonyms: governmental, government, state, parliamentary (English Dictionary, Collins) https://www.collinsdictionary.com/dictionary/english/political Examples of political issues: Changes in parliament and governmental power, power politics affecting nuclear waste management, visions and policies regarding nuclear waste management. Aspects of political issues can also cover issues of future geographical borders of countries.
- ***Financial*** is a field that is concerned with the allocation (investments) of assets and liabilities over space and time, often under condition of risk and uncertainty (Wikipedia). Examples of financial aspects: The sufficiency of financial resources regarding the nuclear waste management and final disposal, the way the financial resources are collected, and the way sufficient resources are estimated, uncertainties related to management of financial resources, economic depressions.
- ***Governance*** comprises both the institutional structure (formal and informal) and the policy process that guides and restrains collective activities of individuals, groups and societies. It aims to avoid, regulate, reduce, or control risk problems (Renn 2014). Risk governance refers to a

complex of coordinating, steering, and regulatory processes conducted for collective decision-making involving uncertainty (Renn 2014).

- ***Technological systems*** include technical devices, the organizational routines and procedures, legislative artefacts, and scientific and other knowledge elements such as skills, rules of thumbs and norms for handling of the technology. (Hughes 1987[14]).
- ***Organizational*** refers to structures, policies, resources, roles and responsibilities, relationships between the members of an organization, shared values, norms, beliefs and practices in an organization. Examples of organizational aspects: safety culture, whether adequate resources are allocated to important tasks, whether organization ensures that there are adequate number of experts.
- ***Socio-technical systems*** refer to intrinsic complexity arising from the multidimensional interactions between the human, technical and organizational systems. This is driven by how humans utilize the technologies within the boundaries of the organizational issues, so it is really the interaction of many of the above categories. Concrete examples of socio-technical challenges in radioactive waste management are: the question of siting, reversibility in case of geological disposal (and capacity of implementing alternatives if needed) versus path dependent strategy proposing no alternatives, monitoring: iterative and safety-oriented monitoring strategy versus weaker surveillance strategy aiming at solely bringing confidence (Bergmmans et al., 2012)[15].

Here also, there may be overlaps between the categories. It is not an issue, as the categories were used mainly as a tool to identify the most relevant uncertainties related to human aspects.

2.2.4 Describing the uncertainty

An uncertainty is basically a question to be dealt with[16], therefore we decided to describe uncertainties by formulating questions. Two levels of questions are presented, the first one is more general, the second one is more specific and generally provides examples. There may be overlaps between the two levels.

In order to enhance legibility, it has been decided to add in the table, in complement to this description of the uncertainty through questions, a column for the object of the uncertainty, i.e. what is uncertain.

Moreover, titles have been added for the uncertainties selected of high priority for further investigation.

2.2.5 Limitations of the methodology and consolidation steps

As the methodology described above is analytical, it might appear able to capture all the most relevant uncertainties related to human aspects. In fact, an attitude of modesty should be kept, because of the variety of human aspects, of the limited time available and of the restricted size of the subtask expert group.

Moreover, there is a risk to think that following the lifecycle, all the uncertainties are accessible to identification. In fact, there are uncertainties cross-cutting several stages. Therefore, it is very important to keep in mind that hanging uncertainties to stages/phases is only a tool.

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[14] The Social Construction of Technological Systems, T. Hughes, 1987, MIT press

[15] Bergmmans, Anne, Schroeder, Jantine, Simmons, Peter, Barthe, Yannick, Meyer, Morgan, Sundqvist, Goeran, Martell, Merixell, Kallenbach-Herbert, Beate (2012). International Socio-Technical Challenges for Geological Disposal (InSOTEC): Project Aims and Preliminary Results - 12236. WM2012: Waste Management 2012 conference on improving the future in waste management, United States

[16] For example, in a more technical domain, uncertainties associated to measurement could be expressed as "Knowing the measured value of the parameter, what possible values should be considered for the studies?" (*I suggest modifying this example because the way the value considered in the studies is selected is not linked to the measurement but the to the uncertainty management strategy)*

In order to help addressing these limitations, complementary views are being incorporated along the development of the subtask, namely from the answers to the questionnaire and from Subtasks 2.1 and 4.2, and Task 5.

2.3 Characterization

The characterization process consisted in filling in the 4 main columns of the Excel table, (plus extra columns for cross-checking and support information for the main columns):

- "detailed characterization": detailed description of the uncertainty,
- a focus on the potential consequences of the uncertainty, as contribution to risk assessment,
- challenges and potential options for risk management,
- uncertainty significance for the actors.

Characterization is more complete for the uncertainties that have been selected as of higher priority for further investigation according to the first step of the process.

2.4 Uncertainties selection (for further investigation)

Selecting a restricted number of uncertainties is necessary because of the wide scope of human related uncertainties and limited resources of the UMAN work package. The expert group performed thus a rating of the level of priority for further characterization and interactions with other subtasks. This rating was based on the following criteria:

- The potential impact on safety,
- The potential impact on decision-making,
- The existence of referenced work in this field and the interest for further studies and research.

In the end, a priority rating (high/medium/low) has been given by the experts' group to each uncertainty. It takes also into account the diversity of situations of the national programmes represented by the members of the expert group: for example, if an uncertainty is considered to have a high priority by one expert, but not so high by another and after discussion positions are unchanged, the high priority rating prevails. The reasons for rating are explained, in order to track back the selection process and allow further inputs.

Only the uncertainties assessed as having a high priority within the rating criteria in the selection process were taken into account for further evaluation.

2.5 Inputs from the questionnaire: general comments

2.5.1 Establishment of the questionnaire

The content of the questionnaire was based on the 10 high priority uncertainties listed in the preliminary list of uncertainties (UMAN MS23 (Dumont 2020)) which were slightly reformulated for better legibility.

Instead of rating the priority for further investigation, which was no longer relevant, the rating asked was about significance for safety (which allowed for confirmation or not of the selection).

Concerned generations were the present and next / close future generations / remote future generations.

Comments could be added through the "why" (relating to the rating) and "other" questions.

The questionnaire could be answered either online or through a word file, with a series of optional questions but without the requirement for answering all aspects (such as not all wastes). It was expected that all organizations respond with respect to human factors on issues that were most critical to their program. This leads to an inherent limitation for result interpretation.

2.5.2 Compilation of the answers

The number of answers received (29 answers, altogether; 16 responding organizations, from 11 countries) is rather significant. It allows for observing some tendencies, but it is too small for a statistical analysis.

Table 2 presents the list and profile of the respondents:

Table 2. List and profile of the respondents.

Acronym		WMO	TSO	RE	CS	Near surface	Subsurface	DGD	Belgium	Czech Rep	Finland	France	Germany	Netherlands	Slovakia	Slovenia	Spain	Sweden	Switzerland	Online answers	Word files
V	**VTT**		1					1			1									1	
A	**Andra**	1				1		1				1								2	
Be	**BelV/FANC**		1			1		1	1												2
Bg	**BGE**	1						2					1								2
Co	**COVRA/NRG**	1						1						1							1
Cv	**CVR**			1		1	1	1		1										3	
Ei	**EIMV**		1			1	1	1								1				3	
En	**ENRESA**	1				1											1				1
G	**GRS**			1				2					1								2
I	**IRSN**		1				1	1				1									2
N	**NAGRA**	1						1											1		1
O	**ONDRAF**	1				1		1	1												1
Sk	**SKB**	1					1											1			1
Sura	**SURAO**	1						1		1										1	
Sur	**SURO**		1			1	1	1		1										3	
Sut	**SUT**			1		1		1							1						1
	Total	8	5	3	0	8	5	16	2	3	1	2	2	1	1	1	1	1	1	13	14

The expert group of Subtask 3.4 faced some difficulties in exploiting the results of the questionnaire.

First, as the possibility had been offered to the respondents to answer either directly online or in a word file, the group had to manage two formats of answers.

Second, unfortunately, the first version of the word file was not totally consistent with the online questionnaire:

- In the word file, question E was erroneously pasted from the questionnaire on waste inventory. Therefore, most respondents of the word file questionnaire have not answered the question on the uncertainty related to the programme schedule to be considered.
- The first word file questionnaire did not correlate the questions with the type of repository, thus leading respondents to provide a general answer valid for all the types of repositories they are involved in.

The answers obtained are either laconic, minimal, or comprehensive qualitative answers.

Overall, despite these difficulties and thanks to the respondents, the answers collected have stimulated the reflections of the group and allowed to populate the description of the uncertainties.

2.5.3 Analysis of the answers

Concerning the selection of uncertainties for the questionnaire, it can be said that it was relevant since:

- The level of significance was generally widely spread, from Low to High level of significance, for each uncertainty
- There were a few extra uncertainties proposed by the participants but the authors decided on a final list of 10 that encompassed the primary drivers. In addition, some of the extra proposed

uncertainties in the questionnaire did not receive sufficient support from the other respondents to be included to the final list of uncertainties.[17]

No correlation could be easily seen between the level of significance and the type of organisation (WMO, TSO or RE); experts from the various types of organisations often rate at the same level of significance.

The overlap of some uncertainties, already noticed by the expert group, was also visible in the answers to the questionnaire.

2.5.4 General lessons learnt from questionnaire

A suggestion for potential further questionnaires (in general) is to have only one format. In case the online one is chosen, a word file may be provided in order to help prepare a collective answer, but the finalized answer should be uploaded online by the respondents.

About the selection of uncertainties: there was no reason to modify the present list beyond what was initially identified. All uncertainties have been considered as highly significant by at least a few experts who replied to the survey, and no new uncertainties were flagged for inclusion.

The phase of the programme seems to be a prominent factor for the level of significance of an uncertainty. On the other hand, variations according to the type of repository are not clear cut.

3. Uncertainties selected to be investigated in more detail

The scope of human-related uncertainties is very large. Therefore, the subtask expert group, after having identified a list as wide as possible (58 uncertainties), rated them according to their priority for further investigation. Ten uncertainties have been rated of high priority. They are presented here. The complete list of uncertainties associated to human aspects is presented in Appendices A and B.

The 10 highest priority uncertainties are presented, first in a table form derived from the preliminary work of the expert group (see Chapter 3.1), then through a description synthesizing the outputs from the various sources (see Chapter 3.3).

Among these 10 uncertainties, 4 were further characterized in the 2nd workshop of task 4 (Mikšová, 2022) and the 3rd seminar of Task 5 (Dumont 2023).

3.1 Presentation of the 10 uncertainties investigated

Table 3 *hereunder* presents the 10 uncertainties selected by the expert group which were elaborated on within more details based on discussions.

The ID number refers to the identification number of the uncertainty among the whole list of uncertainties. How it has been attributed is explained in Chapter 3.3.1, with the identified thematic letters.

The identification of the uncertainties is expressed through the general question raised by different human aspects, sub-questions and comments. A title has been also added for better legibility. This title has been used to describe the uncertainties, sometimes associated with questions and sub-questions, in the second questionnaire sent to EURAD participants.

[17] The possibility of human intrusion has been identified as missing by some participants, but it may be considered as a high-level uncertainty that derives in uncertainties already identified: 1) on the process for defining the requirements associated to the risk of human intrusion (uncertainty A), 2) on the robustness of the associated requirements (C) and 3) on the robustness of the safety case vis-à-vis the risk of human intrusion (F).

Table 3 – List of uncertainties investigated in more detail.

ID number	Chapter topic	Title	Description: 1) General question	Description: 2) sub-questions/examples	Comments
0.1	***A***	***Uncertainties in the process of identification of a workable set of repository requirements*** *(taking account of the sometimes-conflicting expectations of the various stakeholders)*	From the sometimes-diverging requests of the various actors, what should be the consensus on requirements specification for the design?	How should we resolve variations between regulatory requirements and local municipality's expectations to meet the facilities safety?	In addition to the requirements from the regulation and from the needs of the waste producers, the neighbours of the disposal facility may express specific requirements that may conflict safety rules (e.g. regarding close monitoring). The need for repository acceptance requires to take them into account. Refers to governance, democracy, regulation of conflicts, political science. Uncertainty considered here results only from the current map of actors, without time evolution.
0.4	***B***	***Uncertainty in the continuity of the waste management policy along political changes***	Is there assurance of RW policy continuity where political changes can impact the process?	How should the RW disposal process be defined?	Link to existing and binding Waste Directive or other conventions (Joint Convention) where national program is required. The experience with first national reports shows that national programs did not provide all requested information.
1a.2	***C***	***Uncertainties associated with the robustness of the presently considered safety requirements and the scenarios used for the safety case w.r.t. the long term***	Will changes in societal expectations regarding long term protection of Man and Environment (and the level of effort that present and next generations should sustain) to protect remote generations lead to evolution of the safety requirements?	Will changes in assumptions on human habits in the long term impact the safety case? Does it make sense to assess safety at 50 000 years on the basis of scenarios that consider human civilisation as in present state? For long-lived, low-level wastes, which is the suitable trade-off between protection in the long-term (pointing towards deep disposal) and protection against a low level of danger (pointing towards surface disposal)?	Though regulation and safety guides provide a general answer to the question of the safety goal on the long term, safety assessment requires detailed assumptions for the distant future (scenarios, representative persons) that are the product of the present uncertainty management strategy. Ethical dilemmas: inter-generational and intra-generational justice
1b-2.1	***D***	***Uncertainty in the public acceptance of the repository at potentially suitable or projected locations***	Will the repository be accepted there? How should communication/SE be integrated in the decision process?	What is the attitude towards repository in community? Has there been any facility for which the public has shown the NIMBY effect? What possibilities for engagement are given to the public? Are all relevant stakeholders identified and mapped? Is there a relevant process established to communicate and engage with stakeholders? How is the communication and Stakeholder	NIMBY, licensing process, veto right, prospects for new technologies; Communication and SE strategies are tools for managing the acceptance uncertainty but may be unsuccessful.

ID number	Chapter topic	Title	Description: 1) General question	Description: 2) sub-questions/examples	Comments
				Engagement (SE) process integrated in decision making process for site selection?	
1b-2.2	***E***	***Uncertainty in the schedule considered for implementing the different phases of the disposal programme***	How long will the implementation of the disposal programme last?	Under what conditions will the safety case be agreed by the regulator? Are the regulatory requirements set and understood by all? Who are official regulators and how are they involved (nuclear, radiation, environmental…)?	Key phases in licensing. Costs added by delay.
4a.1	***F***	***Uncertainties associated with the robustness of the safety case vis-à-vis socio-technical factors***	Are human and organizational factors together with technical factors properly taken into account in the safety case? How can political uncertainties affect licensing and the different programme phases?	How is efficient communication ensured between the different experts? Who has the expertise to have an overall picture of safety? How do political uncertainties affect licensing? How should we take into account the possibility of unintentional errors?	A nuclear accident may raise opposition also to RW facilities.
4a.2	***G***	***Uncertainties associated with new knowledge***	Will new knowledge, insights or monitoring techniques reveal deficiencies that need to make corrective measures?		
4a.3	***H***	***Uncertainties in the adequacy of safety-related activities (in siting, design, construction, operation and closure) for the implementation of (operational and long-term) safety provisions***	How can changes in organisation and safety culture affect operational and post-closure safety?	How is it ensured that knowledge management is taken care of? How is it ensured that people have got adequate training?	Interactions between human and technology, enhanced by remote control, create uncertainties. .
4a.5	***I***	***Uncertainties associated with the robustness of safety vis-à-vis possible cyber-attacks or programming errors***	How should organisations take into account the possibility of intentional actions and errors?		
4a.8	***J***	***Uncertainties in the availability of well-educated human resources, and relevant experts in radioactive waste management along the repository lifetime until closure***	Are there sufficient human and the corresponding financial resources available?		Ensuring continuous education of experts for the nuclear waste management is mandatory. This task cannot be managed by single organisations, but the education of experts requires support from national and international (e.g. EU) levels.

3.2 Further selection of the four key uncertainties discussed in Tasks 4 and 5

The classification scheme considered in Subtasks 2.1 and 4.2 introduces a first criterion for selecting a representative set of uncertainties:

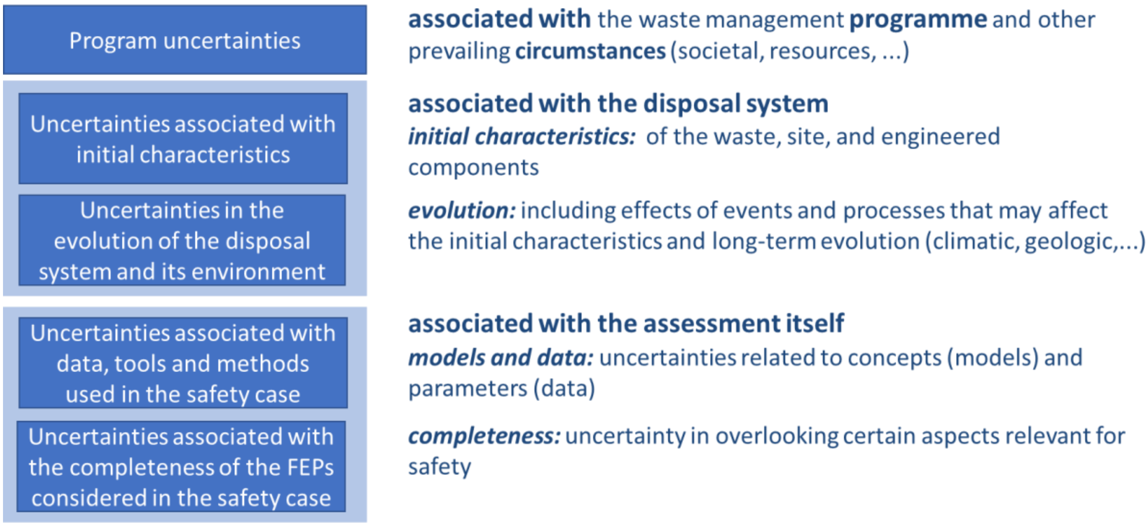

Figure 1 – uncertainty classification scheme considered in subtasks 2.1 and 4.2 (from F. Lemy's presentation, task 5 meeting, 2020-12-11).

Previous collective work (2nd joint workshop IGSC/FSC[18], UMAN seminar n°1[19]) introduced a matrix based on the use and availability of information, that leads to identifying four types of information, of which three them are corresponding to uncertainties. This matrix, related to what could be called "information awareness", is presented in **Erreur ! Source du renvoi introuvable.**.

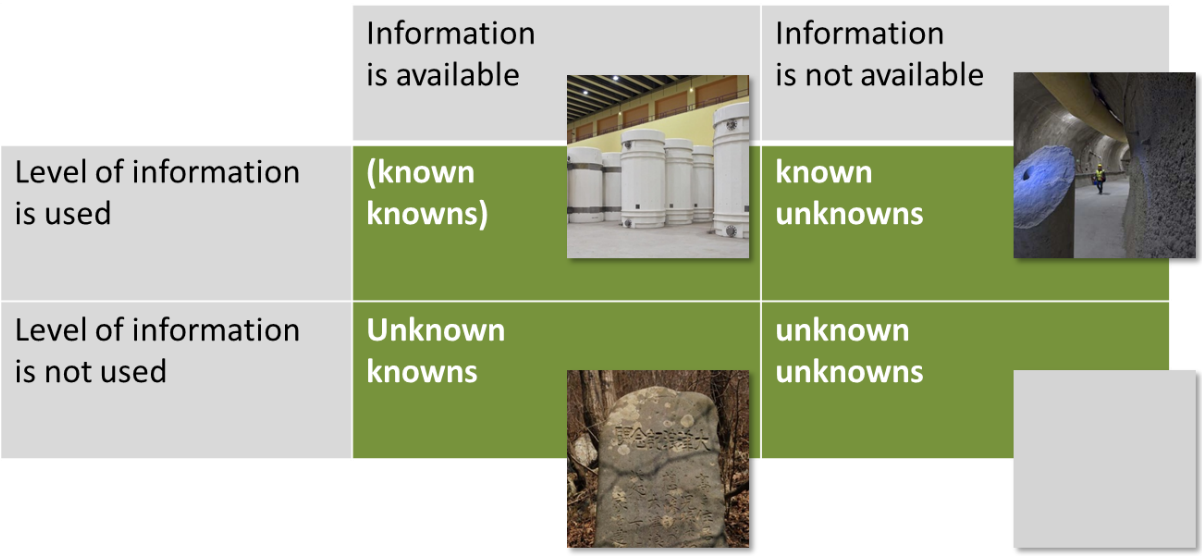

Figure 1. Types of information awareness.

[18] See 2nd joint Workshop IGSC/FSC, 9 October 2019, Perspectives on risk and uncertainty, A. Eckhardt.

[19] The first seminar of Task 5 was held on 26-27 October 2020 and was entitled. What does uncertainty management mean for different types of actors and how is it related to risk, safety, and the safety case?

This introduces a second criterion.

Combining both criteria provides a matrix. The set of uncertainties which was discussed within the 2nd workshop of Task 4 (Mikšová, 2022) and the 3rd seminar of Task 5 (Dumont 2023) was established so that each row and each column of the matrix would be represented at least once, while limiting the number of uncertainties to 4 because of time constraints.

		Known Unknowns	Ignored Knowns	Unknown Unknowns
Programme uncertainties	Schedule (E)	e.g. duration of the licensing process	e.g. ignored lack of financial resources	e.g. unconceived political instabilities
	Public acceptance (D)	e.g. conditions set by a community for accepting the project on their territory		e.g. unconceived negative decision of a community
Uncertainties associated with initial characteristics	Implementation of safety provisions in construction – characteristics of the built components (H)	e.g. uncertainties in as-built repository components (due to construction errors)		
Uncertainties in the evolution of the disposal system & its environment	New knowledge (G)		e.g. ignored possible magnitudes of disturbing events (e.g. Fukushima)	e.g. really new knowledge, unexpected, with possible impact on the safety case
Uncertainties associated with data, tools & methods used in the safety case	Implementation of safety provisions in construction – tools & methods (H)		e.g. ignored mistakes in methods for implementing safety-related activities (e.g. 2nd WIPP incident)	

3.3 Characterization of human aspect uncertainties

3.3.1 A: Uncertainty in the identification of a workable set of repository requirements

Detailed characterization

This uncertainty is described with the main question "How will the set of requirements (regarding long-term safety performance, WAC, environmental impact, etc.) be fixed, taking account the sometimes-conflicting expectations of the various stakeholders?" Several additional sub-questions are linked, and all point out potential different interests and expectations from various stakeholders like: "How should we address the interests and requests of neighbours of existing polluted sites (benefiting from waste being sent far away) together with the interests and requests of neighbours of existing or planned waste final repositories? How could the legitimate requests be included in the RWM policy? How could the irrelevant requests be discarded? What is the willingness to include requests connected to public acceptance of repository? How is the consistency of governance policies maintained?”. This is not only about the process itself, but the uncertainties associated with the process itself.

Depending on how it is performed, the identification of requirements can lead to different results. Some of the requirements regarding operational and long-term safety of the disposal may indeed be different according to who is involved into their identification.

The uncertainty was ranked as high priority for further investigation by the subtask expert group as it has medium impact on safety and high impact on decision making. The growing level of information of all stakeholders leads to a growing need to establish shared decisions, whereas the interests are sometimes diverging. The decision-making processes regarding public decision can no longer be implemented alone without participation of stakeholders. New processes, combining representative and participatory democracy, are emerging. Nevertheless, there is still a need for progress in this field.

Potential consequences of uncertainty

The impact of the uncertainties linked to the process of identification of repository requirements is mainly on the decision-making. If this process does not consider various sources of expectations, from various stakeholders, the acceptance of the project might be at stake.

Delaying the decisions for a repository may have consequences on the whole schedule of radioactive waste management, when for example waste already exists and is stored in surface facilities without sustainable solution (e.g. in France, graphite, radium-bearing waste, LL-LL bitumen waste envisioned for subsurface disposal). The absence of definitive solution may also tend to delay the dismantling of the reactors.

Regarding safety, the level of protection of future generations highly depends on the requirements that will be defined (and how they will be defined).

Significance for the actors and its evolution along the programme

The uncertainty is expected to reduce throughout the different programme phases if the decisions made at each phase are supported by the various stakeholders.

Challenges and potential options for risk management

When developing the approaches to the RWM policy, framework and programme establishment, therefore already at beginning in phase 0, it has to be taken into consideration also the international legal framework which relates to the different and diverging requests of the various actors which will participate in the RWM activities, and RW disposal establishment. Some inputs for such approach are established by Aarhus convention, ESPOO convention and the EU legal framework, like EIA directive, that then govern the national legal requirements. However, the details, when and how different actors with diverging requests can be involved, what requests can be included and how the legal requirements from nuclear and radiation safety can be challenged, is open to national approaches.

The requests of other actors may on one hand conflict with nuclear regulatory requirements, thus cannot be considered, or on the other hand could benefit the process without jeopardizing the safety issues. The approach of what is the appropriate level of inclusion should be developed already at phase 0, with the objective to identify opportunities for constructive participation, and then re-assessed with the successive phases being implemented.

Regarding political uncertainties which are not quantifiable, we are in the perplexity domain of the uncertainty. This requires the development of scenarios on the various potential options: different host rocks, different sites, combined solutions such as storage that can be converted in disposal, etc. For all these identified options, an assessment should be made.

Modelling of repository performance is in particular helpful to guide the definition of the requirements.

As for ethical issues across generations, ethical matrixes may be used in order to detail stakeholders and challenges according to ethical principles or principles of justice.

Other information collected through the questionnaire

In the questionnaire, this uncertainty was described with the main question: "*How will the set of requirements (regarding long-term safety performance, WAC, environmental impact, etc.) be fixed, taking account of the sometimes-conflicting expectations of the various stakeholders?"*

This uncertainty, that was ranked initially to have medium (2) level for safety impacts and high (3) for level of impact on decision making process with high priority for further investigation was assessed by different types of organisations responding to the questionnaire. In total 8 WMO, 5 TSO and 3 RE participants responded to the uncertainty A. Their responses were from low to high for significance for safety or decision-making process at the current stage of their RW programme. Most of the answers were related to the near surface and to the deep geological disposal. The answers can be seen from the graphs hereunder.

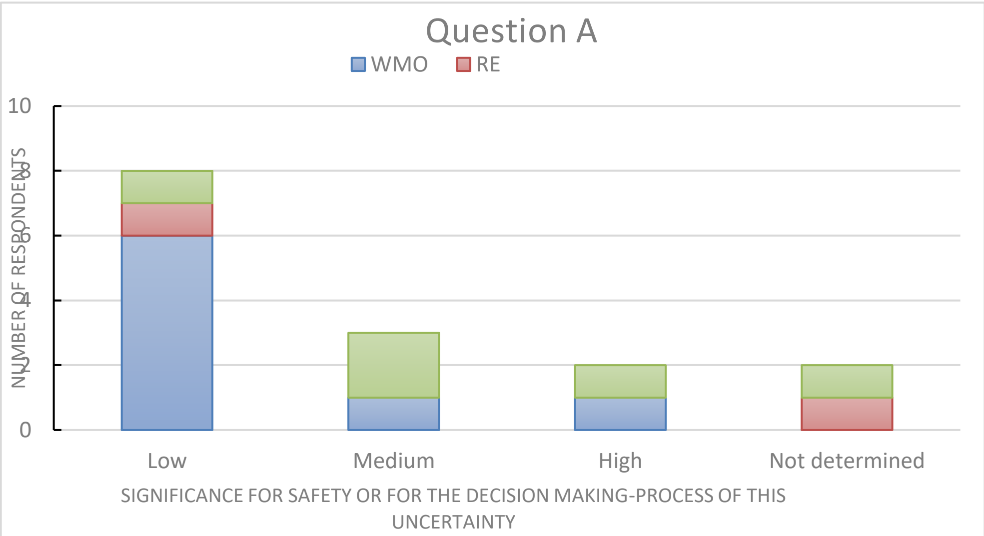

Figure 2. Results from actors on the questionnaire on uncertainty of identification of a workable set of repository regulations for deep geological disposal facility. Note that most actors indicated that the impact on the safety or the decision-making process of this uncertainty is low.

The participants further characterised the uncertainty A. The requirements and approaches should be clearly defined to assure confidence for different actors. For the future generation more important is the assurance of control and resource. In some countries, guides have been published by the safety authority, dedicated especially to geological disposal. However, such guides are essentially (almost only) focussing on long-term safety and not on operational safety. The level of details of course depends on the phase of the disposal programme. For example, for operating disposals the conformity with requirements is controlled by regular inspections performed by the regulatory authority at the facility. Also, international development on requirements and experience with similar facilities is followed.

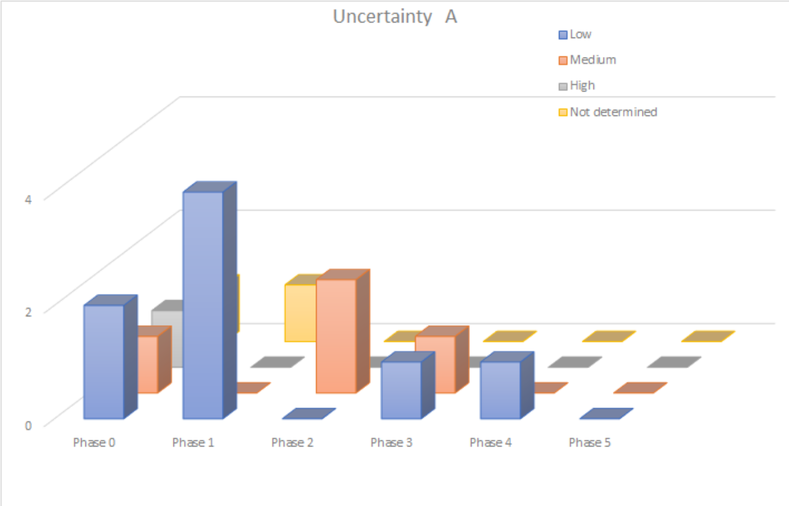

Figure 3. Results from actors on the questionnaire on uncertainty of identification of a workable set of repository regulations for deep geological disposal facility. From the figure, no clear correlation can be deduced between the phase and the impact of this uncertainty on the safety or the decision-making process.The participants further characterised the uncertainty A. The requirements and approaches should be clearly defined to assure confidence for different actors. For the future generation more important is the assurance of control and resource. In some countries, guides have been published by the safety authority, dedicated especially to geological disposal. However, such guides are essentially (almost only) focussing on long-term safety and not on operational safety. The level of details of course depends on the phase of the disposal programme. For example, for operating disposals the conformity with requirements is controlled by regular inspections performed by the regulatory authority at the facility. Also, international development on requirements and experience with similar facilities is followed.

Contextual (or programme) uncertainties are very difficult to characterize. This difficulty needs to be taken into consideration in waste management programmes (e.g., through regular interactions between different stakeholders) so as to reduce the uncertainty and mitigate as far as reasonably achievable the risks associated with this uncertainty.

On one side the near generation is more concerned as the issue is on the table. But radioactivity decreases with time, so uncertainty impact reduces. However, the perception of the public can be different. So, the assurance of control and available resources should be shown over a longer time.

The impact of the uncertainties linked to the process of identification of requirements is mainly on the decision-making. It has to provide the opportunities for all actors to present and expose the expectations which would need to be addressed to reduce the risk of endangering the project.

This uncertainty depends on the current phase of the national programme. This uncertainty is more important during the first phase of the programme where the regulatory framework is developed. The uncertainty is expected to reduce throughout the different programme phases if the decisions made at each phase are supported by the various stakeholders. The set of requirements for facilities which are foreseen in the far future (after 2100) are not an issue and the adjustments still can easily be made.

3.3.2 B: Uncertainty in the continuity of the waste management policy along political changes

<u>Detailed characterization</u>

This uncertainty is described in the questionnaire with the main question “Is there assurance of RW policy continuity where political changes can impact the process?” There are several additional sub-questions linked to this main question, namely: “How should the RW disposal process be defined? Which basic elements should be agreed to assure continuation? What EU level requirements should be set?" More specifically, this uncertainty is characterized by a waste management policy that is unstable and hence could change rapidly or becomes part of a political game.

This uncertainty has been given a high priority for further investigation by the expert group. This high priority has been assessed since political changes can modify the priorities in public decisions. This could result in freezing / stopping of the waste disposal projects, while radioactive wastes are still existing and are in production. The freezing or even stopping the waste disposal project can create a loss of impetus in the process, knowledge management issues, and possible safety issues in the storage facilities.

This uncertainty links to existing and binding waste directives or other conventions (Joint Convention) where a national programme and national regulations, are required.

Potential consequences of uncertainty

This uncertainty has a wide variety of potential consequences.

This uncertainty, for example, could lead to an increase in decision's time and potentially in an increase of cost as longer storage at the surface is needed. Furthermore, if wastes are still produced when no decision has been made, the waste may pile up at different nuclear sites under a wide variety of conditions which might have a deteriorating effect on the waste. This in turn could increase the cost of disposal and might even affect the safety of disposal.

Another potential effect of this uncertainty is that not having a stable waste policy might result in the production of waste that cannot easily be processed or stored. For instance, if there are lacking or change requirements, such as governmental-based WAC, the inventory may be diversified that poses challenges for future handling. Another example could be a changing political party that is not willing to make sufficient continuous budgetary investments towards required waste processing infrastructure.

Or, with no stable policy, there could be a lack of funds for a repository as it is likely that no or insufficient funds will be saved for a repository.

Other impacts of this uncertainty concern transferring the responsibility for the safe disposal of radioactive waste and spent nuclear fuel to next generations, leaving the decisions to generations in the future and hence transferring the responsibility and burden to future generations.

Significance for the actors and its evolution along the programme

Overall, it is agreed from the questionnaire that the uncertainty will decrease over time for a deep geological disposal facility as a deep geological disposal facility will only be built when there is public acceptance. Thus, the uncertainty will last until the site selection period. However, from the questionnaire, some actors find it difficult to characterize the uncertainty and thus to predict its evolution through time. Furthermore, one actor in the questionnaire noted that not implementing any solution at all (and thus no deep geological disposal) might impact the safety because the waste must be stored for longer time periods at the surface.

Challenges and potential options for risk management

The impacts of political changes on the RWM should be assessed in terms of technical steps, timelines, funding demands, and human resources.

Strong disposal statements at the EU level are helpful. Hence, at the EU level, it would be good to have a more precise description of what are the minimum levels of acceptability, transposing such requirements to the national legal framework, and monitoring the implementation at the EU level (similar system as now adopted by the Waste Directive).

But foremost, it is important that the RW policy has a (very) broad governmental support making it more robust to changes in government while keeping the option open to change or reverse the RW policy.

Furthermore, a participatory approach (i.e., local partnership) could help to get good local support that could in turn help to keep the programme on-going.

Other information collected through the questionnaire

In the questionnaire, this uncertainty was described with the *question: Is there assurance of RW policy continuity where political changes can impact the process?*

In general, the different actors agree that this has a relative low impact. For the near surface repository, all the actors except a single TSO indicated that this uncertainty has a low impact on the safety or the decision making-process. This single TSO indicated that this uncertainty has a high impact, but this TSO is situated in a country which is currently in phase three (site characterization). In contrast, the other organizations are currently in phase four (facility operation and closure) and thus a step further. This difference in phase might explain the difference in impact. Hence, when a repository is already operational or closed, it is unlikely that political changes will have an impact; it is easier to stop projects that are only at a phase of concept. A project that is already underway and has already materialized, will be difficult to stop for political reasons (disagreement or changes in priorities, etc). Note that this conclusion is based on a small sample size.

For the subsurface repository, the impact of this uncertainty is low according to the actors. However, the number of responders is limited. For a deep repository, the impact of this uncertainly is also low although some actors indicate that it is medium or high (See Figure 4). However, there is no clear correlation between the phase and the impact (See Figure 5). One TSO actor indicated that this uncertainty became only relevant during the site selection procedure and that strategies for its characterization have yet to be developed. On the other hand, a WMO suggested that changes are not expected as constructing a repository is still too far into the future and is not interesting for the politics.

Overall, thus that includes near surface, sub-surface and deep repository, there is a general agreement that the uncertainty will decrease in time although some suggest that it is difficult to characterize this uncertainty and therefore it is difficult to predict its future. Note that some actors indicate that the uncertainty will only increase with time. Regarding the impact on the generations, most actors do not expect an impact on the present and next generations, no impact on close future generations and no impact for remote future generations. An expectation from a TSO noted that for near surface repositories the absence of a license for the facility, if prolonged, might impact the safety of storage facilities. Hence, changes in or the absence of a national policy for the long-term management of ILW, HLW & SF, if prolonged, might impact the safety of storage facilities as it must be extended. The main drawbacks of extended storage are, according to them:

- (1) The necessity to maintain active measures to ensure the safety and security of the facility until a final solution is found for the long-term management of the waste,
- (2) The ageing management of waste packages and engineered barriers as ageing-related issues that have never been faced up to now may arise beyond 60–80 years,
- (3) The burden and costs associated with the maintenance of all necessary active measures until the solution that will eventually be found to manage the waste in the long-term is fully implemented,
- (4) Higher risks associated with the higher probabilities of disruption of these measures as time goes by.

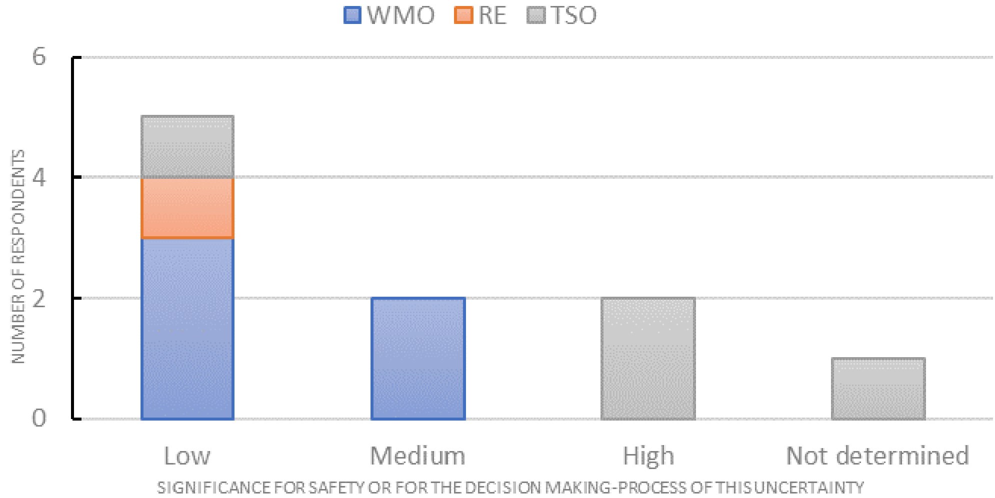

Figure 4. Results from actors on the questionnaire on continuity of the waste management policy along political changes for deep geological disposal facility. Note that most actors indicated that the impact on the safety or the decision-making process of this uncertainty is low.

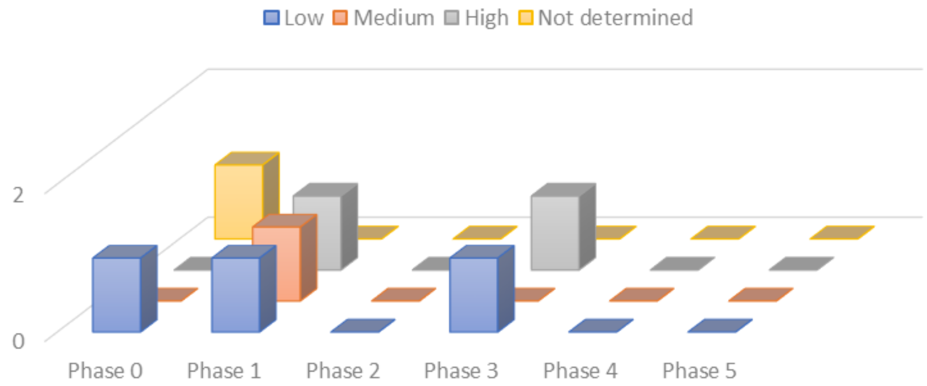

Figure 5. Results from actors on the questionnaire on continuity of the waste management policy along political changes for deep geological disposal facility. From the figure, no clear correlation can be deduced between the phase and the impact of this uncertainty on the safety or the decision-making process.

3.3.3 C: Uncertainty associated with the robustness of the presently considered safety requirements with regard to the long term

Detailed characterization

This uncertainty questions the sufficiency and robustness on the long term of the safety requirements formulated today with respect to how compliance is assessed. It is linked to the following sub-questions: What does the protection of man and the environment mean in the long term? Which level of effort, supported by present and next generations, should we achieve to protect remote future generations? What will Mankind be like in the long-term? Does it make sense to assess safety at 50 000 years based on scenarios that consider human civilization as in the present state? For long-lived, low-level wastes, which is the suitable trade-off between protection in the long-term (pointing towards deep disposal) and protection against a low level of danger (pointing towards surface disposal)?

The uncertainty is further characterized by other questions when considering an intrusion scenario, namely: “What kind of human beings will exist at that time? What will be the level of their technology? What will be humans’ consumption of locally produced food and water? To which extent should we take into account the intrusion scenarios in the design at an acceptable level? Depending on the answers to these questions, for example, the type and number of sealing barriers will vary within a repository and hence the resulting cost of the repository will vary accordingly. This results in defining the effort for present and next generations to be devoted to the protection of remote generations, and not to the nowadays issues. This raises an ethical issue of intergenerational justice (present and next-generation vs remote generations) and intragenerational justice (concerns of present generation on radioactive waste vs concerns on other issues). For this uncertainty, international (ICRP, IAEA) and national regulation and guidelines provide general rules, but the fine-tuning of the requirements depends on interactions between the implementer, the regulator, and other stakeholders.

This uncertainty has been given a high priority for further investigation by the expert group. This is because the uncertainty related to the far future perspective regarding intergenerational ethics has a high impact on safety and more specifically whether a repository should be built or not and what the safety standards must be. It will also have a high impact on the decision-making process, as it could delay and possibly even indefinitely delay the construction of a repository. The research interest is also high for this specific uncertainty.

Potential consequences of uncertainty

A potential consequence of this uncertainty is that it could increase the time (and costs) to reach a decision on the concept and associated changes in safety requirements that most agree on.

Significance for the actors and its evolution along the programme

Most actors responding to the questionnaire consider this uncertainty to have an overall low impact on the safety and/or decision-making process for the various types of disposals, although there are a few actors who indicate that it has a higher impact (medium or high).

There is only one actor who indicated that the uncertainty decreases over time, while others indicated nothing.

Challenges and potential options for risk management

The main challenge is related to the evolution of society, resulting in changing priorities already on the short term (several years to a few decades), and making long-term predictions impossible.

One potential option for managing the risk of this uncertainty is, for example, defining the adequate long-term safety goal by involving the whole society. It is a political decision that requires preparation through a broad and open debate, in which the various arguments (scientific, ethical, economic…) can be presented to an assembly of citizens representing the diversity of the society, but who are not involved in political games.

Furthermore, the holistic radioactive waste management programme, of both surface pre-disposal facilities and eventual repository, should be consistent with the development plans of the affected region and municipalities. There should be continuous engagement with the local region to ensure harmonization and understanding of long-term objectives and implementation of plans and facilities, thus avoiding risks of stopping the programme implementation. If there is a risk for safety, the uncertainty management should include the possibility to stop the implementation, until the problem is solved.

Additional care should be taken to avoid overlooking some processes with potentially significant impact, especially when the requirements are formulated at a general level, while safety must be demonstrated at a detailed level.

Besides, during the programme, sufficient consideration must be paid to the links between environmental issues, social or cultural phenomena, and their interactions. Awareness should be given to how these evolve in the distant generations.

Other information collected through the questionnaire

In the questionnaire, this uncertainty was addressed as follows: *The rating of this uncertainty will depend on* the ease of answering the questions below and broad agreement on*:*

- *What does the long-term protection of Man and the Environment mean?*
- *What level of effort, supported by present and next generations, should we achieve to protect remote future generations?*

The general consensus among actors and the different types of repositories (near-surface, subsurface and deep repository) is that the significance of this uncertainty (uncertainty associated with the robustness of the presently considered safety requirements with regard to the long term) is low. For the near-surface repository, all the actors except one WMO indicated that this uncertainty has a low significance. This WMO suggests that the significance of this uncertainty is medium because the number (interpreted to mean *activity*) of alpha emitters (long-lived radionuclides) that can be accepted into a subsurface repository has been subject to various interpretations in their country. This WMO also indicated that this uncertainty will have an impact on future generation while other actors indicated no impact on future generations. Regarding the evolution of this uncertainty through time, none of the actors indicated how they expect this uncertainty will evolve through time.

For the subsurface repository, two actors indicated that the impact is low while a third actor indicated it is not known or not addressed. None of the actors gave information on how this uncertainty evolves through time and there is no indication regarding the effect on further generations.

For the deep repository, the majority of the actors suggested that its significance is low (six actors), two actors indicated this uncertainty has a medium significance and one other indicated it has a high significance and one actor indicated it is not assessed yet (see Figure 6). For the near surface repository, only one actor indicated that this uncertainty has a medium significance (WMO) while others (1 RE, 3 TSO) gave it a is a low significance. For the subsurface repository, two actors indicated that this uncertainty has a low significance (1 RE, 1 TSO) while one other did not know or did not assess this uncertainty yet (1 TSO). For all the types of repositories, one actor (1 TSO) indicated this uncertainty has an impact on the next generation, two actors (2 TSO) for close future generations, (four actors) for remote future generations (1 WMO, 2 TSO, 1 RE). Other actors (14; 4 WMO, 1 RE, 3 TSO) did not, on the other hand, indicate any impact on future generations. Note that one actor could have selected more than one generation that could be impacted. While there appears to be some difference between actors, a clear (quantitative) trend cannot be observed. This is because the number of respondents is too little to deduce any trend in the data. However, based on the limited data, one could suggest that the significance of this uncertainty is low for WMOs and slightly higher for other actors. Also, more actors do not think future generations will be impacted by this uncertainty. If actors do think future generations will be impacted, it will mostly be the remote generations. An actor (WMO) in the early stage of the programme (phase 0) mentions that changes in requirements for deep geological disposal can easily be incorporated and they have had enough time to discuss this subject. There is also no correlation between the phase and the impact of this uncertainty on the safety or the decision-making process (see Figure 7).

Figure 6. Results from actors on the robustness of the presently considered safety requirements with regard to the long term for a deep geological disposal facility. Note that most actors indicated that the significance for safety or the decision-making process is low.

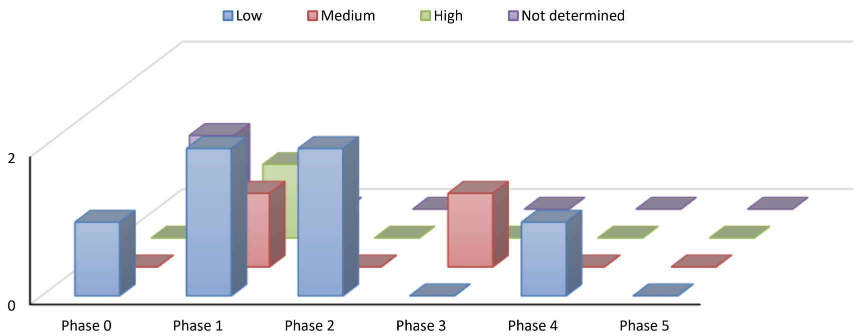

Figure 7. Results from actors on the robustness of the presently considered safety requirements with regard to the long term for deep geological disposal facility. From the figure, no clear correlation can be deduced between the phase and the significance for safety or the decision-making process.

3.3.4 D: Uncertainty in the public acceptance of the repository at potentially suitable or projected locations

Detailed characterization

This uncertainty is described in the questionnaire with the sentence *"public acceptation of the repository at potentially suitable or projected locations*." To this sentence, there are several additional sub-questions linked, namely: "What is the attitude towards repository in the community? Has there been any facility for which the public showed the NIMBY effect? What possibilities for engagement are given to the public? Are all relevant stakeholders identified and mapped? Is there a relevant process established to communicate and engage with stakeholders? How is the communication and stakeholder engagement process integrated into the decision-making process for site selection?". The uncertainty is further characterized by the question of how to increase the acceptance (being open, good communication), how to check how high the acceptance for disposal facility is before site selection, identification of the stakeholders, how to engage with people, and what possibilities are given to the locals (e.g., a veto right), etc. Or, how to deal with locals that express an interest. These may not be strictly limited to the local community hosting the repository, as other communities in the vicinity may feel also concerned, especially because of the transportation of the waste to the repository, and usually will get lower benefits (in terms of jobs, infrastructure...). For CS public acceptance is not an uncertainty as such but a way to manage uncertainty. Public acceptance will result from a well implemented process (including not only technical issues but also socio-technical ones). Public acceptance can be seen as part of the safety system somehow as additional layer. Note that this uncertainty comes into play mostly during the site selection procedure and that it is difficult to decrease this uncertainty through R&D. Social science R&D might help by identifying the best approach towards social acceptance, but it cannot predict or guarantee the outcome.

Another uncertainty concerns the measurement of the public acceptance and how to determine a sufficient level of acceptance.

This uncertainty has been given a high priority for further investigation by the expert group. This high priority has been given based on its impact on the safety assessment and decision-making process. Regarding the impact on safety assessment, it has been noted that different stakeholders may introduce new safety-related issues that need to be reassessed in the safety analysis.

Since this has no direct impact on safety, this uncertainty was assessed as having a medium priority for further investigation by the group of experts. In addition, the stakeholders may require new elements to be included in the decision-making process (more discussion, more meetings, new ideas, ...) which impact the decision-making process in order to improve the system's quality. Based on the latter, this uncertainty is rated as high for the decision-making process. Taking all together, it is assessed that this uncertainty has a high priority for further investigation.

Potential consequences of uncertainty

The uncertainty has a wide variety of potential consequences. One of them is that the site selection can be delayed for a relatively long period, or in the most extreme case, it can even be stopped. Delaying or stopping the siting can have a significant financial consequence as the siting process may have to start from scratch again. This is, however, the most extreme outcome and significant undue costs are unlikely as public acceptance will likely to play (this is certainly advisable) an important factor in the site selection prior to detailed characterization requiring costly fieldwork. Public acceptance could, if not fully achieved, lead to new requirements for the projected disposal facility.

Furthermore, not building a repository, due to lack of public acceptance, requires maintaining active measures to ensure the safety and security of storage facilities that must remain open. Keeping storage facilities open for extended periods will in the long term (1) cost even more money, (2) place the burden on future generations and (3) increase the risk associated with the skills loss political instabilities and aging of the storage facilities. Furthermore, keeping these facilities open increases the exposure times for workers and the number of exposed workers.

Significance for the actors and its evolution along the programme

Overall, it is agreed from the questionnaire that the uncertainty decreases over time and that this uncertainty is most important during the site selection stage. Prior to this stage, this uncertainty is less important although communication is important during these preliminary stages. Furthermore, the actors responding the questionnaire consider that this uncertainty has a low to medium level of significance for near surface disposal facility, low too high for deep geological disposal, but a low significance on the safety and/or decision-making process for subsurface disposal. During Seminar 3, however, TSOs suggest that this uncertainty might not decrease over time as there are large uncertainties in the evolution of public acceptance over multiple decades.

Challenges and potential options for risk management

It is advisable not to start building a repository if public acceptance is not high enough.

Besides local aspects, the public acceptance of a disposal facility may also be affected by larger economic uncertainties, pandemics, etc. Thus, any risk assessment should consider relevant threats and possibilities that go beyond the particular location but may affect local people's acceptability.

Potential options for risk management of this uncertainty are wide. They will be based on open communication, hence access to information, public participation in decision making and access to justice in environmental matters. It is advisable to have participative decision-making processes implemented at each phase.

Specifically, the local community must get strong guarantees that the negative impact on its environment will be low at short term and in the long term, and that the avoid/reduce/compensate strategy has been properly implemented. It must receive recognition and economic benefits from the efforts they make for the good of the country.

In addition, trust building is important during a long-lasting continuous dialog that is independent from future decision points. The trust building process requires clear rules, powers and responsibilities for each actor. A potential challenge is that it takes long time to gain trust, but it can be lost within an instant.

Implementing a stepwise process, as well as popularizing the science (especially to the new generations, so that they become more familiar with the nuclear industry).

Other information collected through the questionnaire

This uncertainty addresses specifically the significance (low – medium – high) for safety or for the decision making-process of the public acceptance of the repository at potentially suitable or projected locations. The related example questions are, for example, what is the attitude towards repository in the community? Has there been any facility for which the public showed NIMBY effect? What possibilities for engagement are given to the public?

Overall, the responses to the questionnaire show that, according to most actors, the significance of this uncertainty for the safety or decision-making process is low. More specifically, for the near surface repository all actors expected that the significance of this uncertainty is low, except for a single TSO who indicated that the significance of this uncertainty is medium. This TSO also indicated that this uncertainty impacts the decision-making process rather than safety. Furthermore, it indicated that nowadays without public acceptance the establishment of a repository is impossible.

Regarding the uncertainty evolution, the overall consensus is that it decreases with time especially if a participative decision process is implemented at each phase to ensure that the decisions made at each phase are supported by the public. For the subsurface repository, with its limited number of responses, the significance for the safety or the decision-making process of this uncertainty is expected to be low with no further information on the evolution of this uncertainty over time. For the deep repository, there is not a consensus on the significance of this uncertainty. Two actors indicated that this uncertainty has a low significance, three actors indicate that the significance on safety or for the decision-making process of this uncertainty is medium, while three other actors indicate that it is high (See Figure 8). There is thus a large variation.

Regarding the impact of this uncertainty on the various human generations, most actors believe that there is an impact on all (present and next generation, close future generations - about a century, remote future generations - more than a century), or only for some of them. The impact, for example, on present and next generation and the close future generations is that the reaction of the civil society is not known during the early stages of the site selection processes. A (not foreseen) negative reaction could lead to a delay in the construction of a deep geological repository effecting the present and next generation and the close future generations when the delay will be relative long. Another actor, who are still in phase 0, indicated that the significance of this uncertainty is low during the present and next generation but increases with time as site selection and the construction of the deep repository is getting closer and hence changing plans under public pressure will have a higher impact. Only when the repository is constructed and subsequently closed, the significance of this uncertainty decreases again. One actor noted that the uncertainties in their current phase (phase 1; site evaluation and site selection) are related to:

- method of measuring acceptance and determining a sufficient level of acceptance;
- active and meaningful participation of all stakeholders - failure to involve any of the important actors,
- building confidence in the programme, possible resistance from local communities,
- special arrangements required by environmental actors and municipalities,
- Expression of interest / VETO right of municipalities – it can have an impact on both the regulatory framework and licensing process and could increase the time required for the entire approval and licensing process.

They noted that most uncertainties related to public acceptance cannot be simply eliminated and/or reduced by developing the degree of knowledge through RD&D activities. The uncertainties can, however, be positively influenced by the timely and active involvement of all interested actors including the public affected, and via a transparent process.

Regarding the evolution of this uncertainty, there is a consensus that it will decrease over time. One actor noted, like for the sub surface repository, that it is better if a participative decision-making process is implemented at each phase to ensure that the decisions made at each phase are supported by the public. Another actor noted that site selection and construction should not start if the support is low. Note that there is also no apparent correlation between the impact of this uncertainty and the phase of the program (See Figure 9).

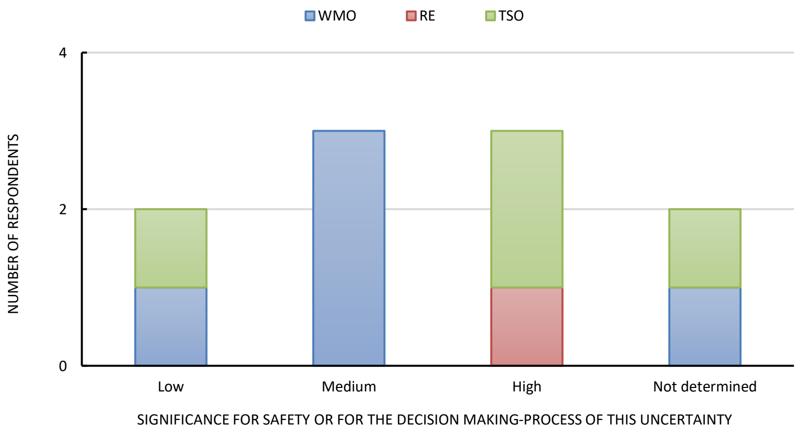

Figure 8. Results from actors on the questionnaire on the significance of the public acceptance for a deep geological disposal facility. From the figure, it is clear that there no consensus on the significance of this uncertainty for safety or the decision-making process.

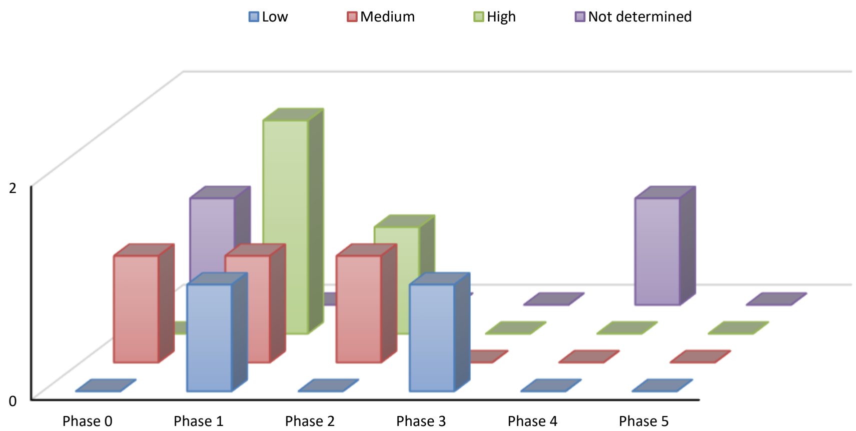

Figure 9. Results from actors on the questionnaire on the significance of public acceptance for deep geological disposal facility. From the figure, no clear correlation can be deduced between the phase and the significance of this uncertainty for safety or the decision-making process. However, most actors indicate that the significance is higher than low.

Other information collected through the workshop of Task 4 (Mikšová, 2022) and the seminar of Task 5 (Dumont 2023) dedicated to human aspects

In addition to the above-mentioned sub-questions, additional sub-questions / uncertainties were identified in the workshop. The WMOs identified the following additional sub questions / uncertainties: are the approvals obtained today stable enough or will there be a reversal in the future? Will there be any constrains (schedule, planning, design, sitting) resulting from the siting processes? TSOs also identified the public acceptance during the (long) disposal phase as an uncertainty.

The Civil Society, on the other hand, identified the following additional sub question / uncertainty: is public acceptance preceded by public acceptability, which would then become a necessary prerequisite for public acceptance, and can public acceptability replace public acceptance? And who are the stakeholders and how does acceptance manifest itself?

In addition, it was mentioned multiple times by the Civil Society that the Aarhus convention is applicable in the site selection procedure. While the latter can be done without public acceptance, if there is none, site selection can become very difficult. It was also mentioned in the workshop that public acceptance should be integrated into the site selection decision for a geological disposal facility.

A way to managing the uncertainty associated with public acceptance is to have regular dialogue with civil society.

3.3.5 E: Uncertainty in the schedule to be considered for implementing the different phases of the disposal programme

Detailed characterization

The main question for this uncertainty is the appropriate timing, for involved decision makers especially, with regard to the agreement on the completeness of the safety case and resources for evaluation. A critical issue is often ensuring an accurate national policy and accounting for the public opinion, in addition to the review by authorities (of both governmental policy and regulatory review), but this is very country dependent. The main question is then supported by several sub-questions that define the uncertainty more in detail:

“To which conditions will the safety case be agreed by the regulator? Are the regulatory requirements set and understood by all? Who are official regulators and how are they involved (nuclear, radiation, environmental, …)? How do political uncertainties affect licensing? Will the regulator have enough resources to judge the safety case according to the schedule?”

The licensing process depends not only on the nuclear safety regulator, but also on several other institutions in charge of environmental issues, land-use planning, heritage preservation; the local communities may also have their say and hosting a repository may require revising the set of urban planning documents in order to make them compatible. Stakeholders may file lawsuits. A minimum time limit for consideration by the regulator is often given, but no deadline, and questions raised require time to be answered. Furthermore, evolutions of regulatory requirements may occur.

This results in a complex licensing process where no final point can be defined in advance, all the more so as a repository is an expense that does not always bring financial benefits for the waste producers. This is dependent on the national funding policy, where in some cases there is no financial incentive to accelerate the elaboration of the required files and answers to the final waste deposition challenge.

Potential consequences of uncertainty

The main consequences of this uncertainty are delays in the development of the programme and increased costs.

Namely, evolutions of regulatory requirements can impact the safety related documentation that have to be prepared and reviewed for licence. If there is no agreed decision-making process with all authorities, different authorities may issue contradictory statements with no clear way to solve this contradiction. This can have impact on modifications of the legal framework, the safety document development, and the time for decisions.

Significance for the actors and its evolution along the programme

Unfortunately, in the questionnaire this question was not addressed in half of the answers (most of the answers provided to the word format), therefore the panel of actors is very limited. In total there have been only 8 respondents: 3 WMOs, 4 TSOs and 1 REs.

According to the subtask expert group, the impact is medium on safety (not direct, but indirect) and high on decision-making (followed by delays and needs for additional financial resources).

This uncertainty will presumably be reduced with the implementation of the disposal programme throughout the phases.

Challenges and potential options for risk management

The actual schedule is the result of a mixture of technical constraints and of strategies of the various actors, with sometimes opposite interests, leading to unreducible uncertainties. The overall schedule is also adjusted based on economical budgeting constraints that can be linked to the national policy for implementation. However, a more robust planning might be developed by establishing a draft planning of the successive major decisions regarding the repository, in the multi-phased licensing steps and beyond, and presenting it for comments to the various stakeholders, so that a consolidated shared view on the planning and important decisions regarding the RW management option may emerge. This process should be reconducted regularly, including at each milestone, for updating the planning.

Scenarios are used to understand the possible evolution of the disposal facility and its surroundings (IAEA SSG-29, 2014), which impact the issues of overall design, construction, operation and closure schedules with respect to human capacity, waste inventory and environmental evolution. In addition, scenarios are used to plan the long-term management of radioactive waste. Scenarios are seen as necessary tools to forecast the waste quantities expected in the future (IAEA NW-T-1.14, 2018). For instance, predictions of future increase of waste, and updates regarding environment and boundary conditions, as well as other uses of radioactive material are addressed. These are important for the planning of facilities needed for storage, treatment, disposal and for establishing adequate funding for future waste management. (IAEA, NW-T-1.14, 2018). Despite the relevance of scenarios, the definition of scenarios is not provided in the IAEA reports.

Other information collected through the questionnaire

The uncertainty E was responded only by seven actors. d It was ranked to have medium level (score 2) for safety impacts and high level (score 3) for the decision-making process, with high priority for further investigation. The actors' responses were from low to high for significance for safety or decision-making process at the current stage of their RW programme. Most of the answers were related to the deep geological disposal. The answers can be seen from the graphs hereunder.

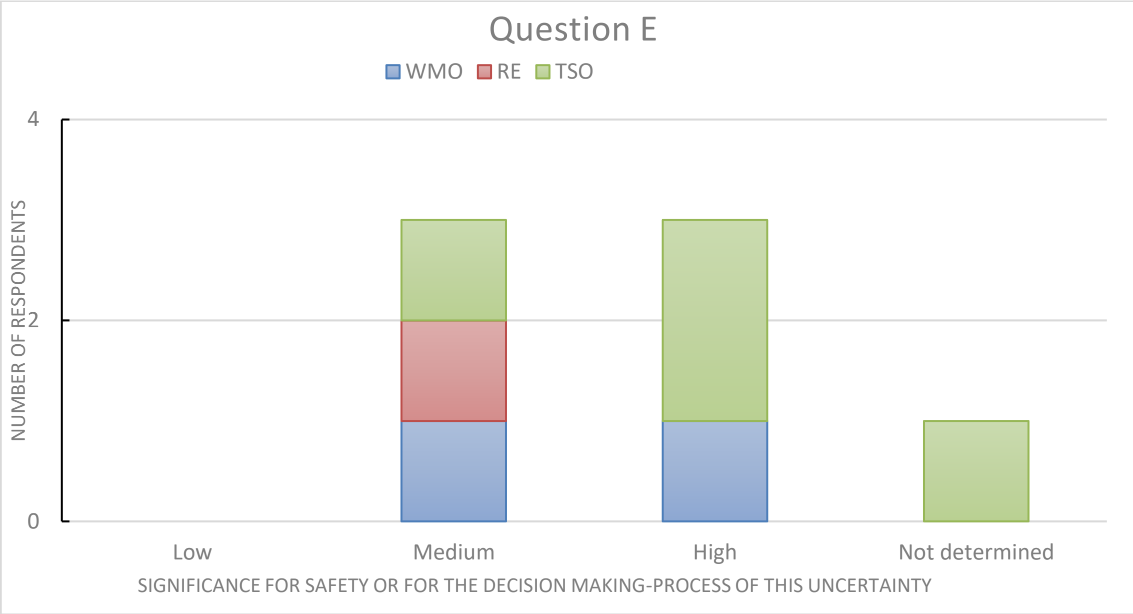

Figure 10. Actors' views on the uncertainty associated with the schedule to be considered for implementing the different phases of the disposal programme for a deep geological disposal facility, as resulted from the questionnaire.. Results show that most actors believe that the significance of this uncertainty for safety or the decision-making process is medium or even high.

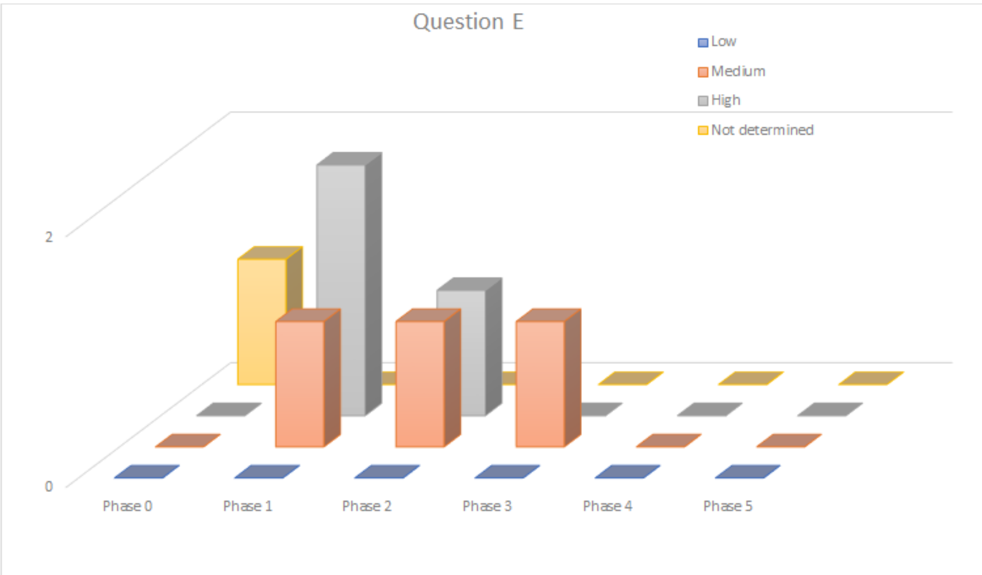

Figure 2: Significance for safety or decision-making of11. the uncertainty on schedule to be considered for implementing the different phases of the disposal programme for a deep geological disposal facility. Results show that most actors assess this uncertainty for safety or decision-making process is medium or even high in particular in Phase 1 and 2.

In addition, the participants stress the robustness of the waste management provisions vis-à-vis potential societal disruptions. Technical, administrative and social issues may drastically change any implementation plan. The schedule of the development of a geological disposal depends on various aspects (costs, politics, knowledge e.g. of the waste to be disposed, public acceptance…). Some of these aspects being subjects to quick changes, these uncertainties are very difficult to characterize.

Once the construction of the geological disposal has started, and between each major decision point (start of operation, closure of the cells/final closure…) these uncertainties are expected to reduce. It is nonetheless expected, according to the preliminary governance of the disposal programme, that the major decision points will be subject to public consultation.

It is acknowledged that various uncertainty can add delays in the implementation of the program schedule due to insufficient support and acceptance by the public and political changes in the phase of site selection, site characterization and decisions on the location of the deep repository and its construction. The schedule may also be affected by uncertainties regarding the provision of sufficient financial and raw material resources (e.g., sufficient bentonite stocks for barriers) and the availability of appropriate technologies.

Other information collected through the workshop of Task 4 (Mikšová, 2022) and the seminar of Task 5 (Dumont 2023) dedicated to human aspects

The participants clearly state an important additional question for this uncertainty: *"Is the planned schedule robust enough?"* If the activities with repository establishment are delayed, they have other impacts on safety like longer interim storage operation, ageing of waste packages and needs for constant maintenance of all SSCs in such facility. The delays in schedules also impacts the future operator of repository in the areas of human resources planning, budgeting and costs assessments (potential for lack of resources) and also if already in construction, its implementation. In some countries concept of retrievability adopted may have a strong impact on schedule. Therefore, the actual schedule should be robust enough and should be the result of a mixture of technical constraints and of strategies of the various actors, with sometimes opposite interests, leading to unreducible uncertainties, including political uncertainties.

Civil society representatives pointed out some additional questions to be taken in this uncertainty: *To what extent should uncertainty on schedule be considered as an uncertainty for safety?* Postponing decisions can be a condition for improving safety (precautionary principle), taking appropriate time to manage unexpected events or uncertainties. Differences of views between several authorities involved in the decision might be at the origin of disclosure of problematic aspects of safety (e.g. the Swedish context and the copper corrosion issue). However, postponing a decision requires an appropriate plan B, in order to minimize unnecessary waste packages ageing and potential deterioration.

In the group discussion during the seminar also the uncertainty related to schedule was discussed. Two cases were used for opening the discussion, first presenting the case of consequences of postponement on safety (shift of start of repository operation for four years, and second on safety issues due to a tight schedule shorten from original 10 years to only 6 year of URL operation). The discussion results proved an agreement between participants that such events are quite possible, the consequences should be anticipated, different actors should address the related RWM issues, discussion with affected stakeholders should be organised. More can be seen from the workshop Deliverable D10.15: Pluralistic analysis of uncertainty related to human uncertainty (Dumont, J.N. 2023, *in review*).

3.3.6 F: Uncertainty associated with the robustness of the safety case vis-à-vis sociotechnical factors

Detailed characterization

This uncertainty is related to the interconnectedness of technical, scientific, and organizational, human related factors, which makes the safety case complex and socio-technical by nature. What must to be taken into account in the scenarios related to the safety case are e.g.:

- external factors, such as climate change, geological events or human actions,

- radiological, mechanical, thermal, hydrological, chemical, biological and radiation-related factors internal to the disposal system,
- in addition, quality non-conformances in the barriers, co-existence of nuclear activities and construction work, obsolescence of technologies, possible reduced availability of construction materials, and the combined effects of all the aforementioned factors.

This is illustrated by questions such as:

- Are human and organizational factors together with technical factors properly taken into account in the safety case?
- How is efficient communication ensured between the different experts? Who has expertise on the overall picture of the safety?

How should we take into account the possibility of unintentional errors? The robustness of the safety case in relation to these sociotechnical factors needs to be evaluated and updated along the repository lifetime, from the site evaluation & selection (EURAD phase 1) to the closure (part of EURAD phase 5).

Human interventions are an indisputable part of the management and operations of all types of industrial and transport activities. People need to ensure the safety and economy of processes by taking proactive measures and react in the event of a breach of normal or required events. On the other hand, the human factor can also be a source of errors; people can be the root cause or accelerate the course of an adverse event and thus exacerbate possible negative consequences.

Socio-technical aspects concerning information technology are addressed specifically through uncertainty I (see section 3.3.9 hereunder).

The socio-technical aspects associated to the activities for the implementation of the safety provisions are addressed through uncertainty H (see section 3.3.8 hereunder).

After closure, in the long term, human involuntary intrusion may be also considered as a kind of socio-technical factor. Because of the lack of knowledge on the technical means and habits of remote generations, the consequences of potential involuntary human intrusion are addressed through stylized scenarios.

Potential consequences of uncertainty

This type of uncertainty may have a significant impact both on safety and on the decision-making process. This is discussed more in detail hereunder. Namely, the impact on safety and decision-making would be high in case of significant disturbance of the political and societal system.

Impact on safety:

Sociotechnical factors can have effects on the safety case development, on operational safety as well as on long-term, post-closure safety.

Impact on decision-making: beyond the safety case itself, it can impact the implementation of a disposal programme across present and future generations. For example, if an accident occurs in the early phases, this may raise opposition to the programme.

Significance for the actors and its evolution along the programme

The answers to the questionnaire provided a wide scope of rating: this uncertainty has been rated of low to high significance for near surface and deep geological disposal. For subsurface repositories, where programmes are less advanced, the rating is low, medium or not known or assessed, nobody considered that it could be rated high at this stage. However, the uncertainty is generally higher at earlier phases.

Challenges and potential options for risk management

Challenges

Regarding the safety case, at an early stage: societal factors remain boundary conditions of a technical safety case. They can impose several safety cases on different sites or different geological conditions.

Should these "boundary conditions" be addressed in the safety case and, if yes, which ones and how? There are several views on these questions. In some cases, it is considered that "boundary conditions" do not have to be addressed in the safety case (in that case one may then ask "where are they addressed?"). In other cases, it is explicitly asked by the regulator to address them (e.g. Belgium).

Regarding the implementation of safety provisions, due to the long timescale of any disposal programme, these last decades or more, available technologies and materials may change (e.g. sources of aggregate used for a specific type of concrete or grouting may run out or a bentonite source may be exhausted).

<u>Potential options for risk management</u>

Basically, passive safety (for a DGR) is a means to mitigate socio-technical aspects after closure. However, they still have to be taken into account, for the operational safety during construction and operation of a repository, and for post-closure safety because the performance of the passive safety depends on proper implementation, through human activities, of the various components.

The management system plays a prominent role (Cf. DI-14 to DI-17 of the WENRA SRL). This type of uncertainty can be mitigated through the safety culture, and specifically by implementing various management tools, such as:

- Knowledge Management (KM) and professional capability assessment: a system of verification of special professional capability for selected personnel of nuclear installations is instrumental in the prevention of human error occurrence,
- Human Reliability Analysis (HRA). The aim of the HRA is primarily to provide data for modelling and quantification of human impact on the safety of operation of a nuclear facility and risk management,
- quality management and quality assessment (QA) systems,
- stepwise implementation with repeated (periodic) safety assessments, long-term research, design and development (RDD) planning.
- In order to address the issue of changing availability of materials and equipment along a disposal programme, continued research e.g. on new construction materials, in collaboration with universities, is also recommended. It allows both for adaptation of the design to the evolution of availability of materials and for maintaining capability in RWM activities in the young generation.

Design and technical tools may also be used:

- synoptic view of the equipment condition, fast and easy orientation, fast and easy equipment control,
- appropriate design of the failure and emergency warning systems which contributes to timely and correct identification of failures,
- appropriate combination of analogue (classic) type signalling and control with digital elements computer-based equipment,
- more extensive computerization improves the personnel's work efficiency and has a favourable effect on the man-machine interface and thus limits possible errors due to the "human factor". This concerns in particular a series of supporting computer programs performing auxiliary calculations enabling the utilization of documentation.

<u>Other information collected through the questionnaire</u>

In the questionnaire, this uncertainty was described with the following information:

By sociotechnical, we refer to interconnectedness of human, social and technical aspects. For example, organization's decision-making processes have an impact on technical investments and choosing of technologies. Similarly, new technologies may require new expertise. In addition, human errors may *occur e.g. when coding models used in the safety case, during construction or during waste characterization/acceptance. The rating of this uncertainty will depend on the answers to, for example, the following questions:*

- *Are human and organizational factors together with technical factors properly taken into account in the safety case?*
- *How could scarcity of experts or economic resources affect safety in the operational phase or the closure phase?*

Depending on the respondents, this type of uncertainty is considered of low to high significance for near surface and deep geological disposal, and of low, medium or not assessed significance for subsurface repositories. It is rated generally higher at earlier phases.

The answers to the questionnaire provided more examples of socio-technical factors, stressing for example the challenges raised by co-existence of nuclear activities and construction work (DGR), and the necessary search for new technologies or new materials due to obsolescence and reduced availability of certain materials along the programme.

It has also been noticed that societal factors remain boundary conditions of a technical safety case. They can impose several safety cases on different sites or different rocks.

This type of uncertainty can impact the development of a repository for present and future generations. It can have effects on the safety case development. The impact would be high in case of significant disturbance of the political and societal system.

Basically, passive safety (for a DGR) is a means to mitigate socio-technical aspects after closure. However, they still have to be taken into account, for the operational safety during construction and operation of a repository, and because the performance of the passive safety depends on proper implementation, through human activities, of the various components.

3.3.7 G: Uncertainties related to emergence of new knowledge

Detailed characterization

This type of uncertainty relates to how new performance results emerging in the course of the development of a disposal programme, from both physical material and system monitoring and computational systems, can be taken into account in the safety analysis. The safety assessment as a basic methodology to assure the consistency of all safety related issues can be challenged when new evidences, knowledge or techniques are developed.

This uncertainty covers questions such as:

- Which are the approaches to systematically identify new knowledge and new technical developments to assure long term safety of repository?
- Are the results of the safety analysis valid for a longer period of time and how often should the safety case be reviewed?
- When during the operation is the last period to investigate in detail the long-term safety of the facility?

A first aspect of this uncertainty is that new knowledge and insights related to the disposal system or monitoring techniques can lead to important safety related findings which then would require corrective measures and renewal of the safety case.

The title of this uncertainty has evolved along the development of Tasks 3 and 4. In the questionnaire, it was called “Reliability of monitoring results and safety analysis”. Unfortunately, the scope of this type of uncertainty, as expressed without more explanations, was excessively large. During the discussions under Task 4, it was thus renamed “New knowledge”, “new” meaning here that the knowledge:

– may have emerged by research and monitoring, both as experimental as well as computational

– but also, is new only for certain actors:
    - new for actors that would benefit from having it (unknown knowns)
    - or known by certain actors but not taken into account (ignored knowns)

New knowledge is generated through RD&D activities and technology development and does not refer solely to the physical (sensor) monitoring aspects.

Potential consequences of uncertainty

To address missing knowledge (known and unknown unknowns), assumptions are made. When new knowledge has emerged by research and monitoring, it may have consequences on the safety case, invalidating assumptions or confirming their appropriateness. Basically, this increases the robustness of the safety case, but it may also induce credibility issues.

Unknown or ignored knowns may lead to inappropriate decisions regarding safety. Regarding the monitoring itself (previous wording of this type of uncertainty), it has been noted that uncertainty on the reliability of monitoring results may delay the decision-making: e.g., reliability of monitoring results and safety analysis is paramount to get the license to close a repository.

Significance for the actors and its evolution along the programme

The answers to the questionnaire have been rather scarce, probably due to the lack of explanations. It has been noticed however that, at the early stage of a programme, depending on the assumptions that are taken into account in the safety case, the issue of uncertainty on monitoring results may be more or less significant.

Later in the development of the programme, enlarging the disposal capabilities of an existing repository requires a reliable monitoring programme.

And finally, reliability of monitoring results and safety analysis is paramount to get the license to close a repository.

Tasks 4 and 5 provided more substantial expressions on the views of the actors regarding new knowledge:

- All actors acknowledge that the possibility of new knowledge is inherent to a safety analysis of a long-term process.
- Basically, new knowledge has a positive effect, as it contributes to increase the robustness of the safety assessment and reinforce the credibility of the safety review. New regulatory requirements may be adopted based on new knowledge. It will help optimize the repository and improve the operational and long-term safety if it is not ignored, for example, if it is used to improve the barrier system or barrier redundancy.
- New knowledge may however create suspicion on the adequacy of the solutions, and distrust, due to misunderstanding within the stakeholders (expressions of WM0 and TSO). It may identify new risks, which were ignored before in repository planning, construction or safety analyses. However, this shall be considered as beneficial for the overall programme even if it may lead to needed changes of the planning or construction (expression of RE). The representatives of Civil Society in Task 5 state that the question is the extent to which new knowledge can be given due attention in the Rolling Stewardship in order to reinforce safety of the implemented solutions all along the disposal programme.

Challenges and potential options for risk management

A challenge is the fact that new knowledge emerges continuously.

Management options identified for this uncertainty refer to the principles and tools usually incorporated in the safety analysis: conservatism, fuzzy sets, deterministic approaches, scenario analysis, etc. New technologies should be incorporated along the programme under strong qualification processes, making new and old technologies work together. At policy level, the consequences of new knowledge should be addressed using a fair comparative assessment of the GDF and its alternatives: same safety criteria, taking into account the technology readiness level (TRL).

The reversibility of decisions is among others based on the possibility of new knowledge. This means namely a stepwise approach, with for example an industrial pilot phase at the beginning of the operation phase, for monitoring and anticipation of new knowledge.

It has been also suggested that there should be a systematic approach on how to identify new findings, what are their impact on safety, and when shall the safety analysis be updated. Related risk should be addressed with a systematic approach for capturing new findings and their consequences on the safety of repository. As a matter of fact, the consideration of the return on experience is also a regulatory requirement. A specific programme should be developed to do that (see e.g. WENRA SRL).

It has also been recommended that the prescribed period of periodic safety reviews every 10 years should also be linked with the obligation to establish a monitoring process for new development and exchange with international experiences.

Other information collected through the questionnaire

This question has not been detailed in the questionnaire, which has led to a very general level of answers, and in one case (TSO) no answer at all. Indeed, the wording of this question appears far too wide, it should at least have restricted the safety analysis to the parts of it that depends on monitoring results.

Answers on monitoring point out its importance for safety and the decision-making process. Unreliable monitoring results can lead to inadequate decisions which can impact safety both during the operational phase and on the long-term. It is also important when designing the monitoring system to clearly identify the objectives in terms of safety as well as the significance of any deviations with respect to expected behaviours and trends. It is also stressed that the rating of significance correlates with the phases of the programme: phase 1 is rated either of high significance, not known or not assessed, whereas phase 5 is mainly rated of low significance. Uncertainties on monitoring results could reduce as monitoring technologies are used and tested.

The safety analysis will be refined progressively along the disposal programme, thus increasing its reliability if adequate measures are implemented to reduce related uncertainties. Nevertheless, it has been stressed that the reliability of monitoring results and safety analysis is paramount to get the license to close a repository. Furthermore, enlarging the disposal capabilities of an existing repository requires a reliable monitoring programme.

Management options listed for this uncertainty refer to the principles and tools usually incorporated in the safety analysis: conservatism, fuzzy sets, deterministic approaches, scenario analysis, etc.

Other information collected through the workshop of Task 4 (Mikšová, 2022) and the seminar of Task 5 (Dumont 2023) dedicated to human aspects

The consequences of new findings may be very limited, when new knowledge fills a gap that was identified and taken into account through conservative assumptions (safety margins) or when it does not change the order of magnitude of secondary phenomena. When new knowledge still creates new issues, this should be addressed properly, through research projects of a size adjusted to their impact (I.e.: if big impact, big research project, and results presented to the public).

Communication on new knowledge is a challenge:

- How communication about new knowledge is performed is important to understand the implication of findings properly. Some participants consider that this is an international issue that should be debated. It is important to inform what happens next, what will be done, which stresses the role of an expert body to be used and consulted on what to do, like changes of inventory or in other issues.

CS are interested in the topics, but local communities do not necessarily want to dig into details; they only want to have transparency and feel honesty. This may be addressed through wide transparency, like forums with exchanges.

3.3.8 H: Uncertainties associated with adequacy of safety-related activities (in siting, design, construction, operation and closure) for the implementation of safety provisions

Detailed characterization

This uncertainty may be described in terms of the following questions:

- How can it be ensured that the safety provisions taken into account in the safety assessment are adequately implemented?
- How robust is the safety assessment vis-à-vis any potential inadequate implementation of the safety provisions?

It is related to the management provisions for the activities related to safety. Socio-technical aspects are at the root of this type of uncertainty. Namely, changes in organization and safety culture, lack of knowledge management, inadequate training, may affect the safety of the operational phase as well as in the long term.

Activities during the successive phases of a disposal programme (in siting, design, construction, operation and closure are governed by operating rules that take into account operational and long-term safety. However:

the rules are subject to interpretation. Implicit requirements, obvious at the time the rules are set, may be ignored lately due to lack of knowledge management.
they may be infringed by ignorance, laziness, greed, or malice. The quality insurance system in place may allow violations to go undetected.

Furthermore, interactions between human and technology (e.g., human-machine interface) create uncertainties.

At an upper level, the activities considered should include those related to the safety analysis itself (are the process, the tools used, the training of safety experts, etc., adequate?). However, this has not been much addressed through the various contributions.

Potential consequences of uncertainty

Consequences of this uncertainty affect both safety and the decision-making process.

Regarding safety, both long-term and operational safety may be impacted:

- Long-term safety: Inadequate safety-related activities in the construction phase potentially affect long-term safety functions of individual components and consequently may affect the performance of the whole system in the long-term.
- Operational safety: Inadequate safety-related activities in the construction phase may cause local instabilities (roof falls, collapse of drift face) with consequences to conventional and radiological safety in the operational phase.

Significance for the actors and its evolution along the programme

This type of uncertainty has been rated of low to high significance for all types of repositories, and generally "high" or "not known or assessed" at early stages.

The safety significance depends on the role the construction work plays in the barrier system of the repository architecture, but it depends also on the local heterogeneity of rock properties. The shrinking of nuclear industry, especially for small countries, is seen as a factor of increase of this uncertainty in the early phase of a programme, that should however decrease when the repository is constructed and operational, as there is (again) more work in the nuclear industry.

It has been expressed that it is important to have an adequate knowledge management already in place at a very early stage. This will help to improve safety for the repository: having more knowledge will increase the safety.

Challenges and potential options for risk management

Challenges

Not everything can be tested beforehand, and any repository is in some way a "first of its kind" realization. Any deep mine and as well any repository bear the risk of deadly accidents linked to the interplay of rock mechanics and excavation activities, to unintended fluid movement etc.

Furthermore, the coexistence of construction and emplacement phases creates many organisational problems, the most important of which being that the safety culture of miners and of nuclear technicians is not the same.

Changes of personnel along the lengthy disposal programme make documentation and knowledge management highly important. Techniques and tools will also change over time, all this learning and improvement will also have unintended and sometimes negative safety implications.

With more advanced evolution models more detailed input data on waste or void spaces or fracture 3D view will be necessary. Construction may in future be accompanied by detailed video mapping and digital twins. This may create new uncertainties relative to pre-existing knowledge, where such data were not generated.

Potential options

It is important to build a strong resilience into the system and of course, strong oversights, audits, strong safety culture, etc. Namely, the following options have been listed:

- **Quality assurance**: quality assurance system, traceability, audit of the QA system itself.
- **Extensive use of expertise and return of experience:** return on experience from similar activities; each step accompanied by expertise in the different fields (SA, mining, civil engineering…).
- **Safety culture**, mutual understanding of different perspectives/core business (mining vs RP).
- **Knowledge management** system, collaborations with universities.
- Safety management based on the identification of the **key specific components and activities** that are important with respect to safety.
- **Monitoring and inspections,** experience feedback programme (experience gained during construction, international experience, industrial experience, and experience from the operation of nuclear facilities), vigilance in involvement of independent peer reviews,
- Robust design with respect to safety,
    - Multi-barrier system, redundancies/diversity, avoidance of common failure modes, defence in depth.
    - Use of proven techniques (BAT).
    - Field of human factor separately evaluated in the Periodic safety reviews.
- **Independent oversight**: strong regulator, transparency.
- **Introduction of new technologies with much care** when they become available, after demonstration through a qualification programme.

Other information collected through the questionnaire

In the questionnaire, this uncertainty was described with the following information:

(For both operational and long-term safety). The rating of this uncertainty will depend on the answers to, for example, the following questions:

- *How can changes in organization and safety culture affect the safety of the operation phase?*
- *How is it ensured that knowledge management is taken care of?*

- *How is it ensured that people have got adequate training?*

This type of uncertainty has been rated of low to high significance for all types of repositories, and generally high or not known or assessed at early stages.

The shrinking of nuclear industry, especially for small countries, is seen as a factor increasing this uncertainty in the early phase of a programme, that should however decrease when the repository is constructed and operational, as there is (again) more work in the nuclear industry.

Management options listed are the same as for question F: periodic safety reviews along the disposal programme, Knowledge management system, quality management system, collaborations with universities are helpful.

For a small country with small waste inventory and nuclear industry, it has been expressed that it is important to have an adequate knowledge management already in place at a very early stage. This will help to improve safety for the repository: having more knowledge will increase the safety.

Other information collected through the workshop of Task 4 (Mikšová, 2022) and the seminar of Task 5 (Dumont 2023) dedicated to human aspects

Monitoring is a very important tool to detect deviations and act before they become a real problem. Therefore, it is important to have a proper monitoring strategy and physical system, with redundancy and extra sensors in case some sensors are not working and cannot be replaced (e.g. rock behaviour, engineering barrier). The monitoring system must include sufficient data management and ICT systems with safety functions.

Furthermore, the compliment of the waste acceptance criteria (WAC) should be checked strictly. WAC are a cornerstone of the safety provisions.

Adequate governance is paramount. It should allow a good dialogue between all actors and whistle blowing when necessary. Controllers must be renewed regularly.

Most of the time, CS enforces orientations of works towards safety, so it is interesting to have them in the process. Involving the managers of the facility and representatives of workers in public hearings, where they will have to face people, not only data, would increase the motivation of the company to keep a better safety culture. The representatives of CS in Task 5 emphasized the role of an enlarged safety culture as a precondition for ensuring continuity of the safety-related activities.

3.3.9 I: Uncertainties associated with the robustness of safety performance vis-à-vis possible cyber-attacks or programming errors

Detailed characterization

This uncertainty focuses, among the socio-technical factors, on aspects related to information technology: malevolent actions (cyber-attacks, intentional programming errors) or unintentional computing, data management, instrumentation-control and other data-based decision-making tools that could have programming errors. It is illustrated by the following questions: Could programming errors or hacking provoke waste packages handling incidents or accidents? How should organizations take into account the possibility of intentional actions and errors?

Throughout industry, the interactions between human and technology (e.g., programming errors), enhanced by remote control enhances the sensitivity to hacking. The reason why this uncertainty becomes more and more significant is that there is an increasing interconnection between information and communication technologies (ICT) and industrial automation and control systems (IACS) (Boyes et al. 2018[20]). When historically the industrial automation and control systems have been closed systems

[20] Boyes, H., Hallaq, B., Cunningham, J. and Watson, T. 2018. The Industrial Internet of Things (IIoT): An analysis framework. Computers in Industry, 101, 1-12.

and separated from ICT systems, the development of digitalisation (e.g., using monitoring sensors, or remote control, and AI tools to analyse the data) and the need to communicate about the results with the managers, or development of industrial internet have led to blurring boundaries between ICT and IACS. In other words, remote control is an activity that creates connections between the control systems and IT systems. This tendency has made IACS susceptible to human intrusion and cybersecurity interferences.

New technologies and software may create unexpected cybersecurity risks and vulnerabilities also in a disposal programme. Even though cybersecurity could be said to be achieved by design (Brun and Unal 2019[21]), one needs to stay alert as regards the various ways cybersecurity may be threatened. For instance, some software companies have failed to establish robust and effective quality assurance processes before writing code for programmes, and this may create cyber security threats. To what extent this development applies to different types of disposals and different phases of disposals needs to be determined.

Another aspect that may create safety concerns is the obsolescence of information technology (software and environment), and the errors that may emerge during the maintenance process. The operational phase of a repository might take years and possibly even decades, and in that period, software and programming languages will change or become out of fashion making it potentially more difficult to keep it up to date and become a security risk.

Potential consequences of uncertainty

Both operational and long-term safety may be affected, especially in the operational and closure phase of the repository.

Cyber-attacks can seriously damage an organization. Programming errors in and hacking of software used for the instrumentation and control (I&C) of safety systems can impact safety during the operational phase. This impact is dependent on the extent to which safety relies on such tools. Programming errors can lead to mistakes in the design and long-term SA calculations and hence affect the reliability of the safety case. Wrong information can lead to wrong data and wrong results.

Significance for the actors and its evolution along the programme

Responses to the questionnaire for this uncertainty varied from low to high. The respondents regarded uncertainty most often as low, then not known or not addressed yet. However, there were also answers in which the uncertainty was regarded medium and high. The highest degree of significance was attributed mainly by TSOs.

Challenges and potential options for risk management

Challenges

To better understand the risks and uncertainties and the management options related to cyber-security and programming, would require collaboration between the IT experts and other experts working with repository and radioactive wastes.

Potential options

The following options have been listed in the questionnaire:

- establishing a department in an organization with experts that are dedicated to protection against cyber-attacks,
- training workers to identify cyber threats,
- inclusion of cyber security in R&D plan,

[21] Brun, R. and Unal, B. 2019. Cybersecurity by design in Civil Nuclear Power Plants. Briefing 2019. International Security Department. Chatham House report. https://www.chathamhouse.org/sites/default/files/2019-07-23-Cybersecurity-Nuclear-Power-Plants.pdf

- identification of all safety-relevant equipment which, in the event of an attack, may lead directly or indirectly to unacceptable radiological consequences,
- physical separation and backups. The project should ensure that, in the event of sabotage, at least one channel of security systems always remains operational.
- taking account in disposal programmes of the possible programming errors which can lead to mistakes in the design and long-term SA calculations in order to minimize and mitigate as far as reasonably achievable the risks associated with this uncertainty, e.g., though a QA/QC measures, model verification and validation, security and safety measures.

Other information collected through the questionnaire

In the questionnaire, this uncertainty was described with the following information:

E.g.: could programming errors or hacking provoke waste packages handling incidents or accidents?

Responses to this uncertainty varied from low to high. The respondents regarded this uncertainty most often as low (12), then not known or not addressed yet (6). However, there were also answers in which the uncertainty was regarded medium (5) and high (3). Altogether there were 18 respondents, but some respondents referred to different types of disposals in their answers, therefore total number exceeds 18 and is 26.

In the context of near-surface disposal risk was regarded also high (2) or medium (3). In sub-surface disposal risk was evaluated to be medium (1), and in the context of deep geological disposal high (1) and medium (1). Organisations that evaluated risks high or medium were TSOs and in one case WMO.

The following risks were mentioned: Cyber-attacks can seriously damage an organization. Programming errors in and hacking of software used for the instrumentation and control (I&C) of safety systems can impact safety during the operational phase. This impact is dependent on the extent to which safety relies on such tools. Programming errors can lead to mistakes in the design and long-term SA calculations. Wrong information can lead to wrong data and wrong results. It was reported as an important uncertainty, especially in the operational and closure phase of the repository.

Responses also included ideas how to tackle with the above mentioned risks: a) Establishing a department in an organization with experts that are dedicated to protection against cyber-attacks, b) training workers to identify cyber threats, c) inclusion of cyber security in R&D plan, d) identification of all safety-relevant equipment which, in the event of an attack, may lead directly or indirectly to unacceptable radiological consequences, e) physical separation and backups should be considered as a protective measure. The project should ensure that, in the event of sabotage, at least one channel of security systems remains operational at all times, f) programming errors which can lead to mistakes in the design and long-term SA calculations need to be taken into account in disposal programmes in order to mitigate as far as reasonably achievable the risks associated with this uncertainty, e.g. though a QA/QC measures, model verification and validation, security and safety measures.

Why this uncertainty is relevant to consider, is that there is an increasing interconnection between information and communication technologies (ICT) and industrial automation and control systems (IACS) (Boyes et al. 2018)[22]. When historically the industrial automation and control systems have been closed systems and separated from ICT systems, the development of digitalisation (e.g., using monitoring sensors, or remote control, and AI tools to analyse the data) and the need to communicate about the results with the managers, or development of industrial internet have led to blurring boundaries between ICT and IACS. This tendency has made IACS susceptible to human intrusion and cybersecurity interferences. To what extent this development applies to different types of disposals and different phases of disposals needs to be determined. For instance, remote control is an activity that creates connections between the control systems and IT systems. To better understand the risks and

[22] Boyes, H., Hallaq, B., Cunningham, J. and Watson, T. 2018. The Industrial Internet of things (IIoT): An analysis framework. Computers in Industry, 101, 1-12.

uncertainties related to cyber-security and programming, would require collaboration between the IT experts and other experts working with repository and radioactive wastes.

3.3.10 J: Uncertainty in the availability of well-educated human resources and relevant experts in radioactive waste management along the repository lifetime until closure

Detailed characterization

This uncertainty is related to the human resources, including skills and knowledge management. It is illustrated by the question: will there be always sufficient human resources available during the repository programme? This question may be complemented by sub questions: Are there established mechanisms for on-going education and trainings? Are there procedures in place for knowledge transfer between generations of employees? Are there available financial resources to support the activities for all involved organisation (WMO, regulatory authorities and TSO)?

Nuclear waste management requires various types of expertise, e.g., radiological, mechanical, thermal hydrological, chemical, biological, and radiation-related issues. How can it be ensured that there is an adequate number of relevant experts available in nuclear waste management? The issue is not only organizational, national, but a European wide question.

Potential consequences of uncertainty

The implications of the lack of adequate human resources on safety are expected to be important and the uncertainties in this field are high since it depends on many aspects, (e.g., financial, political, educational etc.) that are likely to evolve much during the lifetime of the disposal. There will always be uncertainties linked to this topic. The availability of expertise is crucial.

Significance for the actors and its evolution along the programme

The subtask expert group rated this uncertainty as of high level of impact both on the decision-making process and on safety, therefore of high priority for further investigation.

In the questionnaire, responses to this uncertainty were polarised: almost half of the respondents regarded the significance of this uncertainty low, and half of the respondents regarded the uncertainty high or medium, and a few not known or addressed yet.

Challenges and potential options for risk management

Challenges

Even if the nuclear industry ceases activity in power plants, the radioactive waste repositories will need experts long after to account for all issues associated with decommissioning, repositories, and closure. The small size of the RWM sector may have difficulties in developing resources for its own needs and will have to mutualize as far as possible its efforts with other sectors (medical, industrial metrology, etc.).

With phase-out of nuclear energy for instance it will become more challenging to keep on training nuclear physicists, engineers in nuclear reactors, etc. We still probably face the same issue as the one encountered with the mining engineers when mines progressively disappeared. Maintaining well trained staff will be difficult, some capabilities are disappearing.

Potential options

Management options identified at this stage are:

- Keeping this aspect as a key safety feature in safety reviews,
- Working on the "image" of GDF and its related jobs. So far, it is considered as a second bets, not as a "future technology,
- Promoting the disposal of radioactive waste as new technologies, new challenges instead of letting them be considered as second options, to keep expertise and to develop even more specific expertise,

- Identification of education and training needs and developing a national competence-building strategy,
- Developing long-term programmes for the training and education of specialists in the field of RW management and other related scientific fields,
- Monitoring: the effectiveness of national strategies established by WMOs, regulators or others meeting stakeholder expectations must be evaluated and monitored to ensure that it is constantly improved and kept up to date, including beyond repository operation and closure and data preservation,
- International support: if necessary, national education and training program can be supplemented by external sources (IAEA, OECD NEA).

Other information collected through the questionnaire

In the questionnaire, this uncertainty was described with the following information:

(Various types of experts e.g., in water chemistry)

Responses to this uncertainty were polarised: Almost half of the respondents regarded this uncertainty low (11), and half of the respondents regarded the uncertainty high or medium (12), and not known or addressed yet (2). Altogether there were 18 respondents, but some respondents referred to different types of disposals in their answers, therefore total number of responses exceeds 18 and is 25.

In the context of near-surface disposal risk was regarded high (2) or medium (1). In sub-surface disposal risk was evaluated to be high (1), medium (1), and in the context of deep geological disposal high (3) and medium (4). There were both TSOs and WMOs which regarded this uncertainty high or medium.

The following risks were mentioned: The implications of the lack of adequate human resources on safety are expected to be important and the uncertainties in this field are high since it depends on many aspects, (e.g., financial, political, educational etc.) that are likely to evolve much during the lifetime of the disposal. There will always be uncertainties linked to this topic. The availability of expertise is crucial. With phase-out of nuclear energy for instance it will become more challenging to keep on training nuclear physicists, engineers in nuclear reactors, etc. We still probably face the same issue as the one encountered with the mining engineers when mines progressively disappeared. Maintaining well trained staff will be difficult, some capabilities are disappearing.

Responses also included ideas how to tackle with the above-mentioned risks: a) One of the possible ways to reduce them would be to keep this aspect as a key safety feature in safety reviews, b) to work on the “image” of GDF and its related jobs is essential. So far, it is considered as a second bets, not as a “future technology, c) disposal of radioactive waste should be promoted as new technologies, new challenges instead of being considered as second options in order to keep expertise and to develop even more specific expertise, d) It is necessary to develop long-term programs for the training and education of specialists in the field of RAW management and other related scientific fields, e) identification of education and training needs and developing a national competence-building strategy, f) the effectiveness of national strategy must be evaluated and monitored to ensure that it is constantly improved and kept up to date, g) if necessary, national education and training program can be supplemented by external sources (IAEA, OECD NEA).

3.4 Views of the actors

The views of the actors on uncertainties depends on various factors, such as:

- The type of actor (WMO, TSO, RE or CS)
- The phase of the national waste management programme
- The country and including governmental bodies
- The type of repository considered in the national programme.

The views of the actors are summarised based on the questionnaire, and then supplemented by the information gained during the UMAN workshops of other tasks (Mikšová, 2022 and Dumont, 2023).

Initially, the answers to the questionnaire show that:

- selection of uncertainties: there was no compelling reason to modify the list established by the subtask expert group, as all uncertainties have been considered as highly significant by at least a few experts an no other widely supported topics were raised;
- there is overlap between uncertainties. Qualitative answers provided for one uncertainty sometimes relate more to another one as understood by the sub-task expert group. This called, when synthetizing all the information gathered (Chapter 3.3) for a clearer description of the uncertainties, with more explanations of the differences. However, overlapping cannot be totally excluded, as uncertainties often link to each other.
- overall, the WMOs seem to rate uncertainties at a lower significance than TSOs and REs
- overall, there is a trend of decrease of significance of uncertainties along the phases of the programmes.
- Unsurprisingly, the proportion of "not determined nor assessed" is higher in countries where the disposal programme is at an earlier stage suggesting that knowledge transfer in this field is important for these countries and thus knowledge management is a key aspect of the European Joint programmes;
- Variations according to the type of repository are difficult to establish, as most answers refer to DGR.

4. Future priority needs for actions to address fields with human uncertainties

ID number	Title	Description: 1) General question	What Topic is needed?	Why? What challenge/ uncertainty/risk?	Who?	How to achieve (EURAD2 ideas)?			
					WMO/RE/ TSO/CS	R&D	SS	Training/ Education	Guidance/ SoK
0.1	***Uncertainties in the process for identification of a workable set of repository requirements*** *(taking account of the sometimes-conflicting expectations of the various stakeholders)*	From the sometimes-diverging requests of the various actors, what should be the requirements specification for the design?	Ethics, values, impact on safety	Requirements based on an extensive ethical debate, that addresses the various points of view, takes into account the interests of present, near future and remote generations, have the potential of more robustness. This requires a shared understanding of what an ethical debate is. It is also a debate on values of actors and on the impact on safety requirement could have. Not only ethics, goes beyond, also covers the understanding among actors of the technical implications (socio-technical issues).	All stakeholders		X	X	X
0.4	***Uncertainty in the continuity of the waste management policy along political changes***	Is there assurance of RW policy continuity where political changes can impact the process?	Governance including funding aspects	Collecting feedback from the various existing and emerging processes (e.g., national decision vs local veto right, compensation/added value, citizen conferences vs elected representatives (parliament) will help national programmes establish a more robust policy). Having clear roadmap for implementation. Assurance of sufficient collection of funds by the waste generators to enable waste management continuity even under political changes	All stakeholders				X X
1a.2	***Uncertainties associated with the robustness of the presently considered safety requirements with respect to the long term***	- What is the suitable safety goal on the long term? - What does protection of Man and Environment mean on the long term?	futures literacy, communication	Addressing the long term implies making assumptions on the long term, with a transparency for future adjustments based on today's unknown unknowns. We need to be collectively aware of these assumptions, at the various time scales	All stakeholders			X	X

		- Which level of effort, supported by present and next generations, should we achieve to protect remote future generations? - How to explain and communicate different implementations of similar disposal concepts?		(decades, centuries, millennia), in order to be able to open our minds and modify the assumptions as necessary. Need to address while there are similar disposal concepts but with sometimes small but notable differences. Though small, in the public eye may question why discrepancies (leading to wavering confidence or uncertainties).					
1b-2.1	***Uncertainty in the public acceptance (and continued engagement) of the repository at the projected location and future operation***	Will the repository be accepted there? How should communication and social engagement be integrated in the decision process?	governance, communication	What methods and approaches should be used for proper governance also in long term?: rolling stewardship concept, Clear information on local engagement processes over lifetime. Developing case studies to demonstrate local benefits and compensation. Greater engagement of diverse age and cultural groups, as well as activating persons having neutral opinions.	All stakeholders		X	X	X
1b-2.2	***Uncertainty in the schedule to be considered for implementing the different phases of the disposal programme***	How long will the implementation of the disposal programme last?	Need for resources (financial and human)	Need for clear program roadmap, to show disposal programme implementation in case of severe delays or rapid acceleration (for years or even decades), with engagement of competent technical staff, service providers and public stakeholders.	All stakeholders		X	X	X
4a.1	***Uncertainties associated with the robustness of the safety case vis-à-vis sociotechnical factors***	Are human and organizational factors together with technical factors properly taken into account in the safety case? How can political uncertainties affect licensing and the different programme phases?	governance, human resources, communication	Need for clear program roadmap, to handle external changes but also integrating flexible iterations. Transparent information and dialogue on the societal factors taken as boundary conditions of the safety case.	All stakeholders		x		x

4a.2	***Uncertainties associated with new knowledge***	Will new knowledge, insights or monitoring techniques reveal deficiencies that need to make corrective measures?	technology integration, public trust	Utilisation of mass data, new monitoring systems, like wireless sensors. Artificial Intelligence for decision making and risk awareness. Demonstrate reliability and transparency of uncertainties. Stakeholder confidence/acceptance in methods and results.	WMO, RE	X			X
4a.3	***Uncertainties in the adequacy of safety-related activities (in siting, design, construction, operation and closure) for the implementation of (operational and long-term) safety provisions***	How can changes in organisation and safety culture affect operational and post-closure safety?	human resources, communication	Transparent information of organisational/staff roles and technical requirements. Need to maintain over a long period the shared knowledge of operators of the safety reasons that motivate the technical requirements	All stakeholders				x
4a.5	***Uncertainties associated with the robustness of safety vis-à-vis possible cyber-attacks or programming errors***	How should organisations take into account the possibility of intentional actions and errors?	technology integration, public trust	Risks of data accuracy and access, cyber security of information transmissions. Safeguards, risk of human misuse of data.	WMO, TSO	X		x	
4a.8	***Uncertainties in the availability of well-educated human resources, and relevant experts in radioactive waste management along the repository lifetime until closure***	Are there sufficient human and financial resources available?	need for resources (financial and human)	Knowledge and skills management at the level of the whole RWM ecosystem (WMO+TSO+RE+CS) will help maintain human resources over decades despite possible changes in individual organizations involved, including change of responsibilities, freezing of programmes or other schedule changes.	All stakeholders	X	X		X

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Appendix A. List of the uncertainties identified at milestone MS23 and priority rating by the subtask expert group for further investigation

Table A1. List of the uncertainties identified at MS23 (Dumont 2020) and priority rating for further investigation.

Identification							*Selection*	
ID N°	Phase	Object of uncertainty	Origin of uncertainty		Describing the uncertainty			
			Origin	*Typology*	General question	Examples of specific questions	Priority	**Rationale for rating**
0.1	0	Repository requirements	Multiplicity of actors	*Political*	From the sometimes diverging requests of the various actors, what should be the requirements specification for the repository?	How should we address the interests of neighbours of existing polluted sites vs the interests of neighbours of existing or planned waste final repositories?	High	The growing level of information of all stakeholders leads to a growing need to establish shared decisions, whereas the interests are sometimes diverging. The decision-making processes regarding public decision can no longer be implemented alone. New processes, combining representative and participatory democracy, are emerging. Nevertheless, there is still a need for progress in this field.
0.2	0	Waste inventory	Evolutions in energy policy	*Political*	Are there new, emerging needs associated to changes in energy policy?	Should we consider spent MOX as waste (France)?	Medium	Evolutions in energy policy will surely happen. They will modify, at least, the inventory of the various types of RW, but also sometimes will make new types of wastes appear. Nevertheless, the spectrum of already identified RW allows taking into account some future evolutions, when launching a disposal programme and in the design.
0.3	0	Waste inventory	Evolutions in public perceptions regarding waste	*Societal*	Should we consider material that was historically not regarded as waste, or the other way round?	Can waste from nuclear facilities, with radioactive content under a given threshold, be managed as conventional waste?	Medium	Similarly to evolutions in energy policy, evolutions in public perceptions may, and will probably, affect the waste inventory. However, the portfolio of existing disposal concepts is not affected in the first stages of a disposal programme.
0.4	0	Repository requirements: waste management policy	Political changes	*Political*	Is there assurance of RW policy continuity where political changes can impact the process?	How would the RW disposal process need to be defined?	High	Political changes modify the priorities in public decision. This may freeze waste disposal projects, while the RW are still there and still produced. This creates loss of impetus in the process, knowledge management issues and possibly safety issues in the storage facilities.
1.1	1	Repository requirements: regulatory framework regarding long term impact	Possible evolutions of regulatory framework related to doses (e.g. due to various regulations	*Governance*	What is the acceptable impact on the long term?	How should involuntary human intrusion scenarios be considered in the safety requirements?	Low	Although the regulatory framework related to dose can change, these changes will have a very limited effect in this stage as the repository design can easily be modified to adhere the new regulations. Furthermore, if the changes in regulatory framework occur later in the lifecycle, the regulator will take into account what already has been implemented and what is reasonably achievable (Cf. ALARA principle). Hence, the changes in the regulatory framework will

Identification								*Selection*
			between countries)					not (or very limited) affect the decision – making processes: It could delay the construction of a repository but most likely not stop it. It will also have a very limited influence on the safety of a repository as it only sets the regulation on the dose and does not influence whether a repository should be built. Note that stricter doses could lead to better safety although they are currently already very strict. Making it stricter will probably not increase safety significantly. Therefore, both are low, and the priority of research is set to low.
1.2	1	Repository requirements: regulatory framework apart from long-term impact	Possible evolutions of the regulatory framework not related to doses (e.g., retrievability)		Apart from safety, what should be the requirements for a final repository?	How should reversibility of decisions and retrievability of waste be considered?	Low	The regulatory framework not related to dose can change, these changes will have a very limited effect as the GDF is still in this early phase and its design concept can easily be modified to adhere the new regulations regarding the safety. Also, it will have a limited impact on the decision-making process and again because repository is still in an early phase. Furthermore, if the changes in regulatory framework occur later in the lifecycle, the regulator will take into account what already has been implemented and what is reasonably achievable (Cf. ALARA principle).
1a.1	1a	Repository requirements, taking account of stakeholders' expectations	Other evolutions resulting from stakeholder involvement (e.g., regarding monitoring)	*Governa nce*	To which level should wishes of the stakeholders be incorporated in the repository requirements?	How should expectations in repository monitoring be taken into account? To which extent should the wishes of concerned stakeholders be addressed?	Low	Involvement of local stakeholders is important, it will in this stage of the repository have limited impact on the safety as local stakeholders will not have large influence on the safety of a repository. Furthermore, any additional requirements from the local stakeholders can still easily be incorporated into the design. For the decision-making process, this is still an early stage in the whole process of a repository and there is no commitment needed at this stage. Therefore, both are low. As both are low, research interest is set to low (too early yet in the program)
1a.2	1a	Repository requirements regarding long term	Far future perspective regarding Man; Intergeneratio nal ethics	*Governa nce*	What is the suitable safety goal on the long term? - What does protection of Man and Environment mean on the long term? - Which level of effort, supported by	What will be Man in the long term? Does it make sense to assess safety at 50 000 years on the basis of scenarios that consider human civilisation as in present state?	High	The uncertainty related to the far future perspective regarding intergenerational ethics has a high impact on safety and more specifically whether a repository should be built or not and what the safety standards must be. It will also have a high impact in the

Identification							***Selection***	
					present and next generations, should we achieve to protect remote future generations?	For long-lived, low-level wastes, which is the suitable trade-off between protection on the long-term (pointing towards deep disposal) and protection against a low level of danger (pointing towards surface disposal)?		decision-making process it could delay and possibly even indefinitely delay the construction of a repository. The research interest is also high.
1a,3	1a	Repository requirements regarding implementation rate	Assumptions for planning the operation of the waste producers' facilities	*Technological*	Schedule of availability: which waste inventory, along time, should be taken into account?		Medium	Uncertainties related to the operation of the waste producers' facilities has a medium impact on safety as the type of waste and the total inventory should be known before the construction of the repository. Not knowing the inventory correctly, could lead to uncertainties in the safety. It will also have a medium impact on the decision - making process as it could delay the processes. Furthermore, it must be known at this stage already. The research priority is also medium as it is an uncertainty that could have impact on both safety and decision – making process. However, as this is still at an early stage, it is not high.
1a.4	1a	Repository requirements regarding waste inventory	Assumptions regarding energy and waste management policy	*Technological*	Which types of waste should be considered?	Should we consider the disposal of bituminous waste or should they be reprocessed before disposal? (France)	Medium	Uncertainties related the assumptions of the energy and waste management policy will have a low influence on safety as the design can easily be changed if needed; the repository is not constructed yet. It will have a medium influence in the decision process as changes in an energy and waste management policy might delay the construction of the repository, increase the cost, decrease the social acceptance. The research priority is set to medium as this uncertainty needs to be addressed before the repository is constructed.
1a.5	1a	Waste management technologies considered for the repository design	Technology readiness level (TRL) of planned waste management technologies	*Technological*	Will the technology considered for the concept be fully proven in due time?	Based on the results of existing tests at a reduced scale, which assumptions can be made for the size of the planned emplacement cells?	Low	In this stage of the program, this uncertainty will only have a low impact in safety as we are still at the early stage and when a certain technique is not available, a different technique could be used, or the construction could be delayed. For the decision-making process, the impact is also low as, at most, it might delay the program. Furthermore, a government might demand to use only technologies that are proven. And therefore, the research priority is set to low.

Identification							*Selection*	
1a.6	1a	Need for a national repository (country with a small waste inventory)	Perspective of international repository	*Technological Socio-technical*	Should we build a national repository, or will an international repository accept our waste?	Would the local government and / or community accept waste from other countries? Would it be safe and ethical to sell - off the waste?	Medium	If an international repository will be as safe as a national repository, which is very likely to be a requirement by a government before sending their waste to an international repository, it will not impact the safety. Therefore, the safety is set to low. However, the potential of an international repository might delay the decision-making process. Therefore, the impact is medium (2). As a research priority is set to medium as it is a possible option for countries with a relatively small inventory. Furthermore, there is no reason not to do it.
1a.7	1a	Availability of the funds when they will be necessary	Prediction over decades	*Financial*	Will the necessary funds be available?	How much money should the waste producers allow now for the costs of the planned repository and associated research?	Medium	In this stage, funding problems could lead to delays in the decision-making processes and could impact the safety (longer above ground as not enough research is done or no funds are available for the construction of the repository). But as this is still an early stage, additional funding could be found (extra funding from the state) or collected (waste tariffs) and therefore the impact is only medium for both. As both are medium and the consequence of not having enough funds could be high, research priority is set to medium
1a.8	1a	Availability of useful knowledge	Internal (for the company) uncertainties: managing long-lasting projects	*Socio-technical*	Will the necessary knowledge be transmitted?	How can the competences be maintained?	Medium	If already at the beginning of this project, the management of this project is not good, research that should have been done, might not have been carried out or is not good / conclusive enough. But since this is still in the early stage, additional research can be carried out later in a later stage if the problems and gaps in knowledge are identified. The latter is not a certainty and therefore the impact is medium. This has only a low impact on decision making processes as managing long lasting projects is not part of the decision-making process. At most, it might delay this process and therefore the impact is low. Research priority is set to medium as this is an exceptional long-term process that would require good management.

Identification							*Selection*	
1a.9	1a	Robustness of technological choices	Perspective of new technological solutions	*Technological*	Could our present choices be undermined in the future?	Should we shift to extended interim storage in order to allow transmutation technologies to be used?	Low	Both for the safety and decision-making process, the impact is low. Regarding safety, the repository is designed with the latest knowledge available with a safety margin. New insights and new technologies could change insights, but these insights can still be incorporated in this stage. Regarding the decision-making process, although different techniques might be developed in the future, if a country is already in this stage, they already made the decision to use a repository for their waste rather than wait for new techniques. And therefore, impact is low. As both are low, the research priority is also set to low; it comes close to what if scenarios.
1b-2.1	1b-2	Public acceptance	Public acceptance (NIMBY, etc.); Communication/stakeholder engagement (SE)	*Societal Governance*	Will the repository be accepted there? How should communication/SE be integrated in the decision process?	What is the attitude towards repository in community? Have there been any facility for which public showed NIMBY effect? What possibilities for engagement are given to the public? Are there all relevant stakeholders identified and mapped? Is there a relevant process established to communicate and engage with stakeholders? How is the communication and SE process integrated in decision making process for site selection?	High	Different stakeholders may introduce new safety related issues (like new technical, administrative, …) which needs to be reassessed in safety analysis. As this is not direct impact on safety it is assessed as medium. Also, the stakeholders may require new elements to be included in the decision-making process (more discussion, more meetings, new ideas, ...), which impacts importantly the DM process. Therefore, this uncertainty is rated as high in this phase.
1b-2.2	1b-2	Repository planning	Licensing process	*Technological*	How long will the licensing process last?	To which conditions will the safety case be agreed by the regulator? Are the regulatory requirements set and understood by all? Who are official regulators and how are they involved (nuclear, radiation, environmental, …)?	High	Regulatory requirements can impact the safety related documentation which have to be prepared and review for licence. If there is no agreed DM process with all authorities this can have impact on modification of legal framework, safety document development and DM process. The impact on safety is medium (not direct, but indirect) and high on DM (followed by delays and needs for additional financial resources). The overall impact is high.

Identification							*Selection*	
1b-2.3	1b-2	Compliance with repository requirements	Plurality of decision-makers, with various sets of criteria	*Governance*	How will the points of view of the various actors on the compliance with repository requirements be integrated along the licensing processes?	What kind of obstacles could the licensing processes, other than the nuclear safety, be confronted with?	medium	Some other decision makers can bring other views to decision making process, which can impact the safety and the process itself to some degree. The overall is the uncertainty assessed as medium.
1b-2.4	1b-2	Waste management strategy	Local facility for national/regional waste	*Socio-technical*	Which types and amount of waste will be accepted there?	For some wastes, is a single national repository a better solution than distributed repositories in various regions?	low	This uncertainty has limited impact for safety, but medium for DM. In some conditions can have impact on site selection, especially if the local community has perception to be victim in hands of others who imposed repository.
1b-2.5	1b-2	Urgency of the availability of a repository	Possibility of societal disruptions enhancing the risks associated with existing waste	*Societal*	Will the need for such repository be modified?	How should we take into account the possibility of a societal disruption making the availability of a solution more urgent?	low	This uncertainty has limited impacts on safety and decision making and is rated as low.
1b-2.6	1b-2	Relevancy of the repository solution	Possibility of new technologies modifying the inputs for the decision	*Technological*	Will the need for such repository be modified?	How should we take into account the possibility of a new technology making the repository less relevant?	low	As the siting is taking so many years there are possible new technical solutions which could impact the need for repository or modify the design however those impacts are low.
1b-2.7	1b-2	Robustness of present knowledge	New knowledge (on site, on transport phenomena…)	*Technological*	Could our previous choices be undermined?	Will we have enough funds, resources, to start with alternative options?	low	New knowledge could have also impacts on additional research and alternative solutions which needs more resources and could delay the siting. The impact is however low as experienced from 30 years of ongoing activities.
1b-2.8	1b-2	Sustainability of present political decisions	Political changes impact on RWM priorities	*Political*	Can new political decisions (e.g., phase out of nuclear) change the priorities for RW disposal?	Can new political decision slow down the siting of RW disposal?	medium	The new priorities due to political changes can impact the siting process and can have delays in the DM, and also can have impact on safety. Both are assessed as medium, as there are usually already established methods for the safety assessment and also for DM process. However, changes of priorities can delay the siting and could have implicit impact on safety and DM.

Identification								*Selection*	
1b-2.9	1b-2	Sustainability of energy policy	new nuclear built	*Political, socio-technical*	Will decision to construct new NPP impact the siting?	Will there be new siting criteria (higher capacities, mora space, different design, …)?	medium	New decision for new build can have high impacts for safety, as there might be new criteria that can have high impact on safety, (new assessments and analysis) but medium for DM. In total, this uncertainty is ranked as medium as there is already established knowledge available for safety assessments.
1b-2.10	1b-2	Availability of funds	use of dedicated funds for other priorities	*financial, political*	Can lack of financial resources delay/stop siting activities?	How must be RW funding secured?	medium	Lack of funding can have a high impact: on safety (medium) and DM (high). At the end this uncertainty is assessed as high as it can have very important impact and produce significant delay, but also no sufficient knowledge, research and other issues related to appropriate staff.
3.1	*3*	Adequacy of provisions for funding to the costs along time	*Prediction of costs for a long-term project + determination of the discount rates for financial provisions*	*Financial*	*Will the required funds be available at the time they are needed?*	*How should we estimate the costs, along the duration of the project?* *What should be the financial provisions, now and along the next years?*	*Medium*	The decision for constructing a repository is based mainly on long-term safety perspective. It takes into account an estimation of costs and a funding mechanism. Uncertainties on costs and funding will have a limited impact on decision, even if in the end, the lack of funding from the waste producer would lead to a transfer of part of the costs to a public body. The lack of funding might result in degraded implementation of the design. However, for a GDR, type of repository corresponding to the higher costs, long-term safety is based not only on engineered barriers, but also on the depth and the properties of the host rock. Therefore, the impact on safety is medium. Though already investigated, assessing discount rates for the long-term is still an issue for research in economics.
3.2	*3*	Availability of critical materials, equipment and skills	*Growth in competing needs for scarce inputs*	*Financial*	*Will the required materials, equipment, skills be available?*	*Will other competing needs (equipment and skilled manpower for mining and for civil engineering, building materials) raise the costs?*	*Medium*	*Similar arguments as for financial resources. The evolution of resources of all kinds over decades may create tensions on the market, which creates uncertainty, with low impact on decision for construction and medium impact on safety. Research needs are in the field of knowledge management and flexibility of the design vis-à-vis changes of raw materials.*

Identification							*Selection*	
3.3	*3*	Robustness of the design regarding the choice of materials	*Discontinuity in products availability*	*Financial*	*Can we rely on the presently available products?*	*Will the metal alloys tested for the licence application still be available?*	*Low*	*The design of repositories is based on robust materials and equipment. Even if the obsolescence of certain equipment, namely electronic devices, might require the qualification of replacement equipment, which takes time and money, the impact on safety and decision-making is low.*
3.4	*3*	Stability of social context	*Social movements*	*Societal*	*Will opponents disturb construction?*		*Low*	*The decision for constructing a repository is taken before construction. The level of contestation expected during construction is lower than before the decision of construction is made, provided that construction operations are conducted as specified.*
3.5	*3*	Stability of political context	*Political changes*	*Political*	*Once made, will the decision for construction be challenged?*		*Medium*	Political changes may lead to stoppages or moratoria, therefore the impact on decision-making is rated medium. Anyway, the result in terms of safety on the short-term (a few decades) is rated low, as wastes are in any case stored and controlled. The issue of the long-term safety is addressed through the decision-making process.
3.6	*3*	Robustness of the concept of the repository with respect to new knowledge	*New knowledge*	*Technological*	*Will new knowledge related to the repository concept and safety challenge the design that has been decided?*		*Low*	New knowledge, e.g., on KD, may result in modified assessment of the performance. But it should not change drastically the safety of the repository being constructed, because the design includes safety margins. Similarly, the decision-making should not be strongly affected.
3.7	*3*	Sustainability of the repository concept as being the best solution	*R&D on alternative solutions*	*Technological*	*Will new developments on alternative solutions related to waste management challenge the decision for construction?*		*Medium*	In contemporary societies, state decisions are more and more challenged, namely with respect to potential progress in alternative solutions. The impact on safety is rated low because a potential modification of the decision would necessarily take into account the safety criteria. Combining low safety impact and medium DM impact leads to a medium priority on research. The research fields would be on alternative waste management processes and on the adequate provisions, in terms of design and governance, for balancing the benefits of new technologies with the costs (of all kinds, not only financial) of disturbing an on-going process.

Identification							*Selection*	
3.8	*3*	*Management system: safety culture*	*Safety culture within the company*	*Socio-technical*	*Will changes in the safety culture within the company impact safety and/or the decision-making process?*		*Medium*	Would it only be changes in the good direction, the safety impact would be low, and the priority would have been rated low as well. But loss of safety culture may have high safety impacts and lead to inaccurate decisions. Stresses the need for integrating safety culture in the knowledge management processes.
3.9	*3*	*Management system: safety culture*	*Safety of operation*	*Governance*	*How will the safety of operation be assured from the management and other societal points of views?*	*Who will take part in operation? Will there be an independent body to oversight management?*	*Medium*	Similar to the safety culture within the company, at national level. Stresses the need for independent oversight.
4a.1	4a	Robustness of the safety case vis-à-vis sociotechnical factors	Sociotechnical uncertainties related to safety case and political uncertainties related to licensing	*Sociotechnical, Political, Societal,*	Are human and organizational factors together with technical factors properly taken into account in the safety case? How can political uncertainties affect licensing?	How is efficient communication ensured between the different experts? Who has expertise to have an overall picture of the safety? How do political uncertainties affect licensing? Is the possibility of unintentional errors properly addressed?	High	Sociotechnical i.e., interconnectedness of societal, organizational and technical aspects create emerging risks and surprises. They play relevant role in safety case and licensing, and therefore, it is necessary to understand, identify, mitigate and tackle with these sociotechnical issues.
4a.2	4a	Reliability of monitoring results and safety analysis	Sociotechnical challenges related to monitoring and long-term safety	*Socio-technical, technological*	Will new knowledge, insights or monitoring techniques reveal deficiencies that need to make corrective measures?		High	Consequences of weaknesses in monitoring techniques may have safety significance, even though it can be assumed that weaknesses in monitoring techniques will be noticed early enough.
4a.3	4a	Adequacy of activities in operation for the implementation of (operational and long-term) safety provisions	Human and organisational factors	*Socio-technical, organizational, Governance*	How can changes in organization and safety culture affect the safety of the operation phase?	How is it ensured that knowledge management is taken care of? How is it ensured that people have got adequate training?	High	Human and organizational aspects are inherently involved in the management of operation phase and in any decisions regarding operation, resources, and technology. Furthermore, outsourcing of services and work complicates the management of human and organizational aspects. Sociotechnical systems view emphasizes the need for seeing technical and organizational aspects simultaneously (Harvey and Stanton 2014)[23].
4a.4	4a	Robustness of operational safety vis-à-vis	Societal disruptions	*Societal*	How could societal disruptions affect safety?		Low	Societal disruption can have severe impacts on operation.

[23] Harvey, C. and Stanton, N.A. 2014. Safety in System-of-Systems: Ten key challenges. Safety Science 2014, 70, 358-366.

Identification							***Selection***	
		possible societal disruptions						
4a.5	4a	Robustness of safety vis-à-vis possible cyber-attacks or programming errors	Sociotechnical interface, unintentional (e.g. programming errors) or intentional (e.g. cybersecurity threats)	Technological	How could cyber security and security aspects affect safety?	How should organizations take into account the possibility of intentional actions and errors?	High	Remote control, programming and related cybersecurity risks and uncertainties are worth of further investigations.
4a.6	4a	Robustness of long-term safety vis-à-vis the possibility of new knowledge	New knowledge about risks related to materials or geological or hydrological aspects or groundwater chemistry etc.	*Technological, Governance*	How could new knowledge about risks related to materials, or geological or hydrological aspects or groundwater chemistry, affect safety? How is new knowledge communicated inside the organization and between the organizations and experts?		Medium	The impacts of new knowledge about geological and hydrological aspects on safety creates uncertainties. This topic is worth of studying.
4a.7	4a	Robustness of operational safety vis-à-vis the possibility of societal tensions in the area	tensions (big migrations, conflicts, aggression)	*societal, political*	Can tensions in the area influence safety of the repository?	Is there still legal framework and control in place? Are there available resources?	Medium	Tensions in the area have potential for creating major challenges to operation. This is a topic that needs to be taken into account in scenarios but is not necessary priority for further investigation.
4a.8	4a	Availability of well-educated human resources	Discontinuities in needs over time for human resources skilled in waste management.	*governance, financial*	Are there sufficient human and financial resources available?		High	Lack of resources (including adequate number of competent experts and ensuring the continuous education of experts) is fundamental issue, and may create one of the most important uncertainty in the nuclear waste management in general.
4b.1	*4b*	Sustainability of the regulatory framework taken	*Possible evolutions of*	*Governance*	*Are the provisions and studies for closure made in the preceding phases still relevant vis-à-vis present regulation?*		*Medium*	It is highly probable that provisions and studies for closure performed in earlier phases will be questioned when effective closure operations will be

Identification								*Selection*
		into account in the preceding phases	*the regulatory framework*					implemented. However, this would not result in a degraded safety, more probably in a higher level of protection. The decision-making process will take into account the provisions already implemented and the benefits and costs of modifications to the initial design, which will take time. As this does not affect the initial stages of the design nor of decision, this is only considered as a medium priority for research.
4b.2	*4b*	Sufficiency of knowledge on closure provisions required for the decision to implement closure	*Loss of knowledge*	*Socio-technical*	*Have we enough knowledge to perform closure operations?*	*Should we perform new studies to prepare safe closure operations?*	*Medium*	Loss of knowledge on earlier operations and disposed wastes may be a problem when it will become necessary to implement the closure provisions. This would result both in questioning the safety and in delaying the decision for closure. As this does not affect the initial stages of the design nor of decision, this is not considered as a high priority for research. This stresses the need for a structured and efficient knowledge management over decades.
4b.3	*4b*	Sufficiency of knowledge on repository evolution required for the decision to implement closure	*Possibility of new knowledge*	*Socio-technical*	*When will it be considered that the repository evolution is sufficiently stabilised and known to implement operations for final closure?*	*How long should the monitoring last before a decision for closure can be made?*	*Low*	As long as there is no urgency for closing the repository, there will be a tendency to postpone closure operations in order to get new knowledge, therefore the impact on DM is medium. But the results in terms of safety level enhancement will probably be more limited, as the planning established initially and updated during the preceding phases should take already into account the need for stabilisation of the evolution and knowledge acquisition.
4b.4	*4b*	Sufficiency of knowledge on alternative solutions required for the decision to implement closure	*Possibility of new solutions*	*Socio-technical*	*Have we reached enough confidence in the absence/irrelevancy of alternative solution to decide for a high increase in difficulty of retrieval?*		*Low*	Similar arguments as for knowledge related to the repository: high tendency to postpone closure if there is no urgency to close, but limited impact on safety as there should be a safety assessment of the repository showing already a high level of protection.

Identification							*Selection*	
5a.1	5a	Robustness of long-term safety vis-à-vis possible loss of knowledge after closure (institutional control phase)	Loss of knowledge	*Socio-technical*	Is there a system established to maintain knowledge?	How can loss of knowledge impact institutional control in active phase?	low	In active post closure institutional control, the loss of knowledge has low impact on safety as all safety functions are assured by passive systems. The loss of knowledge might have medium impact on DM as there could be some more decisions to be taken. In overall, this uncertainty is low.
5a.2	5a	Robustness of the safety case vis-à-vis possible new knowledge arising in the post-closure institutional phase	New knowledge	*Socio-technical*	Are there any new evidence that impact safety case?	How can we be sure that the safety case assures safety also with new scientific findings? If new knowledge arises will the safety case be reopened?	mediu m	New knowledge findings could impact the safety issues and also reopen the DM. But both impacts are assessed as medium, as there are already approaches and tools available for safety assessment and DM. Also, in this phase, the repository is closed therefore the safety would be approved (with conservative approach).
5a.3	5a	Robustness of the safety case vis-à-vis possible new habits of population emerging after closure	New habits of population	*social*	How can new habits of population impact safety?	Are there new pathways that were not assessed previously? Would there be new scenarios that were not addressed?	mediu m	This uncertainty would have medium impact on safety and on DM. But the priority is medium as in this phase the repository is closed, and also all safety related decisions were taken.
5a.4	5a	Robustness of the long-term safety and DM vis-à-vis possible loss of trust in the governmental institutions	Possible loss of trust	*governan ce*	Is government and operator still trusted?	Does local public trust in governmental institutions?	Low	Both impacts are assessed as low as the loss of trust can have impacts on safety and DM, but their impact is low, the priority is also low.
5a.5	5a	Robustness of the long-term safety vis-à-vis political changes after closure	New political system	*political*	Can new political circumstances change priorities	What impacts such changes could have for the responsibilities of responsible institutions?	Low	In this phase both impacts are assessed as low, while the changes in political system, also with related potential changes (less funds, disappearance of institutions, …) can have low impacts on safety and DM.
5a.6	5a	Robustness of the safety case	climate changes	*technolo gical*	Does climate change endanger safety of the disposal?	Are there sufficient resources for the remediation of the consequences?	Mediu m	Climate changes can impact highly the safety of the disposal and could also reopen the DM process

Identification								*Selection*
		vis-à-vis climate change						(medium impact). But priority is medium as the climate changes could impact mainly near surface repositories and are not so important for geological repositories.
5b.1	5b	Robustness of the repository safety vis-à-vis a possible unintentional human intrusion	Unintentional Risk of human intrusion	*Societal, Political*	Will humans, in the search for new resources, unintentionally drill through a repository or use a salt dome with a disposal facility for salt mining?	Is there still information available on the location on the disposal facility	Medium	Unintentional human intrusion will have a high impact on safety as the consequences of a human intrusion could be high. It will also have a high impact on the decision-making process as it might be a reason not to use a repository for the disposal of rad waste. Although both are high, the research priority is set to medium as a lot of research is already done in this field.
5b.2	5b	Robustness of safety vis-à-vis the risk of intentional human intrusion	Intentional Risk of human intrusion	*Societal, Political*	Will humans or an organization intentionally intrude a disposal facility for economical or military purpose?	Is there a legal framework in place that forbids retrieval of the waste on purpose? Is the information of the location still available?	Low	Human intrusion will have a high impact on safety, but there is little that can be done to prevent it; leaving the rad waste in storage at the surface will probably lead to the same results. Therefore, the impact on safety is high but it is low for the decision - making process as it is likely that this uncertainty will not influence the decision - making process. The research priority is set to low as little can be done to avoid any intentional human intrusion in remote future times.
5b.3	5b	Robustness of the repository safety vis-à-vis a possible loss of awareness	Risk of loss of awareness of the repository	*Societal*	Is there a need to retain the awareness and is there a system in place to retain the awareness	How could loss of awareness impact the long-term safety? Or how can loss of awareness increase the long-term safety?	Medium	This could go either way. It might be better for the long-term safety to lose all information as it will rule out intentional human intrusion. However, it will also increase the potential of an unintentional human intrusion as knowledge on the location of the repository is lost. Therefore, the impact Is set to medium for de safety. Regarding the decision – process, it will also have medium impact as possible loss of awareness is a risk (see above) that should be taken seriously, but the decision to construct the repository has been taken a long time ago and, most likely, this scenario was considered during the decision to build the repository. The research priority is set to medium as the other two are medium as well and needs attention. Note that work has been done in the past.

Identification							***Selection***	
5b.4	5b	Relevancy of the repository design vis-à-vis long-term climate evolution	Climate change	*technological*	Does human induced climate change endanger the long-term safety of the disposal facility.	Will the human induced climate change be more extreme then anticipated?	Low	Extreme weather due to human induced climate change could affect the safety of the repository. As we still do not fully understand climate, have limited knowledge in how climate will change during the repositories life this uncertainty will affect the safety of the repository. But, since there will be safety margins in the design of the repository, the impact will be medium and not high. For decision – process, this uncertainty will have limited effect as the decision to build the repository has been taken at a much earlier stage and precautionary measures have been taken. Research priority is set to low as a lot of research is already done in this field and there are multiple barriers that protect the GDF.
5b.5	5b	Sustainability of the repository as being the ultimate solution for the waste	New political system	*political*	Does the government still support a disposal facility?	Does a new government want to retrieve the waste as they do not support the geological disposal of waste?	Low	Even if a new government does not support a repository, it is already built. Therefore, a new government will not influence de the decision-making process and / or safety. Therefore, the research priority is set to low.
5b.6	5b	Sustainability of trust regarding the repository	Possible loss of trust	*Societal, Political*	How to keep the trust in the disposal facility when (part of) the information is lost, or insight have changes.	Is all information still available?	Low	Although trust could be lost, this will not impact the objective of safety; it might only feel less safe by inhibitions. Furthermore, new insight could lead to the belief that a barrier might not function in the way it should do. However, there are multiple barriers and the potential failure of one should not impact the barrier function of the other barriers. This will not impact the decision-making processes as little more can be done at this stage and it is likely that everything in the past has been done to avoid the loss of knowledge. As both are low, the research priority is set to low as well. Furthermore, research on how knowledge can be retained has been carried out in the past or is still ongoing.

Appendix B. Complete list of uncertainties identified by the Subtask 3.4 expert group as related to human aspects: focus on characterization

Table B1. List of the uncertainties identified with MS23 report (Dumont 2020) and their characterization (multiple pages). Note that not all items were addressed, and thus some rows have empty cells.

Identification				*Characterization*				
ID N°	**Object of uncertainty**	**Describing the uncertainty through the questions it raises**						
		General question	**Examples of specific questions**	**Comments**	**Detailed characterization**	**Potential consequences of uncertainty**	**References**	**Typology of uncertainty consequence**
0.1	Repository requirements	From the sometimes-diverging requests of the various actors, what should be the requirements specification for the repository?	How should we address the interests of neighbours of existing polluted sites vs the interests of neighbours of existing or planned waste final repositories?	In addition to the requirements from the regulation and from the needs of the waste producers, the neighbours of the disposal facility may express specific requirements that may conflict safety rules (e.g., regarding close monitoring). The need for repository acceptance requires to take them into account Refers to governance, democracy, regulation of conflicts, political science Uncertainty considered here only from the present map of actors, without time evolution.		Increased time for decision of action		Decision making process
0.2	Waste inventory	Are there new, emerging needs associated to changes in energy policy?	Should we consider spent MOX as waste (France)?			Modifications of the need for action		Waste inventory
0.3	Waste inventory	Should we consider material that was historically not regarded as waste, or the other way round?	Can waste from nuclear facilities, with radioactive content under a given threshold, be managed as conventional waste?	In the past, low-level materials have not been considered as dangerous and used for example as road fill.		Modifications of the need for action		Waste inventory
0.4	Repository requirements: waste management policy	Is there assurance of RW policy continuity where political changes can impact the process?	How would the RW disposal process need to be defined?	Link to existing and binding Waste Directive or other conventions (Joint Convention) where national program is required. The experience with first national reports show that national programs did not provide all requested information.		Increased time for decision of action and also potential modification	report. from EC https://ec.europa.eu/energy/en/topics/nuclear-energy/radioactive-waste-and-spent-fuel	decision making process and other requirements

Identification				Characterization				
1.1	Repository requirements: regulatory framework regarding long term impact	What is the acceptable impact on the long term?	How should involuntary human intrusion scenarios be considered in the safety requirements?	Consensus seems to be achieved in normal evolution, debate on IHI scenarios (see HIDRA)				Design principles
1.2	Repository requirements: regulatory framework apart from long-term impact	Apart from safety, what should be the requirements for a final repository?	How should reversibility of decisions and retrievability of waste be considered?					Design principles
1a.1	Repository requirements, taking account of stakeholders' expectations	To which level should wishes of the stakeholders be incorporated in the repository requirements?	How should expectations in repository monitoring be taken into account? To which extent should the wishes of concerned stakeholders be addressed?	Cf. the modification of the design of the Belgian surface repository to allow monitoring from below the waste emplacement room.		Increased time for decision on concept	*Socioeconomic Evaluation of Megaprojects- Dealing with uncertainties. Lehtonen et al. Routledge (2017)*[24]	Design principles Process schedule
1a.2	Repository requirements regarding long term	What is the suitable safety goal on the long term? - What does protection of Man and Environment mean on the long term? - Which level of effort, supported by present and next generations, should we achieve to protect remote future generations?	What will be Man in the long term? Does it make sense to assess safety at 50 000 years based on scenarios that consider human civilisation as in present state? For long-lived, low-level wastes, which is the suitable trade-off between protection on the long-term (pointing towards deep disposal) and protection against a low level of danger (pointing towards surface disposal)?	Though regulation and safety guides provide a general answer to the question of the safety goal on the long term, safety assessment requires detailed assumptions for the distant future (scenarios, representative persons) that are the product of conjecture. Ethical dilemmas: intergenerational and intragenerational justice		Increased time for decision on concept		Requirements for siting Design principles Process schedule

[24] M. Lehtonen M., Joly P.-B. and Aparicio L. editors, 2017, Socioeconomic Evaluation of Megaprojects. Dealing with uncertainties., Routledge.

Identification				***Characterization***				
1a,3	Repository requirements regarding implementation rate	Schedule of availability: which waste inventory, along time, should be taken into account?						
1a.4	Repository requirements regarding waste inventory	Which types of waste should be considered?	Should we consider the disposal of bituminous waste, or should they be reprocessed before disposal? (France)	Waste typology results from energy and waste management policy, available technologies, decisions made by waste producers, decisions made by the safety authority				
1a.5	Waste management technologies considered for the repository design	Will the technology considered for the concept be fully proven in due time?	Based on the results of existing tests at a reduced scale, which assumptions can be made for the size of the planned emplacement cells?					
1a.6	Need for a national repository (country with a small waste inventory)	Should we build a national repository, or will an international repository accept our waste?	Would the local government and / or community accept waste from other countries? Would it be safe and ethical to sell - off the waste?					
1a.7	Availability of the funds when they will be necessary	Will the necessary funds be available?	How much money should the waste producers allow now for the costs of the planned repository and associated research?					
1a.8	Availability of useful knowledge	Will the necessary knowledge be transmitted?	How can the competences be maintained?					
1a.9	Robustness of technological choices	Could our present choices be undermined in the future?	Should we shift to extended interim storage in order to allow transmutation technologies to be used?					
1b-2.1	Public acceptance	Will the repository be accepted there? How should communication/SE be	What is the attitude towards repository in community? Have there been any facility for which public showed NIMBY	NIMBY, licensing process, veto right, prospects for new technologies; Communication and SE strategy are a		repository siting can be stopped, delayed, modified	EC projects COWAM I and II, CIP, …	decision making process schedule funding

Identification				Characterization				
		integrated in the decision process?	effect? What possibilities for engagement are given to the public? Are there all relevant stakeholders identified and mapped? Is there a relevant process established to communicate and engage with stakeholders? How is the communication and SE process integrated in decision making process for site selection?	tool for managing the acceptance uncertainty but may be unsuccessful.				
1b-2.2	Repository planning	How long will the licensing process last?	To which conditions will the safety case be agreed by the regulator? Are the regulatory requirements set and understood by all? Who are official regulators and how are they involved (nuclear, radiation, environmental, …)?	Key phases in licensing. Costs added by delay		delay in siting and additional documentation	WENRA SRL for disposal	modification of legal framework, impacts on funding
1b-2.3	Compliance with repository requirements	How will the points of view of the various actors on the compliance with repository requirements be integrated along the licensing processes?	What kind of obstacles could the licensing processes, other than the nuclear safety, be confronted with?	Statement of the environmental authority (e.g., environmental court in Sweden), national interest declaration, archaeological resources protection…		delays in siting, additional requirements		decision making process schedule funding
1b-2.4	Waste management strategy	Which types and amount of waste will be accepted there?	For some wastes, is a single national repository a better solution than distributed repositories in various regions?	perception of sacrifices for national interest, distribution of risks		acceptability of repository		local community sacrifices for nation
1b-2.5	Urgency of the availability of a repository	Will the need for such repository be modified?	How should we take into account the possibility of a societal disruption making the			acceptability of repository		

Identification				***Characterization***				
			availability of a solution more urgent?					
1b-2.6	Relevancy of the repository solution	Will the need for such repository be modified?	How should we take into account the possibility of a new technology making the repository less relevant?			renewal of site selection		cost, funding
1b-2.7	Robustness of present knowledge	Could our previous choices be undermined?	Will we have enough funds, resources, to start with alternative options?			renewal of site selection		cost, funding
1b-2.8	Sustainability of present political decisions	Can new political decisions (e.g., phase out of nuclear) change the priorities for RW disposal?	Can new political decision slow down the siting of RW disposal?			delay in siting		lack of resources (funds, human, …)
1b-2.9	Sustainability of energy policy	Will decision to construct new NPP impact the siting?	Will there be new siting criteria (higher capacities, mora space, different design, …)?			delay in siting		design, documentation
1b-2.10	Availability of funds	Can lack of financial resources delay/stop siting activities?	How must be RW funding secured?			lack of resources		delays
3.1	Adequacy of provisions for funding to the costs along time	*Will the required funds be available at the time they are needed?*	*How should we estimate the costs, along the duration of the project?* *What should be the financial provisions, now and along the next years?*	*The question regards the funding for construction operations during phases 3 and 4). It will be firstly faced in preceding phases.*	*Prediction of costs: uncertainties from the level of definition of the design, from the costs of resources at the time they will be needed (raw material, equipment, salaries), from political decisions regarding taxes and insurances, from level required for security, from possible events that may affect the*	*Risks of lack of funding from the waste producer thus transferring the costs to a governmental/regional body* *Need for financial backup*		Funding

Identification				***Characterization***					
					duration of construction operations (accidents, strikes, social movements, political decisions...)				
3.2	Availability of critical materials, equipment and skills	*Will the required materials, equipment, skills be available?*	*Will other competing needs (equipment and skilled manpower for mining and for civil engineering, building materials) raise the costs?*	*High demand may raise costs (e.g., sand, tunnelling equipment and skills): may be grouped with the uncertainty on prediction of costs*		*Risks of need for modifications of the design, increased costs and time for safety reassessment*			Design
3.3	Robustness of the design regarding the choice of materials	*Can we rely on the presently available products?*	*Will the metal alloys tested for the licence application still be available?*	*Products may become no longer of commercial interest for a company*		*Need for further demonstration with alternative products*			Design
3.4	Stability of social context	*Will opponents disturb construction?*		*Accidents may raise or strengthen opposition*		*Increased time and costs for construction*			Schedule
3.5	Stability of political context	*Once made, will the decision for construction be challenged?*				*Increased time and costs for construction*			Design and schedule
3.6	Robustness of the concept of the repository with new knowledge	*Will new knowledge related to the repository concept and safety challenge the design that has been decided?*		*new knowledge can impact the concept taking account of the safety assessment*		*Risk of increased time for construction*			Design and schedule
3.7	Sustainability of the repository concept as being the best solution	*Will new developments on alternative solutions related to waste management challenge the decision for construction?*							Waste management solution
3.8	*Management system: safety culture*	*Will changes in the safety culture within the company impact safety and/or the decision-making process?*		*Changes in the safety culture in the good direction, resulting from new expressions of opinion, or new attention given to former expressions, or evolutions in the wrong direction resulting from work pressure,*					Safety procedures

Identification				***Characterization***				
				economic disruption… *Ability of the management system to address unexpected events that may impact safety*				
3.9	*Management system: safety culture*	*How will the safety of operation be assured from the management and other societal points of views?*	*Who will take part in operation?* *Will there be an independent body to oversight management?*	*WIPP operation and accident due to not appropriate management* *Safety management system must take into account all the stakeholders, namely the suppliers, contractors…*			*https://wipp.energy.gov/wipprecovery-accident-desc.asp*	Safety procedures
4a.1	Robustness of the safety case vis-à-vis sociotechnical factors	Are human and organizational factors together with technical factors properly taken into account in the safety case? How can political uncertainties affect licensing?	How is efficient communication ensured between the different experts? Who has expertise to have an overall picture of the safety? How do political uncertainties affect licensing? Is the possibility of unintentional errors properly addressed?	An accident may raise opposition		Safety, decision-making, operation		Safety, schedule, decision-making
4a.2	Reliability of monitoring results and safety analysis	Will new knowledge, insights or monitoring techniques reveal deficiencies that need to make corrective measures?				Safety and quality of monitoring	*http://www.posiva.fi/files/3197/YJH_2012_Engl_LOW.pdf*	Epistemic, safety,
4a.3	Adequacy of activities in operation for the implementation of (operational and long-term) safety provisions	How can changes in organization and safety culture affect the safety of the operation phase?	How is it ensured that knowledge management is taken care of? How is it ensured that people have got adequate training?	Interactions between human and technology (e.g. programming errors), enhanced by remote control, create uncertainties. Hacking.		safety, operation		safety, operation, management, decision-making
4a.4	Robustness of operational safety vis-à-vis possible societal disruptions	How could societal disruptions affect safety?		A societal disruption may urge emplacement of existing waste, and/or partial closure		safety, operation		Infrastructure, funding, knowledge management, expertise, resilience, continuation of

Identification				***Characterization***				
								responsible operation
4a.5	Robustness of safety vis-à-vis possible cyber-attacks or programming errors	How could cyber security and security aspects affect safety?	How should organizations take into account the possibility of intentional actions and errors?			safety, security, operation		Safety, security, schedule, decision-making
4a.6	Robustness of long-term safety vis-à-vis the possibility of new knowledge	How could new knowledge about risks related to materials, or geological or hydrological aspects or groundwater chemistry, affect safety? How is new knowledge communicated inside the organization and between the organizations and experts?				safety, decision-making, operation		Epistemic, safety,
4a.7	Robustness of operational safety vis-à-vis the possibility of societal tensions in the area	Can tensions in the area influence safety of the repository?	Is there still legal framework and control in place? Are there available resources?					
4a.8	Availability of well-educated human resources	Are there sufficient human and financial resources available?		Ensuring continuous education of experts for the nuclear waste management is necessary. This task cannot be managed by single organizations, but the education of experts require support from national and international (e.g. EU) level.		safety, operation, nuclear waste management, at national and international level		
4b.1	Sustainability of the regulatory framework taken into account in	*Are the provisions and studies for closure made in the preceding phases*				*Increased time for decision of action*		

Identification				***Characterization***				
	the preceding phases	*still relevant vis-à-vis present regulation?*						
4b.2	Sufficiency of knowledge on closure provisions required for the decision to implement closure	*Have we enough knowledge to perform closure operations?*	*Should we perform new studies to prepare safe closure operations?*	*More relevant in post-closure, but already in closure if it lasts decades*		*Increased time for decision of action*		
4b.3	Sufficiency of knowledge on repository evolution required for the decision to implement closure	*When will it be considered that the repository evolution is sufficiently stabilised and known to implement operations for final closure?*	*How long should the monitoring last before a decision for closure can be made?*			*Increased time for decision of action*		
4b.4	Sufficiency of knowledge on alternative solutions required for the decision to implement closure	*Have we reached enough confidence in the absence/irrelevancy of alternative solution to decide for a high increase in difficulty of retrieval?*				*Increased time for decision of action*		
5a.1	Robustness of long-term safety vis-à-vis possible loss of knowledge after closure (institutional control phase)	Is there a system established to maintain knowledge?	How can loss of knowledge impact institutional control in active phase?					
5a.2	Robustness of the safety case vis-à-vis possible new knowledge arising in the post-closure	Are there any new evidence which impact safety case?	How can we be sure that the safety case assures safety also with new scientific findings? If new knowledge arises will the safety case be reopened?					

Identification				*Characterization*				
	institutional phase							
5a.3	Robustness of the safety case vis-à-vis possible new habits of population emerging after closure	How can new habits of population impact safety?	Are there new pathways that were not assessed previously? Would be there new scenarios that were not addressed?					
5a.4	Robustness of the long-term safety and DM vis-à-vis possible loss of trust in the governmental institutions	Is government and operator still trusted?	Does local public trust in governmental institutions?					
5a.5	Robustness of the long-term safety vis-à-vis political changes after closure	Can new political circumstances change priorities	What impacts such changes could have for the responsibilities of responsible institutions?					
5a.6	Robustness of the safety case vis-à-vis climate change	Does climate change endanger safety of the disposal?	Are there sufficient resources for the remediation of the consequences?	Concerns surface/subsurface repositories only.				
5b.1	Robustness of the repository safety vis-à-vis a possible unintentional human intrusion	Will humans, in the search for new resources, unintentionally drill through a repository or use a salt dome with a disposal facility for salt mining?	Is there still information available on the location on the disposal facility					
5b.2	Robustness of safety vis-à-vis the risk of intentional human intrusion	Will humans or an organization intentionally intrude a disposal facility for economical or military purpose?	Is there a legal framework in place that forbids retrieval of the waste on purpose? Is the information of the location still available?					

Identification				***Characterization***				
5b.3	Robustness of the repository safety vis-à-vis a possible loss of awareness	Is there a need to retain the awareness and is there a system in place to retain the awareness	How could loss of awareness impact the long-term safety? Or how can loss of awareness increase the long term safety?	This could work both ways. Forgetting a disposal facility could increase the long-term safety (nobody is going to look for it) while someone might drilled into it by accident.				
5b.4	Relevancy of the repository design vis-à-vis long-term climate evolution	Does human induced climate change endanger the long term safety of the disposal facility.	Will the human induced climate change be more extreme then anticipated?					
5b.5	Sustainability of the repository as being the ultimate solution for the waste	Does the government still support a disposal facility?	Does a new government want to retrieve the waste as they do not support the geological disposal of waste?					
5b.6	Sustainability of trust regarding the repository	How to keep the trust in the disposal facility when (part of) the information is lost or insight have changes.	Is all information still available?					