Deliverable 10.11: Study on management options for different types of uncertainties and programme phases

Work Package 10

Uncertainty Management multi-Actor Network (UMAN)

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Executive Summary

This report presents the work of Subtask 4.2 of the strategic study "Uncertainty Management multi-Actor Network" (UMAN), initiated in the framework of the European Joint Programme on Radioactive Waste Management (EURAD). The context is Radioactive Waste Management (RWM) programmes for near-surface and geological disposal of radioactive waste. The Work Package (WP) UMAN is focused predominantly on developing a common agreed understanding among different actors of national disposal programmes on strategies and approaches for uncertainties management by sharing knowledge and experience. These actors are Waste Management Organisations (WMOs), Technical Safety Organisations (TSOs), and Research Entities (REs) but also Civil Society (CS). Subtask 4.2 is dedicated to the development of a comprehensive overview about different approaches and uncertainty management options to assess and, where is possible and relevant, to reduce risks and optimise safety.

The work focuses on four topical sources of uncertainties, namely on uncertainties related to site and geosphere, human aspects, spent nuclear fuel, and waste inventory. For each of these topics, specific examples were selected from comprehensive lists of uncertainties developed in UMAN Task 3. They were generally those of highest safety significance according to WMOs, TSOs, and REs, but care was taken that the examples cover the spectrum of uncertainties according to the classification schemes developed in UMAN.

The overview about different approaches and uncertainty management options was developed by using information on generic strategies in uncertainty management and possible management options (from Subtasks 2.1 and 3.1) together with the exemplary topical uncertainties. Focusing on the latter, existing documentation/information and examples of good-practice and pitfalls were compiled, reviewed, and synthesised. The experience of organisations participating in UMAN were gathered from the responses to UMAN questionnaires and from additional input collected with a specific template. The information was then extensively discussed and compiled by the UMAN Subtask 4.2 participants (WMOs, TSOs, and REs). The compilation, topic by topic, formed the basis for broader discussions in the UMAN workshops organised by Subtask 4.3.

The present report is the synthesis of the results achieved, taking feedback from the workshops into account. On the one hand, it contains a compilation of relevant regulatory requirements, safety assessment strategies, activities aimed at reducing or avoiding uncertainties or mitigating their consequences, and on other hand techniques for representing uncertainties in safety assessments. Best practices and potential pitfalls are illustrated with specific examples. Furthermore, the evolution of uncertainty management strategies and options along EURAD programme phases is addressed.

It becomes apparent that a common understanding of what safety relevance means for any given uncertainty is fundamental for adequate uncertainty management. Moreover, uncertainties and hence their safety relevance evolve along the disposal programme. Thus, this common understanding must therefore be maintained over time. At any given milestone, the relevant questions to be asked and answered are: Is an uncertainty safety-significant and relevant for the given decision at hand? Must and can it be reduced, avoided, or can its consequences be mitigated? Can it be dealt with accordingly in the safety case that accompanies the decision at hand? An outlook to further steps in the programme is also warranted. In general, it is preferred to reduce or avoid uncertainties as early as possible, so that they are not safety relevant anymore. However, care must be taken that decisions do not prevent adequate uncertainty management in the future. This is particularly true for so-called unknown unknowns that link to the completeness of knowledge and assessment. Keeping options open to deal with such uncertainties in the future might contradict rapid reduction of other uncertainties. Finally, uncertainties remain, and they need to be represented adequately in safety assessments and the safety case. For quantifiable uncertainties, probabilistic safety assessments and bounding deterministic calculations are common. For badly or non-quantifiable uncertainties and to demonstrate the robustness of a system with respect to remaining uncertainties, alternative scenarios or so-called what-if cases or scenarios are used as bounding cases.

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List of Abbreviations

ASR	alkali-silica-reaction
ATF	accident tolerant fuel
BAT	“best available technology” principle
BIOMASS	IAEA project “Biosphere Modelling and Assessment”
BUC	burn-up credit
BWR	boiling water reactor
CORI	EURAD Work Package “Cement-Organic-Radionuclide interactions”
CS	Civil Society
DEF	delayed ettringite formation
DGR	deep geological repository
DiD	defence in depth
DOPAS	project “Full-scale Demonstration of Plugs and Seals”
DTM	difficult to measure
EBS	engineered barrier system
EDZ	excavation damaged zone
EU	European Union
EURAD	European Joint Programme on Radioactive Waste Management
FEPs	features, events, and processes
FUTURE	EURAD Work Package “Fundamental understanding of radionuclide retention”
GAS	EURAD Work Package “Mechanistic understanding of gas transport in clay materials”
GEOTRAP	OECD/NEA project “Performance Assessment Methodologies in Application to Guide the Development of the Safety Case”
HLW	high level waste
IAEA	International Atomic Energy Agency
ILW	intermediate level waste (ILW-L and ILW-H are sub-groups)
IRF	instant release fraction
ISA	isosaccharinic acid
LLW	low level waste

MOX	mixed oxide fuel (specific nuclear fuel type)
NEA	Nuclear Energy Agency
NIMBY	“not in my backyard” phenomenon
NPP	nuclear power plant
NRS	Nuclear and Radiation Safety
NSD	near-surface disposal
OECD	Organisation for Economic Co-operation and Development
QA	quality assurance
QC	quality control
PAMINA	EU project “Performance Assessment Methodologies in Application to Guide the Development of the Safety Case”
PREDIS	EU project “Pre-disposal management of radioactive waste”
PSR	periodic safety review
RAW	radioactive waste
RD&D	research, development, and demonstration
RE	Research Entity
REV	representative elementary volume
RWM	radioactive waste management
SAHARA	safety as high as reasonably achievable
SE	stakeholder engagement
SNF	spent nuclear fuel
SF	scaling factor
SFC	EURAD Work Package “Spent fuel characterisation and evolution until disposal”
SFL	final repository for long-lived waste planned by SKB in Sweden
SoTA	state-of-the-art report
THM	thermo-hydro-mechanical
TRL	technology readiness level
TSO	Technical Safety Organisation
UMAN	EURAD Work Package “Uncertainty Management multi-Actor Network”
UO_2	uranium dioxide

VLLW	very low level waste
WAC	waste acceptance criteria
WIPP	Waste Isolation Pilot Plant
WMO	Waste Management Organisation
WP	Work Package
XRF	X-ray fluorescence

1. Introduction

1.1 Background

The Work Package (WP) “*Uncertainty Management multi-Actor Network*” (UMAN) of the European Joint Programme on Radioactive Waste Management (EURAD) is dedicated to the management of uncertainties potentially relevant to the safety of radioactive waste management. The context is Radioactive Waste Management (RWM) programmes for near-surface and geological disposal of radioactive waste. The WP includes various activities such as exchanges on views, practices, and preferences regarding uncertainty management options as well as the review of existing strategies, approaches, and tools. Interactions between different types of actors involved in radioactive waste management, including Waste Management Organisations (WMOs), Technical Safety Organisations (TSOs), Research Entities (REs), and Civil Society (CS) are central to this WP. These interactions aim at meeting the objective of fostering a mutual understanding of uncertainty management strategies, approaches, and preferences.

Task 4 of WP UMAN concerns “*Uncertainty management options and preferences of different actors across the various phases*” with the overall objective to identify, for different phases of a disposal programme and the associated decision-making, a bundle of possible options for:

- treating uncertainties associated with specific topics in the safety assessment (e.g., uncertainty propagation methods, scenario development, stylisation approaches, …),
- avoiding or reducing uncertainties or mitigating their consequences,
- making a safety case robust vis-à-vis remaining uncertainties.

Subtask 4.2 concerns the “*Compilation and review of available information on possible uncertainty management options*”. First, this serves as basis for the interactions with different types of actors on their views on uncertainty management, in particular in the UMAN workshops of Subtask 4.3 and the seminars of Task 5 that include CS. Second, in its synthesised form in this report, it is a reference for the actors in any RWM programme. It highlights commonalities and differences in approaches and in some cases preferences as well as illustrates uncertainty management strategies and options with examples of good-practice and hinting at possible pitfalls.

1.2 Objectives and scope

The objective of this report is to provide a comprehensive overview about different approaches and uncertainty management options to assess and, where it is possible and relevant, to reduce risks and optimise safety. The overview shall span over different types of uncertainties and over the RMW programme phases.

The work focuses on four topical sources of uncertainties, namely on uncertainties related to site and geosphere, human aspects, spent nuclear fuel, and waste inventory. Uncertainties related to near-field aspects are out of scope and are presented in Becker et al. (2024). The evolution of uncertainty management strategies and options along the phases of RMW programmes is illustrated where appropriate.

The overview is based predominantly on the experience of the participating actors and on existing documentation (e.g., regulations, guidelines, handbooks, national reports) from national and European programmes, international initiatives (e.g., IAEA, NEA/OECD) and relevant past/ongoing European RD&D projects. As such, it represents a compilation based on the knowledge and experience available at the time of writing, knowing that some RWM programmes were in dynamic phases during that time and views or preferences might evolve. Moreover, the perspective might be somewhat biased towards the view of the participating actors (i.e., WMOs, TSOs, and REs). The overview does thus not aim at providing a complete overview of all possible or existing uncertainty management options or strategies.

1.3 Methodology

The identification of management strategies and options was structured along the following four topics:

- uncertainties related to site- and geosphere, particularly during the site and host rock selection process,
- uncertainties related to human aspects,
- uncertainties related to spent nuclear fuel (SNF), including those associated with SNF characterisation, intermediate storage (wet or dry), long-term storage, and disposal,
- uncertainties related to waste inventory, including uncertainties associated with pre-disposal management having an impact and implications for the safety of the disposal facility.

To facilitate focused discussions, specific topical uncertainties were selected from the comprehensive lists of uncertainties developed by Subtasks 3.2, 3.3, 3.4, and 3.5. The primary selection criterion was the safety significance as assessed by the actors responding to the 2nd UMAN Questionnaire (i.e., WMOs, TSOs and REs) and by the Subtask 4.2 participants. For the waste inventory related uncertainties, a complementary survey broadened the decision basis. As a second selection criterion, care was taken to cover all the uncertainty types according to the classification schemes developed within UMAN (see Chapter 2). Details on the selection process, which differs slightly between the topics, and the selection per se can be found in the first section of the respective topical chapters, i.e., Sections 4.1, 5.1, 6.1, and 7.1.

For each specific topical uncertainty, management strategies and options were then identified and assessed. The work was driven by topical core-groups, where the core-group compositions were optimised according to the expertise and availability of information in the organisations participating in Subtask 4.2. As a common basis for the assessment served the overviews on generic strategies in uncertainty management and possible management options (from Subtasks 2.1 and 3.1; see Chapter 3). The experiences of organisations participating in UMAN and topically related EURAD WPs were gathered from the responses to the above-mentioned questionnaires and from additional input collected with a specifically designed template (Appendix A). Exchanges with topically related EURAD work packages as e.g., CORI or FUTURE, provided additional insight.

When describing the identified management strategies and options, it was strived for:

- associating possible management options to uncertainties and types of uncertainty,
- identifying the strengths and weaknesses of these options,
- where appropriate, highlighting dependence on programme phases and actors.

During the information gathering and assessment, care was taken that uncertainty management options and strategies are illustrated with adequately referenced examples from literature or experience of the WP UMAN participants, showing good practice and hinting at potential pitfalls. Temporal aspects were addressed via the programme phases according to the EURAD roadmap (see *Table 1*).

The collected information was then reviewed, extensively discussed, and compiled by the core-groups in dedicated topical milestone documents (MS89, MS113, MS118, MS145; unpublished and for internal use in WP UMAN). These formed the basis for broader discussions in the first four UMAN workshops organised by Subtask 4.3 and the "*Interactions between all categories of actors, including Civil Society*" during the seminars of Task 5. Finally, additional information gained during the workshops was integrated and the topical compilations synthesised into this comprehensive overview.

Table 1 – Phases of a radioactive waste management programme according to the EURAD roadmap[1], which are based upon the IAEA phases for implementation of a deep geological repository (DGR).

Phase 0	Policy, framework, and programme establishment
Phase 1	Site evaluation and site selection
Phase 2	Site Characterisation
Phase 3	Repository Facility Construction
Phase 4	Repository Facility Operation and Closure
Phase 5	Post Closure

1.4 Report structure

After the introduction in Chapter 1, the next two chapters provide a more detailed description of the approaches adopted in this study, namely the uncertainty classification schemes (Chapter 2) and the generic uncertainty management strategies and uncertainty management scheme (Chapter 3). Strategies and options that are used in practice for the uncertainties related to site and geosphere, human aspects, spent nuclear fuel, and waste inventory are presented in Chapters 4 to 7, respectively. These chapters all start with an overview section explaining the selection of specific topical uncertainties and comprising general comments (Sections 4.1, 5.1, 6.1, and 7.1), followed by sections with management strategies and options grouped according to the classification scheme presented in Chapter 2. Chapter 8 summarises and concludes on the overarching aspects of uncertainty management that were identified and discussed.

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[1] The definition of phases as presented here corresponds to the phases as they were defined during the time the work was performed. The definition and phase numbers differ slightly compared to the current version of the EURAD roadmap.

2. Uncertainty classification schemes

Based on the responses to the 1st UMAN Questionnaire, the views of different actors (WMOs, TSOs and REs) on uncertainties associated with safety analyses and the safety case have been assessed in Subtask 3.1 of WP UMAN (Grambow, 2023). The goal of this assessment was to provide a high-level integrated picture of the types of uncertainties that the various actors consider potentially relevant for the safety case and how they estimate these uncertainties to evolve over time.

Based on the identified views of these actors, a three-level uncertainty classification scheme (Grambow, 2023) was synthetised and adopted in this study. At the highest level, the following five types of uncertainties were identified (*Figure 1*):

- **programme uncertainties** associated with the waste management programme and other prevailing circumstances (e.g., societal, resources, …),
- uncertainties associated with **initial characteristics of the system** (e.g., waste, site, engineered components, …),
- uncertainties in the **evolution of the disposal system and its environment**, including uncertainties in the interaction between the disposal system and the environment, effects of events and processes that may affect the initial characteristics (e.g., uncertainties associated with the transport of radioactive waste and spent fuel) and human influence (e.g., intrusion),
- uncertainties associated with **data, tools, and methods** used in the safety case, including Quality Assurance (QA) and Quality Control (QC) measures,
- uncertainties associated with the **completeness** of Features, Events, and Processes (FEPs) considered in the safety case.

The three-level scheme is illustrated in *Figure 2*, where the second level is represented in full and the third level with the association of specific topical uncertainties is shown schematically.

It is also possible to categorises uncertainties with respect to availability and use of knowledge as illustrated in *Figure 3*. Since the distinction between *unknown/ignored knowns*[2] and *unknown unknowns* is particularly relevant for uncertainties associated with the completeness of Features, Events, and Processes (FEPs), a so-called classification matrix has been developed in WP UMAN (*Figure 4*). With respect to knowledge, the level and specificity of knowledge (e.g., popular or scientific; superficial or in-depth) might also influence associated uncertainties and how to deal with those.

The classification schemes served as guideline when selecting specific topical uncertainties in the following chapters, whereby the goal was to cover the full spectrum of the classifications.

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[2] The term “ignored knowns” is understood as knowledge that is voluntarily discarded without proper justification.

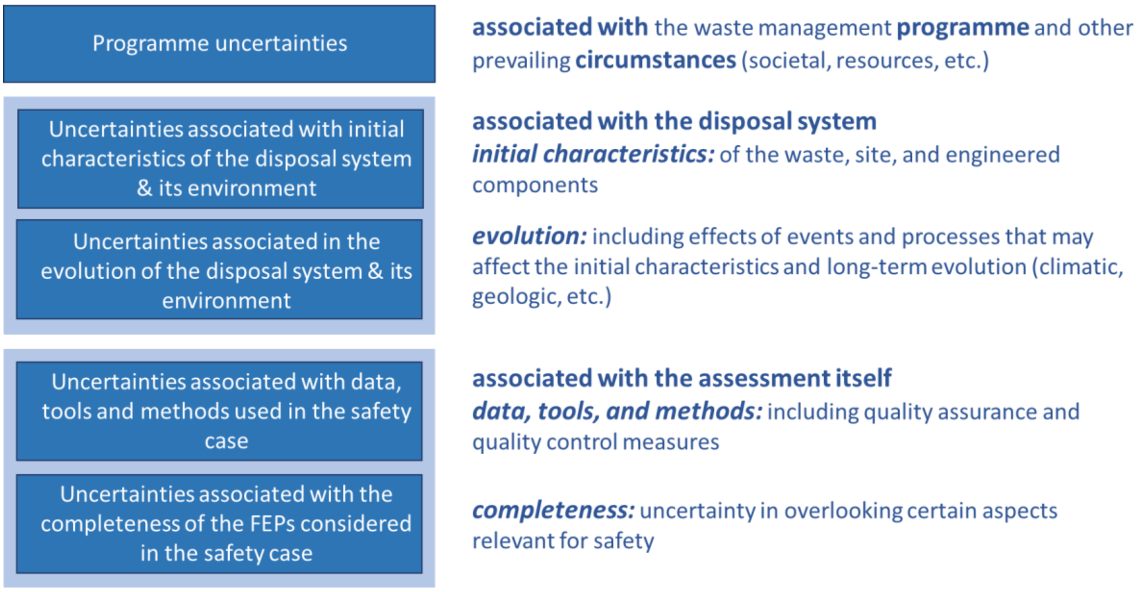


Figure 1 – High-level uncertainty classification scheme.

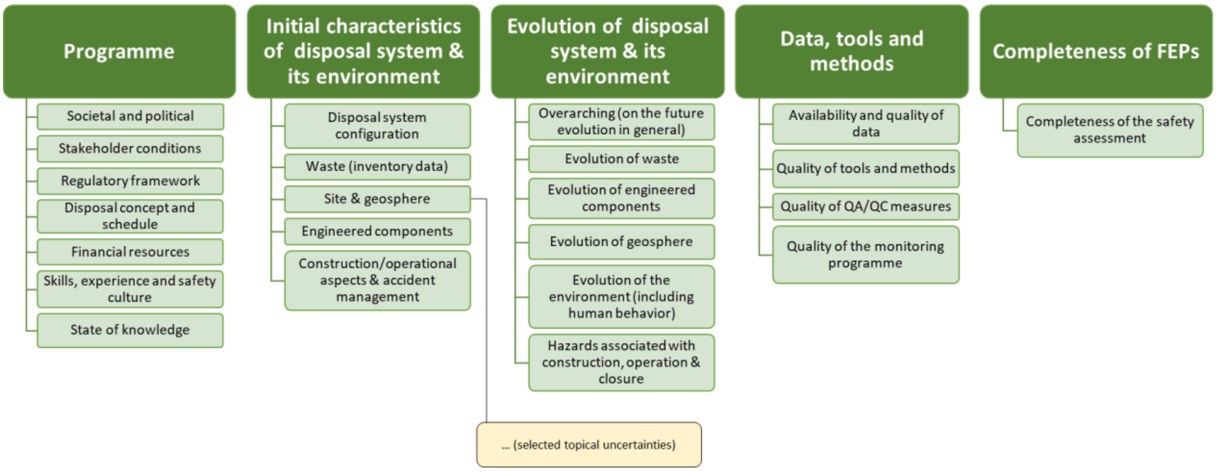
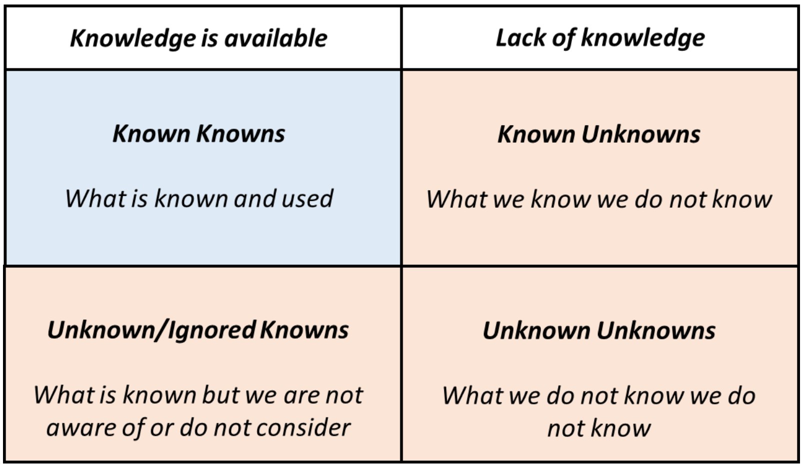
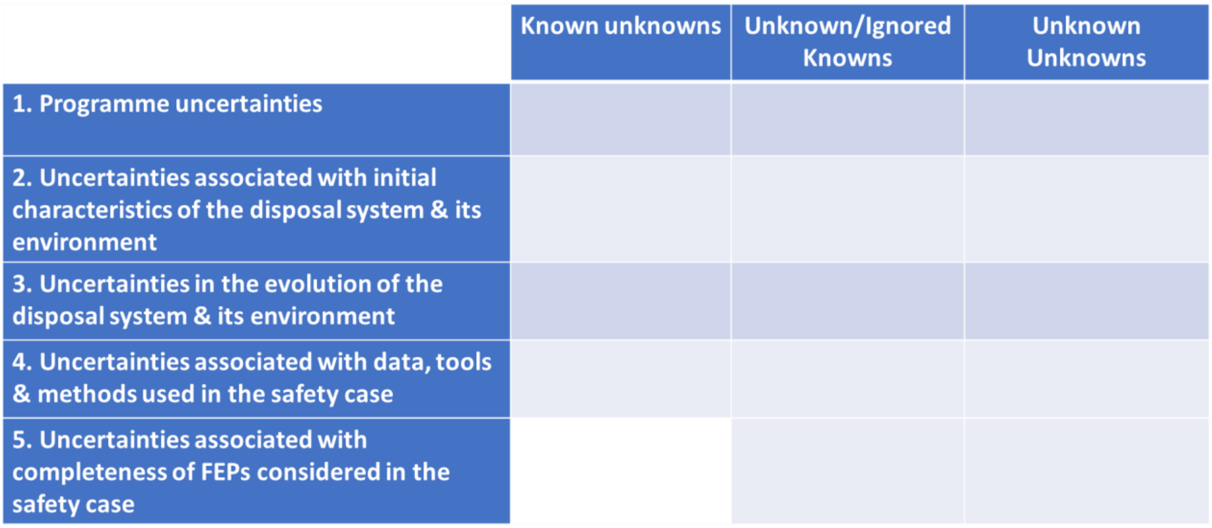


Figure 2 – Three-level uncertainty classification scheme. Note that the third level, representing specific topical uncertainties, is shown schematically and solely for uncertainties related to site and geosphere.



Knowledge is available	*Lack of knowledge*
Known Knowns *What is known and used*	***Known Unknowns*** *What we know we do not know*
Unknown/Ignored Knowns *What is known but we are not aware of or do not consider*	***Unknown Unknowns*** *What we do not know we do not know*

Figure 3 – Uncertainty classification scheme with respect to availability and use of knowledge. Uncertainties are represented by orange fields.



	Known unknowns	**Unknown/Ignored Knowns**	**Unknown Unknowns**
1. Programme uncertainties			
2. Uncertainties associated with initial characteristics of the disposal system & its environment			
3. Uncertainties in the evolution of the disposal system & its environment			
4. Uncertainties associated with data, tools & methods used in the safety case			
5. Uncertainties associated with completeness of FEPs considered in the safety case			

Figure 4 – Uncertainty classification matrix developed in WP UMAN.

3. Generic uncertainty management strategies and uncertainty management scheme

Within Subtask 2.1 of WP UMAN, generic uncertainty management strategies were identified (Hicks et al., 2022). Based on this work, uncertainty management elements have been structured as follows (*Figure 5*; Appendix B for details).

General principles and strategies (left in *Figure 5*) comprise:

- a stepwise, iterative approach,
- regular stakeholder dialog,
- safety-oriented management processes and principles.

For the management of uncertainties in the safety assessment, the scheme contains the following elements (right in *Figure 5*):

- identification of uncertainties,
- characterisation of uncertainties,
- assessment of the safety relevance, which can be done either through a preliminary analysis of the safety relevance or through a comprehensive evaluation of the results of the safety assessment,
- identification of uncertainties that must be reduced, mitigated, or avoided,
- specific actions to:
    - avoid or
    - reduce uncertainties or,
    - mitigate consequences,
- representation of (remaining) safety-relevant uncertainties in safety assessment.

This schematic representation of options, strategies, and tools served as guideline when analysing the management options for the specific topical uncertainties in Chapters 4 - 7. In particular, the evolution from generic to specific techniques and the applicability in function of programme phases was assessed.

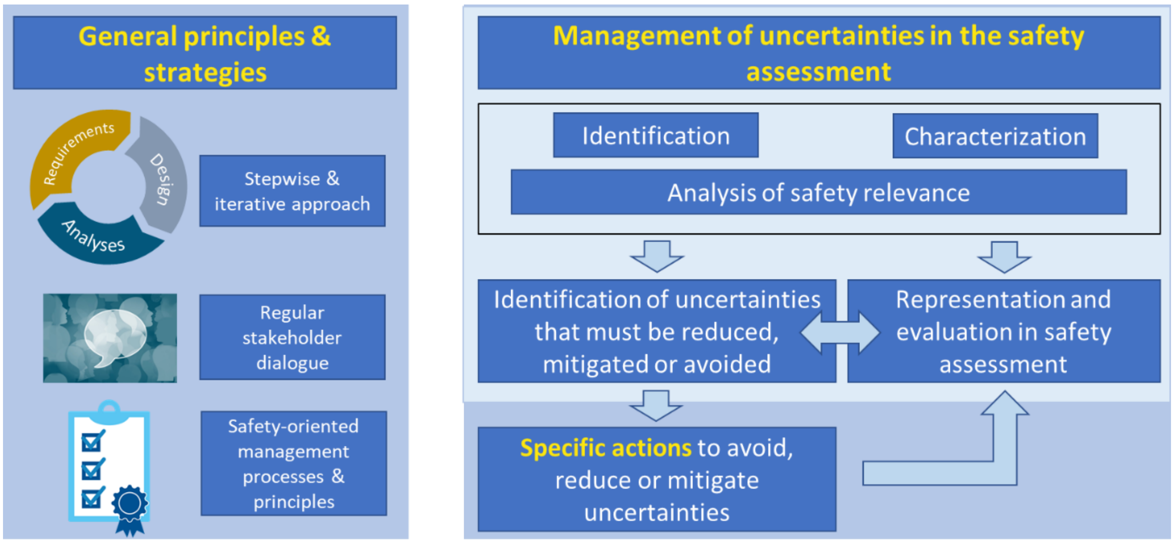


Figure 5 – General principles and strategies (left) and uncertainty management scheme for safety assessments (right).

4. Management options for site and geosphere related uncertainties

4.1 Selection of topical uncertainties and general comments

Subtask 3.3 of WP UMAN analysed views of the different actors (WMOs, TSOs and REs) on the identification, characterisation, and potential significance of uncertainties on site and geosphere (Diaconu et al., 2023a). A preliminary list of uncertainties from Subtask 3.3 together with a preliminary evaluation of the responses to the 1st and 2nd UMAN Questionnaires served as basis for the present chapter. Of particular value were the responses to the 2nd UMAN Questionnaire, where information on uncertainties safety relevance, evolution and chosen approaches for their characterisation was collected.

The preliminary list of uncertainties from Subtask 3.3 was structured according to the uncertainty classification schemes presented in Chapter 2 and analysed in view of selecting specific topical uncertainties to be investigated in more detail. The primary selection criterion was the safety significance, while a second selection criterion to be considered overall was to cover all the uncertainty types according to the classification schemes developed within UMAN. Considering these aspects, management options and strategies for dealing with site and geosphere-related uncertainties were identified and discussed for the following specific topical uncertainties:

1. **Hydraulic conductivity** of the host rock (and other geological units) as an example of uncertainty related to the **initial state** of the disposal system. Aspects regarding the evolution might also be addressed but are not the focus here.
2. **Sorption capacity** of the host rock (and other geological units) as an example of uncertainty related to the **initial state** of the disposal system and **data, tools, and methods**.
3. **Heterogeneities** of the host rock (and other geological units) as an example of uncertainty related to the **initial state** of the disposal system and **data, tools, and methods**. Of particular interest are heterogeneities in the context of examples one and two above.
4. **Fault locations**, **detection,** and **reactivation** as an example that addresses the **initial state** and **evolution** of the disposal system.
5. **Climatic evolution** with focus on **glaciations and permafrost** as an example for **evolution**-related uncertainty and allowing to address arguments **completeness** (FEPs, scenarios).

For some other a priori relevant uncertainties, it has been decided to discuss them not in the context of the site and geosphere topic but elsewhere:

- Very few programme uncertainties have been identified for the specific topic “site and geosphere” and they rather link to human factors. This type of uncertainty will thus not be explicitly addressed in this chapter but will be a focus point when addressing the uncertainties related to “human factors” (Chapter 5).
- Uncertainties on the initial characteristics of the site and geosphere include e.g., those linked to geomechanical properties and the formation and impact of an excavation damage zone (EDZ). To allow for better focus in the discussions and synthesis, these uncertainties are not addressed here but are one of the points discussed in the context of near-field aspects (Becker et al., 2024).

It was further noted that uncertainties associated with data, tools, and methods are often linked to specific properties (and uncertainties) associated with the disposal system (including the host rock). Management options and strategies related to this type of uncertainty are thus discussed in the context of the initial characteristics of the disposal system in section 4.3, albeit they also concern topics related to the evolution, e.g., via flow and transport models.

For the selected uncertainties 1-5, further input was gathered via the UMAN Subtask 4.2 template (see Appendix C) and discussed by the partners involved in the Subtask 4.2 site- and geosphere core-group. The discussions during the 1st UMAN Workshop, organised by Subtask 4.3, have been considered during the finalisation of this chapter. As a result, general management strategies and options (Chapter 3) that can be used to handle the specific uncertainties are presented and discussed. While this is done in a structured way along the elements of the management scheme (*Figure 5* in Chapter 3) in the subsequent sections of this chapter, the following general comments resulted from the work:

- On the one hand, programme establishment in phase 0 is impacted by the geological conditions available. On the other hand, the programme establishment may influence the uncertainties to be considered.
- Site and geosphere related uncertainties with (post-closure) safety relevance need predominantly be dealt with in the phases 1 and 2. There is also a link to construction, operation, and closure (phases 3 and 4, respectively), but, in general, it is expected that site and geosphere related uncertainties are adequately addressed before these phases, at least with respect to their (post-closure) safety relevance. Construction work provides an opportunity to confirm or verify assumptions made during earlier phases and, where possible, to reduce existing uncertainties. Throughout the disposal programme, monitoring activities also serve a similar purpose.
- Not only do site and geosphere related uncertainties depend on the type of host rock and the disposal facility (here mainly deep geological repository (DGR) or near-surface disposal (NSD)) but also different uncertainty management strategies might be adopted, depending on the host rock and system considered.
- On a high level, there is quite good agreement on relevance and management preferences among the different actors that contributed to WP UMAN. If there are differences, they manifest at lower levels of detail and are best discussed using specific examples.
- According to the scope of WP UMAN, the focus is on safety-relevant uncertainties and how they are handled in safety assessments respectively safety cases. For a given decision at hand, one should thus always ask:
    - if an uncertainty is safety relevant,
    - if it must and can be reduced, avoided, or if consequences must and can be mitigated,
    - if it can be dealt with accordingly in the safety case.

  An outlook to further steps in the programme is also warranted e.g., in the sense “this accuracy is ok now and we can reduce the uncertainty for the next step using a given approach or strategy”. The importance of this aspect, also expressed as “when to stop; when is it enough?”, was discussed with respect to communication aspects and regular stakeholder dialogue during the 1st UMAN Workshop of Subtask 4.3.
- During the 1st UMAN Workshop of Subtask 4.3, it has been emphasised by the RE actors group that there is value in not only focusing on safety-relevant uncertainty. Research helps to create background information for arguments related to the assessment of uncertainty significance, independently of the research itself being directly linked to safety-relevant features, events, or processes.

4.2 Programme uncertainties

Programme uncertainties are not addressed in the context of site and geosphere related uncertainties but will be a focus point when addressing the uncertainties related to human factors (Chapter 5).

4.3 Uncertainties related to initial characteristics

4.3.1 Hydraulic conductivity

(1) Identification and assessing the safety relevance

The geosphere (and host rock in particular) is an important or even the dominant barrier in a geological disposal system (OECD/NEA, 2012; Diaconu et al., 2023, and references therein). Thus, their properties – namely the flow regime and therefore also hydraulic conductivity – are relevant parameters linked to the safety functions of the geosphere (e.g., immobilisation, retention, and slow release of radionuclides). Accordingly, uncertainty in hydraulic conductivity is "naturally" identified as potentially relevant with respect to post-closure safety; albeit its safety relevance depends not only on the programme phase but also on the magnitude of the uncertainty which is e.g., influenced by the disposal system design, safety concept, and the type of host rock. An extreme case with low safety relevance might be a near-surface disposal facility with unsaturated conditions, where the safety of the facility does not rely on the geology as hydraulic barrier, as was highlighted in the 1st UMAN Workshop of Subtask 4.3.

The safety relevance is usually determined by (preliminary) safety assessments comprising sensitivity analysis (Saltelli et al., 2008; Galson and Richardson, 2021) and the impact on safety may be explored by uncertainty analysis (Marivoet et al., 2006; Galson and Richardson, 2021). To evaluate safety relevance in more detail, e.g., expert judgement is planned to be used in Germany.

For sensitivity analysis, it can be stated that the simpler, mostly regression or rank regression-based methods or screening methods (e.g., Morris, 1991) usually serve their purpose well (Courbaud et al., 2015; NEA, 2021). If methods based on Monte Carlo sampling are used, considerations on sample size and, depending on the method used, the structure of the model (e.g., parameter dependencies) must be taken into account (Nummi 2019; Galson and Richardson, 2021). If there is doubt, graphical methods as e.g., scatter plots might give insight into which methods would be most appropriate for the problem at hand. Note also that it should be kept in mind that sensitivity by nature is about models rather than about systems. If a process is not mapped or conservatively simplified in a model, sensitivity analyses will hardly reveal sound information about its importance (NEA, 2021). This latter point becomes also relevant in the context of characterisation (and associated concepts).

It was noted that hydraulic properties (e.g., hydraulic conductivity, hydraulic heads and gradients, including abnormally high pore pressures) might also be of some relevance regarding (conventional) operational safety, e.g., during construction of the repository. For example, the EDZ hydraulic properties influence the determination of the underground excavation design, stability evaluation, and the optimisation of ground support systems.

(2) Characterisation

Hydraulic properties, in particular hydraulic conductivity, of the host rock and geosphere are mainly determined based on measurements during site characterisation and using conceptual models. Several aspects must be considered when characterizing related uncertainty (Diaconu et al., 2023a):

- the accuracy of the measurements, be it in the laboratory or in the field, must be assessed and is a source of uncertainty,
- direct measurements of hydraulic conductivity (in particular in the field) are necessarily limited in extent since they correspond roughly to "point measurements". Thus, upscaling is usually required in order to obtain values for the entire rock unit, thus introducing uncertainty,
- also when deducing hydraulic conductivity of the host rock or geosphere from laboratory experiments, uncertainty due to upscaling might become relevant,
- heterogeneities or anisotropic effects and associated uncertainty must be considered (see also Section 4.3.3),
- when hydraulic conductivity is deduced from other materials properties, conceptual (model) uncertainty is introduced. Exemplarily, values of kinematic porosity are generally deduced from the experimental total porosity based on empirical laws or expert judgement; when hydraulic

conductivity is then computed using kinematic porosity, uncertainty related to the deduction of the latter from total porosity will propagate through to hydraulic conductivity.

If there is enough data available, uncertainty can be represented quantitatively using statistical methods; in doing so, consideration of the accuracy of measurements is possible. This is true for either direct measurements of hydraulic conductivity or measurements of underlying material properties as e.g., porosity.

With respect to model uncertainty, alternative conceptualisations may shed a light on their extent and safety relevance. A prominent example could be a homogeneous porous media approach vs. fractured media with transmissive features embedded in a porous matrix vs. dual-porosity models.

Additionally, complementary arguments as e.g., from large-scale tracer profiles, may be used to deduce or bound hydraulic properties (Gautschi, 2017; Nagra, 2002b). Exemplarily, parabolic tracer profiles hint at diffusion dominated transport with limited advective flow. Pore overpressures are another example of complementary data respectively arguments that may be explored in above sense. Natural analogues may further strengthen the line of reasoning (EC, 1988).

(3) Classification and associated actions

It is recognised that uncertainty with respect to hydraulic properties and thus the hydraulic conductivity must be adequately reduced until the end of site characterisation (end of phase 2). In particular, site characterisation of appropriate detail respectively extent is needed, so that the uncertainty in hydraulic conductivity can be well bound and the remaining uncertainty has no safety relevance anymore.

Local and regional model development can (and potentially must) go hand in hand with site characterisation. It helps guide the latter and keeps conceptual uncertainty in check.

In general, it is expected that, due to improved system understanding, the uncertainty with respect to hydraulic properties can be significantly reduced over time.

For certain disposal systems, uncertainty in hydraulic conductivity might also be mitigated by the engineered barrier system.

(4) Representation in safety assessments

It is usually strived to use best estimate values for hydraulic conductivity in models illustrating the expected evolution and behaviour of the disposal system. Remaining uncertainty and its consequence are then studied using conservative assumptions. More generally, deterministic or probabilistic sensitivity and uncertainty analysis are often used to illustrate the impact of hydraulic conductivity changes on solute transport through the system and demonstrate that sufficient safety margins remain (see e.g., NWMO, 2017; NWMO, 2018 for examples in a safety case for a system in crystalline and sedimentary rock).

A similar methodology, termed "stress-test" approach was proposed by the TSO actors during the 1st UMAN Workshop of Subtask 4.3, whereby assumptions regarding parameter values are modified to determine at which point the system might fail. This approach makes it possible to quantify available safety margins. The TSO actors stressed as well that best estimate values should be used if optimisation is at stake, but that a conservative approach might be favourable for the assessment of the possible radiological impacts associated with the disposal system.

There seems to be a tendency among WMOs towards using best estimate assumption – when possible – also for safety demonstration. E.g., in Germany, there is a regulatory requirement (§9(2) in EndlSiUntV, 2020) that puts strong weight on realistic assumptions when analysing the behaviour of the disposal system within the assessment period. This means that the behaviour analysis should be performed by means of "*sufficiently qualified numerical modelling […] based on assumptions close to reality*". Further, realistic values of input parameters should be used (such as median values determined from exploration) as conservative values can negatively affect some important aspects of sensitivity analysis (p. 52 in BTDrs. 19/19291, 2020). In contrast, the Swiss regulatory precisions for the last stage in site selection (ENSI, 2018) require the use of conservative values for irreducible parameter uncertainty. There was consensus during the 1st UMAN Workshop of Subtask 4.3 that the choice must be made carefully and dependent on the exact purpose of the assessment and that the choice must consider communicative aspects.

Note that it must not necessarily be the hydraulic conductivity per se that is varied in the uncertainty analysis. Uncertainty might as well be explored by varying water flow rates directly, i.e., combining uncertainty in hydraulic conductivity and flow driving hydraulic potential differences (e.g., Nagra, 2002a).

(5) Specific additional comments on uncertainties related to hydraulic conductivity

With respect to the evolution of safety significance of this uncertainty over time, i.e., across the phases of a disposal programme, hydraulic properties and thus hydraulic conductivity of the host rock and geosphere are most relevant during phases 1 and 2. They may have a strong impact on site selection (and the repository concept; thus there might be some relevance already in phase 0) and uncertainty must be adequately reduced to not compromise decisions during these phases. One approach, e.g., proposed in the United Kingdom (Radioactive Waste Management, 2016) is "designing out" significant uncertainties as the design of the preferred disposal concept is optimised. In site selection processes, there might be minimum requirements associated with hydraulic properties, as e.g., in Germany (§23 in StandAG, 2017).

It is expected that from phase 3 on, remaining uncertainty with respect to hydraulic conductivity should not be safety relevant anymore, i.e., that it is well enough bounded to allow for implementation of a safe disposal system.

Nevertheless, the construction work during the construction and operational phases might introduce additional uncertainty. This is two-fold:

- one may discover that previous assumptions do not hold; in this case, the overarching uncertainty management strategy "stepwise approach", which includes the principles of "reversibility", to "keep options open" and "maintain flexibility", will help to overcome the challenges. This is also relevant in the context of faults (see Section 4.4.1).
- construction will disturb the host rock; this might alter the host rock properties (at least in the near-field) and it may locally modify hydraulic properties (or sorption capacity – see Section 4.3.2).

Regarding the evolution of hydraulic properties over time themselves, it is expected that arguments are built and evidence gathered that the flow properties remain within a range of uncertainty that is not critical to safety for the chosen site and disposal system.

4.3.2 Sorption capacity

(1) Identification and assessing the safety relevance

High radionuclide retention capability is, besides low permeability, a second very favourable property of host rocks or the geosphere (and engineered barriers) for geological disposal. In fact, sorption capacity directly impacts the safety function "retention of radionuclides", albeit sorption may play a different role with respect to its safety relevance in granitic or clay rock systems.

Accordingly, sorption capacity is regularly identified as a sensitive parameter in (preliminary) safety assessments respectively sensitivity analysis. It must however be noted that sensitivity varies depending on the radionuclides considered, as e.g., stated in one of SKB's safety cases (SKB, 2019): "*The sensitivity of the relative geosphere release to changes in diffusivity and Kd* [sorption coefficient] *values is larger for radionuclides with a higher proportion of decay in the geosphere. Thus, the choice of retardation parameters is most important for relatively strongly retarded and dose-contributing radionuclides*".

Furthermore, in low-permeability rocks, such as clay with very long transport times through the geosphere, the safety relevance (respectively sensitivity) may almost be restricted to an on/off situation:

as soon as there is some sorption of a radionuclide, all the inventory will be sufficiently retarded as to not contribute significantly to dose rates in the biosphere. For example, in Nagra's last safety case (Nagra, 2002a), pessimistic geosphere sorption coefficients only lead to an increase of the dose rate maxima by a factor of two, still remaining far below the regulatory safety criterion. "*This is because the dominating radioelements remain the same within the sorption ranges considered and are either weakly sorbing (I) or non-sorbing (Se, Cl) in the reference dataset.*"

In above sense, it can be noted that sorption in the disposal system barriers may retain many relevant radionuclides (e.g., actinides) in the very near-field. The sorption properties in the near-field are thus of particular relevance, which implies that potential disturbances during the construction and operational phases must be considered. This may lead to additional uncertainty, as was pointed out in the 1st UMAN Workshop of Subtask 4.3.

As already discussed in the context of hydraulic conductivity, safety relevance is often also determined by (preliminary) safety assessments comprising sensitivity analysis and the impact on safety may be explored by uncertainty analysis.

(2) Characterisation

Sorption capacity can be measured during site characterisation. Since measurements are often constrained to a few characteristic elements and are often performed in diluted systems, several aspects induce related uncertainty that must be considered:

- deducing sorption coefficients for a bulk porous material from diluted systems requires theoretical approaches, conceptual models, or data fitting,
- extending measurements for characteristic elements to the full set of radionuclides requires theoretical approaches and conceptual models. For simplicity, one might often focus on radionuclides with the potentially highest radiological impact,
- a further aspect that may only be partially captured in experiments is competitive sorption phenomena,
- the accuracy of measurements and detection limits of equipment induce uncertainty,
- upscaling, e.g., linked to heterogeneities at larger scales (see also Section 4.3.3 below) introduces uncertainty,
- sorption capacity is linked to the chemical conditions in the pore water; this should be considered when transferring experimental values to estimates for in-situ conditions and when postulating sorption capacity evolution over time (e.g., constant sorption over the entire period of concern),
- for safety analysis, sorption is often modelled using linear relationships (*Kd*-approach), which introduces additional conceptual uncertainty.

As for other materials properties determined from experiments (see also hydraulic conductivity above), quantitative representation of uncertainty using statistical methods on data is strived for. With respect to model uncertainty, alternative conceptualisations may be used to characterise it. Plausibility of data may be assessed by expert judgement.

With respect to sorption, we note that the process is rather strongly linked to diffusive properties, at least for clay rocks. An assessment of uncertainty that encompasses sorption and diffusion (both experimental and conceptual) together may thus be beneficial.

Note that Subtask 2.2, dedicated to "*Uncertainty identification, classification, and quantification*", developed a fishbone diagram for sorption values, highlighting the mutual relationship between uncertainties contributing to the overall uncertainty of distribution coefficients (reproduced in *Figure 6*).

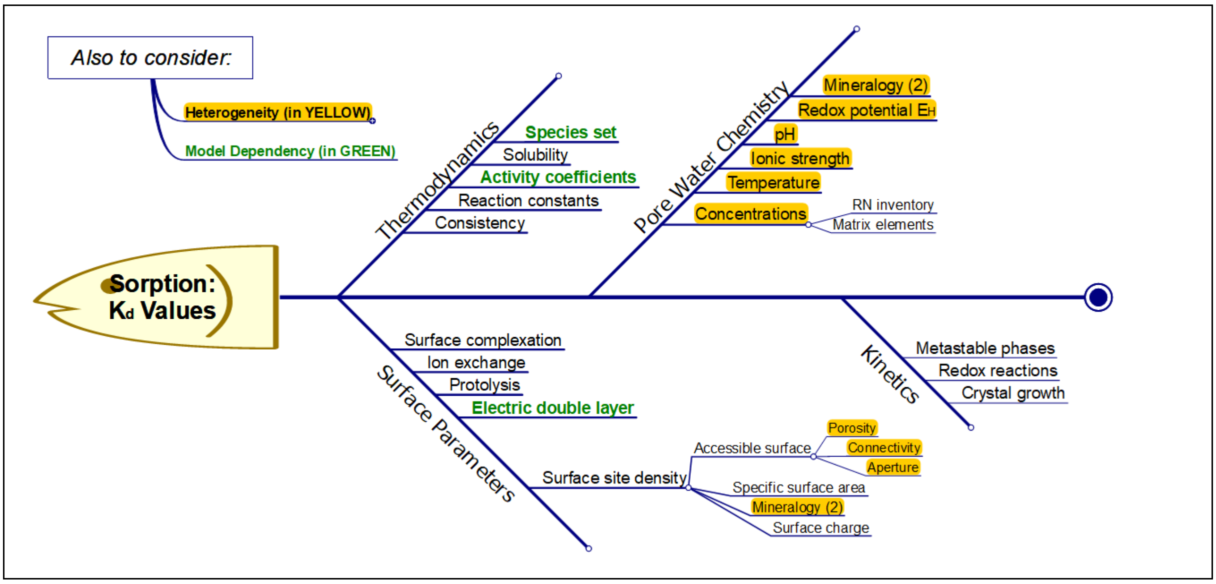


Figure 6 – Example for fishbone (Ishikawa) diagram, highlighting the mutual relationship between uncertainties contributing to the overall uncertainty of distribution coefficients (from Brendler and Pospiech, 2023).

(3) Classification and associated actions

Uncertainty with respect to sorption capacity must be adequately reduced until the end of site characterisation (end of phase 2). Accordingly, site characterisation of appropriate detail respectively extent is needed.

Particularly with respect to sorption, theoretical considerations and geochemical modelling are considered an important second cornerstone to reduce uncertainty. Examples include Smart-*Kd* (Stockmann et al., 2017) or predictive modelling using the so-called bottom-up approaches (Bradbury and Baeyens, 2011).

(4) Representation in safety assessments

As for hydraulic conductivity, it is usually strived to use best estimate values for sorption capacity models illustrating the expected evolution and behaviour of the disposal system. Remaining uncertainty and its consequence are then studied using conservative assumptions. Note, however, that whether best estimate values or conservative values are used depends on the exact application (e.g., assessment of the radiological impact vs. optimisation; similar as for hydraulic conductivity – see Section 4.3.1) and the choice must be made carefully and should consider communicative aspects as well. More generally, deterministic or probabilistic sensitivity and uncertainty analysis are often used to illustrate the impact of sorption capacity on resulting dose rates in the biosphere and to demonstrate that sufficient safety margins remain. Examples can e.g., be found in the recent safety cases of NWMO (NWMO, 2017; NWMO, 2018) or SKB (SKB, 2019). Sometimes, conceptual uncertainty is avoided using conservative assumptions and considering certain effects as “reserve FEPs”. Exemplarily, one might postulate no sorption on certain materials in the safety assessments but use additional argument that sorption is likely.

One challenge encountered is represented by phenomena that might only be marginally characterised for a repository system but impact sorption capacity in a negative way. Examples include competitive sorption or the presence of organic matter. In such cases, one might be forced to use very conservative sorption values simply because uncertainty remains large.

Note that it is not always clear which sorption values are to be considered conservative with respect to radiological impact. In fact, ingrowth and different sorption properties along the decay chain may make for a considerably non-linear system behaviour. Also, the impact of sorption on release times of the radionuclides and how they are summed-up to dose rates may lead to a non-monotonous dependency of dose rates on sorption coefficients.

Furthermore, in performance and safety assessment calculations, sorption is usually described with linear distribution coefficients (linear *Kd*-model) and applied in the classical advection-diffusion equation as a retardation factor *R*. Thus, through constant *R* factors, the impact of possibly changing hydrogeological and geochemical conditions is neglected and additional uncertainty is introduced, which must be accounted for e.g., by conservatism or bounding cases.

(5) Specific additional comments on uncertainties related to sorption capacity

Note that the EURAD WP FUTURE was dedicated to the fundamental understanding of radionuclide retention. Representatives of WP FUTURE were involved in the UMAN networking activities, e.g., the 1st UMAN Workshop of Subtask 4.3, and the WP FUTURE SoTA report (Maes et al., 2021) provides valuable insight with respect to sorption processes.

With respect to the evolution along time, i.e., across the phases of a disposal programme, uncertainties in the sorption capacity of the host rock (and to a weaker extent the geosphere) are most relevant during phases 1 and 2. They may have a strong impact on site selection (and the repository concept; thus there might be some relevance already in phase 0).These uncertainties must be adequately reduced to not compromise decisions during these phases.

It was observed that there could be also uncertainty due to sample collection, e.g., that the measurements of sorption properties are performed only on samples taken at the surface or from insufficiently deep boreholes and that rock samples from the required depths in which the DGR is planned are not available.

It is expected that from phase 3 on, remaining uncertainty with respect to sorption capacity should not be safety relevant anymore.

The aspects regarding the impact of the construction and operational phases as discussed for the hydraulic conductivity (see Section 4.3.1) also apply here.

4.3.3 Heterogeneities

(1) Identification and assessing the safety relevance

Natural materials and rocks are inherently heterogeneous. The heterogeneities arise at different spatial scales and identification of related uncertainty and assessing its safety relevance may depend on the host rock, type of repository (DGR or NSD), and on the scales considered. For example, uncertainties in heterogeneity are usually of lesser importance for NSD since site characterisation is easier and allows for more detailed characterisation. With respect to safety assessments of geological disposal, the following two aspects are of specific relevance:

- heterogeneities that must be considered when defining representative elementary volumes (REV), e.g., to characterise and parametrise a rock as homogeneous material at a larger scale. An example is the homogeneous porous media approach for e.g., clay rock with bulk conductivity and diffusivity (and sorption capacity), by “smoothing out” heterogeneities at the pore-scale,
- heterogeneities that become relevant when extrapolating local properties (e.g., measured in deep boreholes) to the larger – often km – scale relevant for the repository system as a whole.

Sometimes, the above two aspects overlap. For example, it may be useful to conceptualise fractured rock using a large enough REV or by representing fractures explicitly as discrete features. But in any case, heterogeneities (and associated uncertainty) may impact the (long-term) safety functions of the geosphere, e.g., “retention and slow release”, be it by influencing transport pathways or transport and retention properties. Heterogeneities may furthermore be relevant regarding mechanical properties of the rock.

Heterogeneities, e.g., concerning hydraulic, mechanical, or geotechnical properties might also be of relevance regarding (conventional) operational safety, e.g., during construction of the repository.

There is a vast literature concerning the impact of heterogeneity on effective properties of rock and geological media, e.g., Berkowitz (2002); Dentz et al. (2011); Kitanidis (2015); Conil (2018). The impact and safety relevance can be assessed using numerical modelling respectively (preliminary) safety assessments, including sensitivity analysis. In fact, numerical calculations allow rather easily to determine REVs or to quantify the impact of heterogeneities during upscaling processes. Experimental work, on the one hand, also helps to understand the impact of heterogeneities on transport properties (e.g., Boon et al., 2017). On the other hand, measurements and conceptual assumptions are used together with statistical and mathematical techniques to feed heterogeneity into assessment models (Koltermann and Gorelick, 1995; de Marsily et al., 2005).

(2) Characterisation

It is strived to characterise uncertainty related to heterogeneities quantitatively using statistical techniques. Conceptualisations and theoretical aspects such as e.g., conceptual models, upscaling considerations, that are often linked to expert assessments, play a considerable role.

(3) Classification and associated actions

There is broad agreement that uncertainty related to heterogeneities must be adequately reduced to allow for robust decisions to be made. This is particularly relevant up to and during the phase of site characterisation. Accordingly, site characterisation at different scales, combined with statistics and conceptual model development, is predominantly used.

With respect to heterogeneity, combining analyses of different data sets, ideally representative at different scales, and linking them using dependencies (e.g., mineralogy, porosity, sorption, diffusion, tracer profiles) can help in reducing the overall uncertainty. Quality and relevance of samples and measurements must be accounted for.

For certain disposal systems, uncertainty in heterogeneities might be reduced by site selection or its uncertainty relevance reduced by engineering solutions. This was e.g., stressed during the 1st UMAN Workshop of Subtask 4.3 in the context of NSD.

Note that specific site selection criteria that relate to uncertainty in heterogeneity are sometimes used. E.g., in Switzerland, one of the site selection criteria is on the characterisability of the site (SFOE, 2008).

(4) Representation in safety assessments

That site characterisation and predictive assessment (and thus also model development) must go hand in hand has been recognised early in the context of geological disposal (Tsang et al., 1994). Note also the OECD/NEA project "*Performance Assessment Methodologies in Application to Guide the Development of the Safety Case*" (GEOTRAP) with one of its workshops dedicated to modelling of the effects of spatial variability (NEA, 2002).

It is strived to explicitly address remaining uncertainty related to heterogeneity on the one hand by using statistical approaches and on the other hand by assuring appropriate uncertainty propagation through upscaling processes. In the context of the project "*Performance Assessment Methodologies in Application to Guide the Development of the Safety Case"* (PAMINA), a review on approaches for spatial variability in performance assessments has been compiled (Plischke and Röhlig, 2008). In general, the ideal approach depends on the scale of the heterogeneity vs. the scale of the modelled domain (i.e., the host rock). If these scales are similar and heterogeneities govern radionuclide transport, they need to be represented explicitly in the models. If the scale of the heterogeneity is significantly smaller than the scale of the modelled domain, then the REV concept can be used.

For consequence analysis (e.g., dose calculations), it is common to use bounding cases (pessimistic assumptions) or what-if scenarios to demonstrate safety despite the remaining uncertainty. An example with respect to heterogeneous flow properties might be an undetected fault with high transmissivity that can be treated as a specific assessment case.

(5) Specific additional comments on uncertainties related to heterogeneities

Similar to the other topical uncertainties related to site and geosphere properties, the uncertainties related to heterogeneities are most relevant during phases 1 and 2. They may have an impact on site selection (and the repository concept; thus, there might be some relevance already in phase 0). These uncertainties must be adequately reduced to not compromise decisions during these phases.

4.3.4 Fault locations and detection

Uncertainties related to the initial state of the disposal system in the context of fault locations and detection are discussed together with fault reactivation and the disposal system evolution in Section 4.4.1.

4.4 Uncertainties in the evolution of the disposal system and environment

4.4.1 Fault locations, detection, and reactivation

(1) Identification and assessing the safety relevance

With respect to fault locations and detection, uncertainty identification and safety relevance share many similarities with other site and geosphere properties and depend on the host rock. Fault detection (and thus location) uncertainty is linked to site characterisation (e.g., resolution of seismic imaging). When it comes to fault reactivation over time, the related uncertainty results from uncertainty in the fault detection and characterisation itself but, probably more so, from uncertainty in the evolution of the geosphere, as e.g., changes in stress states due to erosion or tectonics and uncertainty in the evolution of the properties of (reactivated) faults.

Faults – their frequency of occurrence, locations, and properties and how they evolve over time – are potentially relevant for post-closure safety since they influence transport pathways. This safety relevance is very much dependent on factors influencing radionuclide transport like their transmissivity or on the possibility to damage engineered system components in case of reactivation (see e.g., Garisto, 2018). The relevance of remaining uncertainty can be assessed by (preliminary) safety assessment and sensitivity analysis.

Note that fault locations are also part of spatial considerations (e.g., available size of “undisturbed” host rock) and may, in this sense, have indirect safety relevance.

Faults and related uncertainty may furthermore be relevant for operational safety (e.g., reactivation during construction, compromising of constructions).

(2) Characterisation

Uncertainty regarding fault locations and detection can be considered as a special case of uncertainty due to heterogeneity (see Section 4.3.3) and quantitative descriptions using e.g., statistical techniques are preferred. It should be noted here that uncertainty in fault detection may arise during phases 1 and 2 as boreholes can only be drilled around the site to avoid damaging the host rock during site characterisation. Non-invasive geophysical methods might thus be the only methods available during these phases to detect faults. Furthermore, it might be very difficult to detect subvertical faults using vertical boreholes. Field data and observations becoming available during construction are therefore useful to verify the assumptions made during previous phases.

Regarding fault reactivation, the uncertainty is two-fold:

- Uncertainty related to the evolution of the geosphere and thus if and when faults might be reactivated. One might apply statistical methods on relevant data from observations in the past and extrapolate to the future by modelling. This can help deducing the likelihood of relevant events. However, quantitative characterisation of uncertainty related to long-term evolution is difficult and one often must rely on expert judgement. The latter can systematically be gathered e.g., using formal expert elicitation (Scourse et al., 2017).

- Uncertainty related to the properties of potentially reactivated faults and how they evolve over time. This can be tackled by experiments and data from e.g., site characterisation and the uncertainty may be characterised quantitatively using statistical techniques. Again, conceptual modelling is usually another building block, particularly when it comes to properties evolution over time.

(3) Classification and associated actions

Uncertainty in fault locations and detection must be adequately reduced up to the phases of site selection and characterisation. This is mostly achieved by adequate site characterisation (e.g., geophysical methods and geological mapping) and finally adequate site selection (e.g., assuring a large enough volume of “undisturbed” rock).

During construction, e.g., if one discovers that previous assumptions do not hold and faults are encountered, one may mitigate the uncertainty by adapting the repository design (e.g., adapt the location of an emplacement cavern or backfill an area). The success of these measures will depend on an appropriate overarching uncertainty management strategy that “maintains flexibility” (see also related discussion in Section 4.3.1).

Regarding fault reactivation, there might be little possibility to reduce uncertainty significantly along the programme phases, at least after the first steps in site selection. Thus, seismic and geodynamic stability is one of the important criteria for siting and appropriate indicators[3] should be defined and applied. Selected indicators should be in accordance with legislative requirements and should be designed so that their parameters can be clearly quantified. The selection of indicators should reflect the complex geodynamic characteristics of the area. Furthermore, a monitoring network can help to reduce uncertainty.

Mitigation of consequences also plays a significant role. A prominent example is the self-sealing property of clay host rock (Bock et al., 2010) that assures that reactivated faults will not lead to dominant transport pathways nor safety relevant enhanced transport through these rocks. It can then be deduced that uncertainty related to fault reactivation is not safety relevant if it can be shown that the conditions are such that self-sealing works reliably (i.e., that uncertainty related to the self-sealing process is small).

Another example of mitigation is the specific adaptation of the multi-barrier system so that the overall disposal system is robust with respect to fault reactivation.

(4) Representation in safety assessments

Uncertainty related to faults can partially be addressed explicitly, e.g., through systematic uncertainty analysis in safety assessments, e.g., during site characterisation. However, as discussed above, particularly with respect to reactivation, remaining uncertainty is hardly quantifiable. Possibly, one might be able to argue, e.g., based on expert judgement, that the probability of extreme events, i.e., events that lead to reactivation, is (very) low. Nevertheless, arguments are usually built do demonstrate that consequences would be low, i.e., not safety relevant, in any case. This can e.g., be achieved by conservative assumptions e.g., assuming that fault reactivation will occur and assess its possible consequences through a specific scenario (see e.g., SKB, 2011). The decision on how to treat an extreme event with a low probability of occurrence but with significant safety implications must be carefully taken.

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[3] e.g., maximum horizontal acceleration value, altitude gradient, percentage of the area of relief affected and deformed by young cycles of reverse erosion and slope deformations, occurrence of volcanic rocks of Paleogene to Holocene age and acids.

(5) Specific additional comments on uncertainties related to fault locations, detection, and reactivation

Uncertainties related to faults are strived to be reduced mainly in phases 1 and 2 of the disposal programme. They may have an impact on site selection (and the repository concept; thus, there might be some relevance already in phase 0). These uncertainties must be adequately reduced to not compromise decisions during these phases and such that remaining uncertainties are not safety relevant anymore from phase 3 on. However, for crystalline rocks, uncertainties regarding faults might also be of relevance during the operational period, e.g., they can strongly influence the choice of an excavation method and the dimensioning of the proposed repository.

In general, there was good agreement on the aspects related to uncertainties of faults among WMOs, TSOs and REs.

4.4.2 Climatic evolution with focus on glaciations and permafrost

Strategies and management options for uncertainties related to the climatic evolution with focus on glaciations and permafrost were explored as examples for evolution related uncertainty. Furthermore, aspects related to completeness (FEPs, scenarios) were also addressed.

(1) Identification and assessing the safety relevance

Several uncertainties related to glaciations and their possible consequences are potentially safety-relevant. Depending on the site, safety concept, and design, these uncertainties may be due to:

- the timing of occurrence and duration of the next glaciations,
- the extent and thickness of the ice sheet,
- the depth and location of glacial erosion (e.g., formation of glacial channels),
- the magnitude of the isostatic adjustment associated with glaciation/de-glaciation (i.e., glaciation-induced tectonic movements), e.g., crustal depression or glacial rebound rate,
- the depth of the permafrost layer or temperatures at repository depth,
- induced loading/unloading and related changes in hydraulic conductivity,
- induced changes in groundwater flow regimes and chemistry,
- induced changes in the biosphere (surface hydrology, flora, fauna, human habits, etc.).

These uncertainties are potentially relevant mainly to post-closure safety as they may impact the long-term stability of the disposal system and/or radionuclide migration in aquifers and the biosphere. Their relevance is greatly dependent on:

- the waste inventory to be disposed of and the associated period of consideration[4],
- a number of site and host rock characteristics (site location, host rock depth, thickness and properties, erosion potential, etc.),
- as well as on the safety concept and design (depth of the emplaced waste, strength of barriers with respect to induced loads, etc.).

For instance, the maximum thickness of the ice sheet that could occur at the site might determine the maximum isostatic load on canisters. Glaciation-induced erosional processes could remove (parts of) geological layers affecting to the isolation and/or containment of the waste. The maximum depth of permafrost that could occur will determine whether critical parts of the repository could freeze. It could also impact the extent to which water generated by the melting of an ice-sheet may infiltrate the subsurface (Peltier, 2011). The modification of the groundwater flow regime (magnitude and patterns) by ice sheets approaching or retreating from the site may have an impact on buffer erosion, canister corrosion, or radionuclide transport.

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[4] e.g., for near-surface disposal facilities for low level waste, glaciation is not relevant because of the time-span until a next glaciation might occur.

The identification of uncertainties relevant to a specific safety concept or site is typically performed through the FEPs analysis included in the overall FEPs management process.

It is worth noting that the assessment period, for which these uncertainties need to be assessed may be prescribed by regulatory requirements or guidelines. For instance, according to the ASN safety guide for the deep geological repository (ASN, 2008), climatic cycles with exceptional magnitude need to be considered until the waste activity in the repository system will have decreased significantly. According to the Swiss regulatory guideline ENSI-G03 (ENSI, 2020), scenarios, in which the underground disposal area is increasingly exposed to surface influences as a result of geological processes, have to be taken into consideration for periods exceeding one million years.

(2) Characterisation

The characterisation of uncertainties related to future climatic events is founded on the geoscientific understanding of the evolution of the disposal site. For instance, geological mapping of quaternary sediments may provide an indication of possible future locations and depths of glacial channels. Site-specific natural analogues to examine past geosphere stability may also contribute to this characterisation.

Statistical methods on (past) observation data with extrapolation to the future can then be used to characterise the uncertainties. This can be done e.g., by using alternative models and conservative model assumptions. However, in situations where relic indications at depths relevant for geological disposal are non-existing, performing simulations could be the only way to estimate the depth of permafrost. In this case, various sources of uncertainty need to be accounted for, such as those in the type and impact of vegetation, snow cover, surface temperature gradients, hydraulic conditions on site, possible errors in paleoclimate reconstructions, porosity, lithology, and geothermal heat flux (Govaerts et al., 2016).

Expert judgement can also be used where uncertainties cannot be inferred from field observations or estimated by means of models.

Uncertainty arises as well from possible future human behaviour regarding the emission of greenhouse gases and their possible impact on future glaciations.

(3) Classification and associated actions

Safety-related principles related to siting and design typically provide the framework for the handling of climatic events (e.g., Nagra, 2002):

- predictability,
- avoidance of and insensitivity to detrimental phenomena,
- stability and longevity of the barrier system.

Such principles might be specified by or derived from regulatory requirements relating to the implementation of the defence-in-depth principle.

For instance, German regulations (such as §10(5) in EndlSiAnfV, 2020) require demonstration that "*the safety functions of the disposal system and its barriers are insensitive to internal and external influences and interference and that the behaviour of the barriers can be predicted well*". In addition, "*the evolutions of the disposal system and the geological situation at the disposal site relevant for the design of the disposal facility and the assessment of long-term safety within the assessment period shall be systematically determined, described and classified as (1) expected evolutions or (2) deviating evolutions*" (§3(2) in EndlSiAnfV, 2020).

Such requirements imply that no credit should be taken for the geological layers that might be significantly affected by extreme climatic events. This may lead to specific design requirements or site selection criteria regarding e.g., the depth of the repository.

Therefore, the following options might be adopted to avoid or mitigate uncertainties:

- Site selection criteria and minimum requirements can be defined to ensure that any significant effects of (extreme) climatic events on the safety functions fulfilled by the disposal system can be excluded. This can be done by requiring e.g., that the depth of the repository sets the entire or a sufficient part of the host rock below the maximum anticipated erosion thickness or permafrost depth (see e.g., ten Veen J. (2015); §23 in StandAG, 2017). Safety margins can also be included in these criteria to address the uncertainties.
- Where the occurrence of significant glaciation-induced perturbations cannot be excluded, potential perturbations can be mitigated through the consideration of specific design requirements or of “design-basis glacier scenarios” (Peltier, 2011). Induced conditions and their uncertainties can then be taken into account in models using conservative or bounding assumptions e.g., when designing canisters or assessing their performance. Safety margins can also be included in the design to address the uncertainties.

Any remaining uncertainties that could have significant effects on the disposal system need to be assessed in the safety assessment.

RD&D is also performed for climatic events in order to reduce uncertainties where needed: climate models for the prediction of future glaciations, dating of quaternary sediments, erodibility of the overburden, influence of decompaction on host rock properties, etc. (e.g., ESK, 2016; Nagra, 2016; BGE, 2021). Reducing uncertainties can lead to less conservative assumptions regarding these events and their consequences in the safety assessment, which in turn may lead to less stringent site selection criteria or design requirements.

Note that uncertainties related to biospheres are usually treated using stylised approaches and it is not strived to reduce those. Such aspects are discussed e.g., in the context of the IAEA project “*Biosphere Modelling and Assessment*” (BIOMASS) (Plischke and Röhlig, 2008) and are not elaborated on further in this report.

(4) Representation in safety assessments

Climatic events are usually treated through FEPs management, where events that cannot be ruled out in FEPs screening are addressed in the safety assessment. Their representation (or not) in the safety assessment and the way to represent them will thus depend on their probability of occurrence and impact on safety functions and/or radiological consequences. It is thus dependent on site and host rock characteristics (site location, depth and thickness of the host rock, erosion potential, etc.) as well as on the safety concept and design (depth of the emplaced waste, etc.).

The following options are identified when significant effects of future glaciations cannot be excluded by site selection or design:

- In cases where such events are expected to occur during the assessment period, the effects of glaciations are considered in the normal, expected, or reference evolution scenario (see e.g., SKB, 2014; Thorne and Towler, 2017). Conservative assumptions or bounding cases may be considered to address remaining uncertainties.
- In cases where no significant effects of glaciations are expected but cannot be excluded or where more severe or earlier glaciation-induced perturbations than those expected cannot be excluded, such perturbations can be assessed through dedicated altered evolution scenarios (see e.g., Vangeet et al., 2012). What-if or disruptive scenarios not directly linked to a specific cause but bounding the consequences of glaciations (e.g., considering the loss of one or several safety functions) may also be used in safety assessments, e.g., as done for the Bruce repository in Canada (NWMO, 2018). Alternative evolution and what-if scenarios are typically used to evaluate whether:
  - the design of the disposal system is robust with regard to inherent uncertainties, or
  - the disposal system is designed to mitigate the effects of very unlikely, but possible, natural events.

The consideration using such scenarios of natural events with an exceptional magnitude might also be expected by regulator (see e.g., ENSI, 2020).

- Stylised approaches can also be used in specific situations e.g., to illustrate the impact of uncertainties regarding the possible exhumation of the repository over very long time-frames (Nagra 2008; ENSI, 2020).

(5) Specific additional comments on uncertainties related to climatic evolution

The consideration of climatic events and the associated uncertainties is particularly important during the siting and design phases of the programme (phases 1 and 2). They may have an impact on site selection (and the repository concept; thus, there might be some relevance already in phase 0). From phase 3 on, remaining uncertainty should not be safety relevant anymore but the validity of assumptions regarding possible future climate evolutions should be verified as new scientific knowledge becomes available.

It was noted during the 1st UMAN Workshop of Subtask 4.3 that it should be strived for unified approaches across national boundaries when addressing climatic evolution and the related uncertainty.

Not directly linked to climatic evolution but to long-term evolution in general, also other eventual extreme events, such as an earthquake in the area, may have to be considered separately, regardless of reducing probability through site selection. Emergency plans must be in place during operation and possibly also during the monitoring period. Furthermore, adequate monitoring could be considered for early detection of precursor phenomena of extreme events.

4.5 Uncertainties associated with data, tools, and methods used in the safety case

Management options and strategies regarding uncertainties associated with data, tools, and methods have been addressed in the context of the topical uncertainties in Section 4.3.

4.6 Uncertainties associated with the completeness of FEPs considered in the safety case

Management options and strategies regarding uncertainties associated with the completeness of FEPs may be linked to some extent to the evolution of the disposal as discussed in Section 4.4. For broader aspects, the reader is referred to Chapter 5 on human-related uncertainties.

5. Management options for uncertainties related to human aspects

5.1 Selection of topical uncertainties and general comments

Subtask 3.4 analysed views of the different actors (WMOs, TSOs and REs) on the identification, characterisation, and potential significance of uncertainties on human aspects (Dumont et al., 2023). A preliminary list of uncertainties from Subtask 3.4 together with a preliminary evaluation of the responses to the 1st and 2nd UMAN Questionnaires served as basis for the present chapter. Of particular value were the responses to the 2nd UMAN Questionnaire, where information on relevance, actors' preferences, evolution, and chosen approaches to handle specific uncertainties was collected.

Based on the feedback to both UMAN questionnaires and using criteria combining potential impact on safety, decision-making, and interest in research, Subtask 3.4 proposed ten uncertainties considered as of a high priority for further investigation. These were structured according to the uncertainty classification schemes presented in Chapter 2 and four of them were subsequently selected as specific topical uncertainties for the present work:

1. **Public acceptance** of the repository at potentially suitable or projected locations as an example of **programme uncertainties**,
2. **Schedule** to be considered for implementing the different phases of the disposal programme as an example of **programme uncertainties**,
3. **Reliability of monitoring** results and **safety analysis** as an example of uncertainty the **evolution** of the disposal system and its environment,
4. **Adequacy of safety-related activities** (in siting, design, construction, operation and closure) for the implementation of safety provisions as an example of uncertainty related to **initial characteristics** of the disposal system and its environment.

One selection criterion was the coverage of all three categories of "information awareness", i.e., the categories "known unknowns", "ignored knowns", "unknown unknowns", which is achieved as illustrated in *Table 2* (specific topical uncertainties in *italic red*).

To optimise the discussion and analysis of the selected uncertainties, some specific elements have been selected, leading to slightly modified descriptions of the 3rd and 4th topical uncertainties as compared to their original formulation in the 2nd UMAN Questionnaire:

- the 3rd topical uncertainty does not refer solely to the monitoring aspects but is extended to include any new knowledge becoming available during an RWM programme (e.g., generated through RD&D activities or technology development) and any knowledge that was ignored by certain actors,
- the 4th topical uncertainty refers solely to construction phase.

Table 2 – Uncertainties matrix for topical uncertainties related to human aspects.

Uncertainty category	Topical uncertainty	"information awareness" classification		
		Known Unknowns	**Ignored Knowns**	**Unknown Unknowns**
Programme uncertainties	*Public acceptance*	e.g., conditions set by a community for accepting the project on their territory		e.g., unconceived negative decision of a community
	Schedule	e.g., duration of the licensing process	e.g., ignored lack of financial resources	e.g., unconceived political instabilities
Uncertainties associated with initial characteristics	*Implementation of safety provisions in construction – characteristics of the built components*	e.g., uncertainties in as-built repository components (due to construction errors)		
Uncertainties in the evolution of the disposal system & its environment	*"New" knowledge*		e.g., ignored possible magnitudes of disturbing events (e.g., Fukushima)	e.g., really new knowledge, unexpected, with possible impact on the safety case

For the selected uncertainties, further input was gathered via the UMAN Subtask 4.2 template (see Appendix C) and discussed by the partners involved in the Subtask 4.2 human aspects core-group. The discussions during the 2nd UMAN Workshop, organised by Subtask 4.3, have been considered during the finalisation of this chapter. As a result, general management strategies and options (Chapter 3) that can be used to handle the specific uncertainties are presented and discussed. While this is done in a structured way along the elements of the management scheme (*Figure 5* in Chapter 3) in the subsequent sections of this chapter, the following summarising comments can be made:

- The uncertainty related to **public acceptance** comes into play e.g., during the site selection process and it is difficult to decrease this uncertainty through RD&D. Different stakeholders may introduce new safety-related issues that need to be reassessed in the safety analysis. In addition, the stakeholders may require new elements to be included in the decision-making process (more discussion, more meetings, new ideas, etc.), which impacts the process itself and potentially the schedule. Also, if public acceptance criteria impact site selection, other appropriate measures might have to be undertaken to assure long-term safety of a disposal facility at the selected site (e.g., adapt the engineered barrier system). In the worst case, the loss of acceptance may result in the loss of all favourable sites during site selection. Another concern is the loss of acceptance during the operational phase or at facility closure when waste retrievability and monitoring aspects might become dominant. All of the above might have an impact on safety if not dealt with appropriately. Another uncertainty concerns the measurement of the public acceptance and how to determine a sufficient level of acceptance but also how to measure the acceptance level.
- The uncertainty regarding **delays in the implementation of the programme schedule** is related to insufficient support and acceptance by the public or political changes in the phases of site selection and site characterisation, namely regarding decisions on the location of DGR

and its construction. The schedule may also be affected by uncertainties related to the provision of sufficient financial and raw material resources, the availability of technologies at the appropriate readiness level (TRL) and resources for evaluation.

- The safety case **as a basic methodology to assure the consistency of all safety related issues can be challenged when new evidence, knowledge, or techniques are developed**. Constantly emerging new knowledge may create suspicion on the adequacy of the solutions that are implemented along a disposal programme. The following uncertainty management options were identified: conservatism, fuzzy sets, deterministic approaches, scenario analysis, etc. A systematic approach on how to identify new findings, on how to assess what their impact on safety is, and when the safety analysis shall be renewed should be applied. The prescribed period of safety reviews (e.g., every 10 years) should also be linked with the obligation to establish a **monitoring process** for new developments and exchange with international experiences.
- The uncertainty regarding adequacy of safety-related activities (in siting, design, construction, operation, and closure) for the implementation of safety provisions is related to the management provisions for the activities related to safety. Changes in organisation and safety culture, lack of knowledge management and inadequate training may affect especially the safety in the construction and operational phases as well as in the long-term.

5.2 Programme uncertainties

5.2.1 Public acceptance of the repository at potentially suitable or projected locations

(1) Identification and assessing the safety relevance

Public acceptance related uncertainties can be identified and characterised in the framework of a decision-making process, involving open communication among the different stakeholders and public participation. In some national RWM programmes this uncertainty is already indirectly addressed in the regulatory framework; e.g., in the recent German regulations (StandAG, 2017; EndlSiAnfV, 2020; EndlSiUntV, 2020) that have established a transparent, participative, science-based, self-questioning and learning procedure for the search for and selection of a repository site for HLW, starting from a white map of Germany (i.e., with no preferences on a possible site). Stakeholder analysis could also be applied to identify the different groups of actors involved in or influencing a RWM programme (including organised groups or individuals, with or without expertise in waste disposal, representing Civil Society) and to determine their interest, attitude, influence, and role in the site selection process.

These uncertainties, if not dealt with appropriately, may have an impact on safety.

First, they can cause important delays in the implementation of the disposal programme, which may eventually lead to safety issues in storage facilities or during waste transportation due to e.g., ageing phenomena (see Section 5.2.2). Their safety relevance is therefore very much dependent on resulting delays in programme implementation, on the lifetime and capacity of storage facilities, and on possible ageing phenomena affecting the waste and these facilities.

Second, new requirements set by stakeholders may result in both positive and negative implications for safety of a disposal facility.

Furthermore, if e.g., site selection is (also) driven by public acceptance criteria, safety concepts and finally disposal facility safety, may depend indirectly on public acceptance.

While public acceptance criteria can thus be considered as very important for the disposal programme, measures must be taken that they do not become determining factors for the safety of a disposal facility. Safety must be professionally ensured at the highest level and set as a non-negotiable requirement. Note that this does not exclude that the overall optimal solution takes socio-economic constraints into account but only that "unsafe" options must be avoided. It was recognized that a high degree of competencies of the key actors is crucial in helping to achieve this.

It was also noted that one could possibly argue that the participatory process strengthens the disposal programme and thus contributes to safety. It might point out the questions that were not resolved or asked before or make clearer the remaining uncertainties of issues already investigated. In fact, participation can be seen as another kind of review process for programme steps. This can be one way to avoid negative "surprises" in the process (from all sides).

(2) Characterisation

The stakeholder acceptance, and in particular public acceptance, becomes an increasingly important issue in a number of national programmes (e.g., the existence of a requirement that the siting of the facility does not take place without the consent of the public concerned).

The uncertainties regarding public acceptance are closely related to the consideration of the expectations of different stakeholders notably on various operational issues (such as operational monitoring, the retrievability of the waste, costs, conditioning of radioactive waste, location of surface installations, etc.) as well as post-closure issues (such as post-closure monitoring, radioactive waste recoverability, overall decision-making, etc.) and also political factors. They should be identified and characterised during the early stages of disposal programme development: programme initiation, siting and site characterisation. The public concerned usually expects long-term guarantees that the site selection process for a DGR will not be affected by changing political attitudes (e.g., after election), which has sometimes happened and severely undermined public (and other interested parties) confidence in the process.

Possible approaches to characterise public acceptance and the related uncertainties include:

- multi-channel communication with stakeholders: public meetings, newspapers, door to door, webinars, web site, etc.,
- identification of the different stakeholder categories (with the focus on those representing Civil Society) as well as their interest, influence, and relationships through stakeholder analysis,
- quantitative representation using statistical methods on data, consideration of accuracy of measurements, e.g., socio-economic studies.

Note that these approaches should 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...). It is thus recommended to carry out public discussions, consultations, etc. on district level or higher.

(3) Classification and associated actions

It is clear that uncertainty regarding public acceptance must be adequately reduced. In particular, achieving a level of sufficient public acceptance is needed. Thus, these uncertainties cannot be avoided but must be reduced or consequences mitigated through various measures or means as discussed below.

The implementation of a participative and transparent decision-making process within each phase of a disposal programme is an essential prerequisite for ensuring that those decisions made at each phase are supported by the various stakeholders (including a significant respectively sufficient part of the public). Significant changes in the approach to participation and transparency in the area of RWM across European countries occurred in the context of preparation and ratification of the two important pieces of international legislation, which are generally applicable in procedural aspects of environmental protection: the Aarhus Convention and the Espoo Convention. In particular, development and establishment of a fair, sustainable, transparent procedure for the search for and selection of repository sites are important, as e.g., Deep Geological Repositories Sectoral Plan in Switzerland (BFE, 2020), the site selection procedure for HLW in Germany (StandAG, 2017), or the design and consent based DGR siting process in the USA (Espoo Convention).

This also involves ensuring mutual dialogue among stakeholders and the timely involvement of the public in the decision-making process. There should be a continuous dialog with the public instead of one-way communications (i.e., issuing of information), particularly with a network of public experts.

The degree of uncertainty regarding public acceptance, respectively the public's attitude towards the intention to build a repository at a given locality, can e.g, be positively influenced by:

- ensuring mutual understanding of the repository safety during the operational phase and in the long-term (timespan of one million years) and on possible site and repository evolutions; in particular, uncertainties should be described in a way that stakeholders can understand what is not known and why it is not relevant or why it is relevant for safety and, if so, how and when it will be addressed,
- meeting the expectations of different stakeholders on various issues related to safety such as post-closure monitoring, or the possibility and duration of recoverability/retrievability,
- good compatibility of the disposal project with the site development plan,
- adequate resolution of conflicts of interest (including the interests of the public concerned),
- the development of support or motivation programmes in preselected sites that motivate the public concerned to cooperate more closely and actively participate in the decision-making process,
- independent safety reviews by the regulator and its TSO and/or by other independent experts mandated e.g., by civil society organisations. The role of the various reviewers, namely the regulator and its TSO, is prominent to foster confidence on facility safety. Reviews by habilitated people from institutes and universities, in the role of individual independent experts, may build trust in society and contribute to public acceptance.

Building and/or improving credibility of the responsible organisations and institutions involved in the management of radioactive waste (e.g., clearly defined roles and responsibilities, independency, transparency, learning organisations, self-questioning process, science, open to criticism) is essential for building public trust in the whole programme implementation, including decision-making processes. Trust is difficult to gain but easy to be lost. Many examples of past failures can be explained by the absence of trust in the stakeholder (including the public) engagement process. Many national programmes have restarted all over in the past and one may expect similar challenges in the future. Examples are Sweden, Germany, the US, the UK, France, and Switzerland among others. Some of these countries have now developed more stable management approaches with new concepts including public engagement, while others still struggle. For a review of past attempts to site repositories, see e.g., US NWTRB (2015).

Performance of RD&D activities with a focus on transdisciplinary research and social science (e.g., option survey, socio-economic and social studies, development of novel communication and participation approaches in the field of DGR decision-making process, etc.) should be an integral part of the RD&D activities regarding geological disposal. Nevertheless, it must be kept in mind that communication and stakeholders' engagement strategy or concepts are a tool for managing the public acceptance uncertainty but may be unsuccessful.

(4) Representation in safety assessments

It may be appropriate to assess the possible implications of this uncertainty on facility safety in the safety case. In particular, possible consequences of the delays resulting from a lack of public acceptance could be evaluated in the safety assessment.

If certain requirements related to the repository are set due to acceptability constraints (e.g., reversibility), the consequences of the resulting provisions on safety shall be presented in the safety assessments. For instance, in Switzerland, it is required to demonstrate that measures for retrievability do not impact post-closure safety (ENSI, 2020).

(5) Specific additional comments on uncertainties related to public acceptance

This uncertainty may be significant during phase 1 (site evaluation and site selection). In the case of Germany (StandAG, 2017), surface and subsurface explorations are executed in phase 1, with the aim of narrowing down the potentially suitable sites (i.e., starting from a white map of Germany → sub-areas → regions for surface exploration → regions for subsurface exploration → site recommendation). In the early programme phases, uncertainty regarding public acceptance may lead to a failure of a siting process as in the case of Gorleben site (i.e., the Gorleben-Rambow salt dome) for disposal of high-level radioactive waste in Germany (https://www.bge.de/en/sitesearch/history-of-the-search-for-a-repository/). It may not be strictly limited to the local community hosting the repository, as other communities in the repository vicinity may feel also concerned, especially because of the transportation of the waste to the repository, and lower benefits expected (in terms of jobs, infrastructure, etc.). Other factors affecting the public opinion and degree of uncertainty regarding public acceptance are NIMBY (Not-In-My-Backyard) effect, delays in the licensing process, veto right and prospects for new technologies.

From phase 3 (facility construction) onwards, it should be demonstrated that any remaining uncertainty will not jeopardise the safety of the facility. However, it must be said that there is no complete consensus (among the representatives of WMO, RE and TSO) on the fact that the safety significance of the uncertainty regarding public acceptance would necessarily decrease over time. In the planning phase, the degree of consensus of the waste management programme with the public might be higher than at the moment of site selection. A new challenge to consensus will then emerge when the decision is to be made to start constructing the repository and emplacing the waste. The following quote illustrates this fact: "*Over the last half-century, implementers of national waste management programmes in more than dozen countries have launched at least 24 efforts to site a deep-mined, geologic repository. In only five of these efforts was a site chosen. Nearly one-half of the initiatives prematurely ended because the projects failed to gain and sustain social acceptability*" (US NWTRB, 2015).

The uncertainty is indirectly addressed e.g., in EURATOM (2011), with basic requirements for ensuring the transparency of the process with the active involvement of the municipalities and the public concerned. These requirements are usually implemented also into national legislation.

The advances in science and technology over future decades may allow development of novel concepts that not only meet stakeholder requirements and/or expectations but also provide benefits in terms of both pre- and post-closure safety. It is important though that possible advancements are anticipated (see the discussions about "new knowledge" in Section 5.4.1), so that they cannot suddenly undermine public acceptance of a (previous) disposal system.

Setting the legislative framework to ensuring that the public is given the necessary opportunities to participate effectively in the decision-making process is needed (e.g., requirement to discuss the draft legislation for the strengthening of the position of local communities in the deep geological repository siting process and submission to the Government for approval set out in Policy of Radioactive Waste Management and Spent Fuel Management in the Czech Republic in 2002).

For example, in the Republic of Bulgaria, according to the Environmental Protection Act (2002) and the Regulation on the conditions and procedure for performing an environmental impact assessment (2003), the consultations and public discussions are mandatory steps in the EIA process. Example for that is the Environmental Impact Assessment Report (EIAR) on the Investment proposal/IP for Construction of National disposal facility for Low and Intermediate Level Radioactive Waste (NDF) at the "Radiana" site (SE RAW 2015).

It is also important to popularise science and introduce educational measures particularly for new generations, such as summer schools, visits to advanced facilities (e.g., Onkalo, underground research facilities), and public discussions/debates on various intergenerational aspects, etc.

5.2.2 Schedule to be considered for implementing the different phases of the disposal programme

(1) Identification and assessing the safety relevance

The identification of these uncertainties should start in phase 0 and be pursued during subsequent phases (phase 1, phase 2 and phase 3). Their identification and monitoring can thus be performed through a stepwise approach and open communication/dialogue among the different stakeholders.

The uncertainty regarding possible delays in the programme implementation should be identified through risk analysis (e.g., risk matrix, risk register, hazard identification, scenario analysis) and project management.

Depending on the phase of the programme, the impact of this uncertainty on disposal safety can be indirect and/or direct. No direct consequences are expected before construction of the facility. Indirect consequences are possible during all disposal programme phases and remain until repository closure.

In terms of interim storage, possible impacts of this uncertainty on the safety of final disposal operations, due to the evolution of the waste characteristics in the storage facilities, could be critical independently of the programme phase in which delays are encountered. The safety significance of this uncertainty with respect to storage will increase with time until waste disposal.

Regarding disposal safety, there is no safety significance of this uncertainty before the start of the construction of the disposal facility. Possible impacts of this uncertainty on the safety of the repository could be critical if delays are experienced during the construction, operational, and closure phases.

Uncertainties on the date of availability of a disposal facility may lead to necessary decisions for extending the duration of interim storage. This prolongs the need for long-term maintenance (in particular due to enhanced ageing processes of waste packages before final disposal) and active measures to ensure safety and security of both storage and disposal facilities. Prolongation of the interim storage can also lead to insufficient storage capacity. Delays on the date of availability of the disposal facility lead also to a diminished robustness vis-à-vis potential societal disruptions and increasing burden on future generations.

In the case of a DGR, delay of installation of stabilising measures in the construction phase may cause stability problems and may affect long-term safety as well. It is possible to assess the potential consequences of this uncertainty through available mining experience as well as numerical calculations considering stability of mining excavations and barrier integrity.

Further, delays in the programme implementation can cause increasing costs, which in turn may affect the quality of the execution of future activities due to lack of resources and can thus adversely affect the repository safety.

Delays can cause loss of expertise and knowledge, which can also have an indirect effect on the safety.

The significance of delays for safety in the construction, operation, or closure of a disposal facility is dependent on several factors like the impact of ageing of waste packages (especially in case of monitoring missing for that) or the ability to retrieve the waste safely according to an approved plan if necessary.

(2) Characterisation

The actual schedule of a disposal programme is the result of a mixture of technical constraints and societal aspects (e.g., mixture of strategies of the various actors with sometimes contradictory interests) and, for this reason it can lead to certain kinds of uncertainties, in some cases only partly reducible or even irreducible.

The uncertainty related to possible delays in the implementation of the programme schedule should be characterised during the early stage of disposal programme development and subsequently reviewed during the next phases (site selection, characterisation,…).

This uncertainty is very difficult to characterise and quantify and is directly related to a number of other “programme uncertainties” such as:

- the societal/public support of the decisions made in the programme (see Section 5.2.1),
- socio-political factors with the possible consequences of early closure or abandonment of the disposal facility,
- the loss of know-how with the possible consequences of poor execution of future activities,
- changes in the production of the waste, possibly resulting in the required size of the repository,
- changes in the regulatory framework with the possible consequence that the repository no longer complies with this framework,
- lack of sufficient financial and human resources,
- lack of raw material resources (e.g., availability of sufficient bentonite stocks for engineered barriers),
- unavailability of appropriate technologies with the possible consequences of poor execution of future activities.

These uncertainties need thus to be identified and taken into consideration in RWM programmes in order to reduce or mitigate the associated risks (as far as reasonably achievable).

Characterisation of these uncertainties can be realised via a stepwise approach, with intense communication with the stakeholders (including public) at each step as well as draft planning of the successive major decisions to be updated and shared regularly.

The level of these uncertainties could also be derived through the determination of the degree of public acceptance in the frame of socio-economic studies. Public acceptance as well as the level of “not in my backyard” (NIMBY) effects depend on the communication with the public and on the level of active stakeholder engagement (SE) as well as on flexibility of the disposal facility development programme.

The trust in the government has an impact on the perception of fairness of a given decision-making process, perceived risk and also potential benefit, and therefore the trust in the government influences the public acceptance.

(3) Classification and associated actions

The uncertainties associated with possible delays in the implementation of the programme schedule need to be reduced and consequences mitigated but cannot be completely avoided. Actions that can be implemented to reduce or mitigate the uncertainty are very much dependent on other uncertainties that might cause possible schedule changes (e.g., lack of resources, political decisions, lack of societal support, etc.).

This can be realised (to a certain extent) through the implementation of good project and risk management practices. However, it should be kept in mind that excessive optimism and belief in a "good project management" may lead to overconfidence about operational safety, which in turn may result in managers being caught by surprise if a real problem (event/accident) arises, as shown by the accident at Waste Isolation Pilot Plant (WIPP). Like for any complex industrial project, accidents at a repository can occur. It is therefore preferable that managers are prepared to deal with “normal” accidents or system accidents - accidents that are unavoidable in extremely complex systems (see definition in Perrow, 1999). Given the characteristic of the disposal system involved, multiple failures that interact with each other can occur, despite efforts to avoid them. Operator’s error is a very common problem, and many failures relate to organisations rather than technology (Perrow, 1999). The uncertainties related to schedule delay can thus only be managed if all key stakeholders are involved in the decision-making process and one accepts upfront that the schedule will strongly evolve. The schedule should be flexible enough to be modified and take account of possible delays through implementation of appropriate mitigation measures. We must expect significant delays in the schedule as the normal evolution of the project, thus it requires managers and scientists to accept it as an irreducible uncertainty and to plan suitable mitigation measures. Past experiences have shown sufficient evidence of schedule changes.

This uncertainty will presumably be reduced through a stepwise implementation of the disposal programme throughout all phases. The following other actions can also be undertaken to reduce this uncertainty:

- a more robust planning by establishing a draft planning of the successive major decisions regarding the repository in the (pre-)licensing phase and beyond, and presenting it for comments to the various stakeholders, so that a consolidated shared view on the planning is achieved,
- a holistic approach for the RWM programme with clear links between components, and
- professional, forward-looking-resources planning, including human resources,
- implementation of a participative and transparent decision-making process at each programme phase in order to ensure that the decisions made at each phase are supported by the various stakeholders.

The following measures allowing to mitigate consequences of this uncertainty are identified:

- planning the necessary resources (not only financial) to complete corrective actions in connection with delay,
- flexibility measures:
    - provision of a flexible disposal programme implementation,
    - designing a disposal facility that will be flexible and adaptable, i.e., robust vis-à-vis modifications of the waste emplacement schedule, robustness of the design with respect to ageing processes,
    - retrievability of waste (for safety or “societal” reasons),
    - development of a RWM programme (interim storage and disposal facility) that will be flexible, i.e., where the licensing decisions for the disposal facility cannot be suspected of being dictated by the fact that the storage facility capacity is reached.

Another mitigation measure could be robust and systematic monitoring provisions to enhance the flexibility of the RWM programme (especially disposal programme) and to support decision-making process. In case of delays in RWM programme development, civil society and/or safety authority (regulators and/or its TSO) can turn to the implementer and demand an analysis of the impact of such delays on facility safety. Monitoring data would then provide the basis for this analysis.

In the construction, operation, and closure phases of the programme (i.e., phases 3 - 4), the potential consequences of this uncertainty on the stability of the disposal system can be handled by observation methods such as monitoring (e.g., monitoring of deformations of mining cavities). This can be quantitatively described applying different engineering methods and assessed by numerical calculations, e.g., according to the Eurocode series of European Standards in Geotechnical Design (Bond et al., 2013).

(4) Representation in safety assessments

The risks related to “programme uncertainties” can be analysed in the safety case to identify measures to reduce and mitigate these risks during subsequent programme phases and periodic safety reviews (see e.g., the safety case for the LLW disposal facility in Dessel, Belgium, Wacquier and Cool, 2013). This also allows fostering a risk-based decision-making.

This can be done by defining scenarios for assessment/evaluation of the potential impact on safety of delayed backfilling or disposal facility closure. Several scenarios resulting from changes in the programme schedule can be investigated in the safety case/assessment, such as:

- collapse risk scenario (in case of extended duration of operation or delayed backfilling),
- scenario of accelerated degradation of materials,
- scenario of pessimistic extent (or absence of self-sealing) of EDZ,
- scenarios of accelerated process for immediate closure (which might as well be a plausible scenario in favour of robust and simple closure works, seals, etc.),

- scenarios of absence or partial construction of some system components.

The consequences of this uncertainty for the stability of the disposal system may also be explicitly addressed in the licencing procedure by the regulatory authorities in charge of underground safety aspects.

(5) Specific additional comments on uncertainties related to the programme schedule

Regarding the evolution of these uncertainties and their safety significance over time, they can be reduced and consequences mitigated but they cannot be avoided throughout all the phases of the disposal facility life cycle; they persist until closure. Uncertainty on robustness of the presently considered safety requirements with regard to the long term, related to the far future perspective regarding intergenerational ethics (namely, issues and interests of present and next generation vs. remote generations) will also have a high impact in the decision-making process as it could delay and possibly even indefinitely delay the construction of a repository. Thus, it is also closely linked to the uncertainty regarding the implementation of the programme schedule.

5.3 Uncertainties associated with initial characteristics

5.3.1 Adequacy of safety-related activities for the implementation of safety provisions in construction

(1) Identification and assessing the safety relevance

This type of uncertainty includes the socio-technical aspects associated with the activities required for the implementation of the safety provisions during the construction phase, e.g., uncertainties in as-built repository components due to construction errors.

Activities during construction and operational phases of disposal facilities are governed by construction codes and operating rules that consider 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 later due to lack of appropriate knowledge management,
- they may be infringed by ignorance, laziness, greed, or malice of employees. The quality insurance system in place may allow violations to go undetected,
- interactions between humans and technology, and work environment (e.g., human-machine interface, impact of the work environment factors) create uncertainties.

Consideration of the “return on experience” from similar construction activities (i.e., in other disposal facilities or in other fields such as mining and tunnelling) can be very useful in identifying possible construction errors and assessing their impact (IAEA, 2014).

During repository construction, operation, and closure, uncertainty identification can be complemented by accompanying monitoring measures (i.e., in case the behaviour of the repository system differs from expectation) as well as by inspections of accessible parts of the facility.

The oversight of several design and construction steps by licensing authorities, having expertise in different relevant fields (safety assessment, mining, civil engineering, etc.), can contribute to uncertainty identification through:

- deep scrutinising of the safety case by the regulator and its TSO,
- external audits or inspections by the regulator and its TSO.

With regards to the safety relevance, these uncertainties can, on the one hand, have an impact on occupational health and safety as well as on radiological safety in the operational phases (i.e., operational safety). On the other hand, inadequate or low quality construction activities and processes, as well insufficient building supervision/control could also jeopardise long-term safety functions of individual components of the disposal system.

Human factor is a separately evaluated element within safety cases and Periodic Safety Reviews (PSRs). For this purpose, it is necessary to establish the safety case iteratively, in several steps (feasibility, safety options, preliminary safety report, etc.) over a long period, allowing for extensive reviews by the regulator or TSOs.

This uncertainty has to be addressed early, in phase 2, in order to develop and establish safety culture. The safety significance of this uncertainty must be considered as high in phases 3 (as indicated by the formulation of this topical uncertainty) and 4 (due to the fact that some types of construction works will be executed in the subsequent phase). Some implications for safety can be expected also in phase 5.

(2) Characterisation

This uncertainty addresses the management provisions for the activities related to safety during repository construction. It is affected by changes in organisation and safety culture, lack of knowledge management, and inadequate training and thus even in a lack of experts involved in construction activities.

Therefore, the quantitative description of these uncertainties may be limited. However, their quantification, respectively quantification of their impact, might be needed when their representation in the safety assessment is necessary. For instance, a certain percentage of undetected defects may be quantified based on return on experience from construction activities of other disposal facilities.

(3) Classification and associated actions

These uncertainties need to be reduced and where possible avoided or mitigated. With respect to construction errors, one must acknowledge that the disposal of radioactive waste should be treated from the socio-technical perspective (and not as a solely technical issue), which imposes that the safety encompasses interactions between humans, technology, and the organisation (Eckhardt and Rippe, 2016). Options available to reduce or mitigate these uncertainties are discussed below.

The appropriate design of a disposal facility according to current national and international standards needs to be considered to reduce future construction errors or uncertainties. Guidance on requirements management related to facility design changes, incl. practical approaches to define design requirements and accounting for uncertainty and constraints, can be found in NEA/OECD (2003).

Implementation of a quality assurance system within the organisation (quality assurance documents, training, dedicated teams of quality experts, independent levels of quality management and control within the organisation, etc.) is one of the basic means to reduce the uncertainties linked to safety provisions in a construction phase (e.g., construction errors) or to mitigate consequences. The quality assurance system ensures that the parameters stay within the domains considered in the safety assessments.

Uncertainty reduction, avoidance, or mitigation of consequences can be also achieved through: (i) inspections of the proper implementation of procedures as well as of as-built properties during or following the repository construction and (ii) external audits by the regulator or its TSO and by quality certification auditors during the design phase of the repository project as well as during construction activities.

Another important step to reduce these uncertainties is to set behavioural expectations and foster a strong safety culture (Safety Culture Development Programme) among the employees involved in construction activities (including subcontractors) (Eckhardt and Rippe, 2016). It is important to insist on a strong safety culture among workers in the repository. However, given safety may be perceived differently between miners and involved nuclear technicians, and thus it is important that the industrial culture of the WMO (implementer) brings both aspects to a joint culture. As parallel construction/waste emplacement may occur over a period of 50 years or more, it is difficult to always keep a high level of alert across several generations of workers. Workers will be involved in the construction activities or repository operation for several decades; therefore, the construction site will become a part of their everyday life environment and thus they will create their own habits, some of them of potential safety significance. Getting used to or underestimating danger are frequently manifested negative human factors in long-term work in hazardous environments. These temporal day-to-day aspects must be duly considered.

The implementation of a feedback programme is essential to reduce the uncertainties and the risks associated. This would require introduction of processes ensuring compliance of the disposal facility design and construction methods with the current state of science and technology, international experience, experience from the operation of nuclear installations regarding ageing of its systems, structures, and components throughout the life cycle of the disposal facility. This includes the consideration of processes from other repositories already in operation (at least for L/ILW) to benefit from available experience and expertise.

The safety case should be iteratively established in several steps (feasibility study, safety options, preliminary safety report, etc.) over a long period of time allowing for extensive reviews by the regulator and its TSO. The safety case shall specify how uncertainties are identified, how they are characterised and what is the approach for their management (IAEA, 2012). The safety assessment must address the technical feasibility of the proposed repository design options to demonstrate that as-built properties are as assumed in the safety case. This implies use of proven methods/techniques - see e.g., ENSI (2020), in which the following is stated: "*The licensee shall construct the disposal facility in accordance with the design as described in the safety case and by application of appropriately proven techniques*". These new techniques need future confirmation through experimental tests: demonstrated through qualification programmes defining systematic approaches to the qualification of new technology, ensuring that the technology functions reliably within specified limits. The approach is applicable for components, equipment, and assemblies, which can be defined as new technology.

This raises another question or challenge, namely, how to reconcile the goal of applying advanced technologies and the latest scientific results on the one hand, with the application of the best proven methodologies and technologies (BAT principle) on the other hand. Therefore, a choice has to be made between the uncertainties associated with this latest scientific and technological progress and the robustness principle. A balance must be found between such progress uncertainties and the SAHARA principle (Safety As High As Reasonably Achievable). With respect to this, Technology Readiness Level (TRL) has to be taken into account (e.g., two technologies with different levels of maturity cannot be compared) and also its potential effect on a possible optimisation process has to be considered. Optimisation should be kept reasonable and efficient (see e.g., European ALARA Network, 2019; NEA/OECD, 2020a).

Implementation of the repository "Defence in Depth" principle (DiD) in the design is one of the fundamental safety principles identified by IAEA (see e.g., IAEA, 2006; IAEA, 2011). It includes protective measures against disturbing events and processes and corrective measures to prevent defects and damages to the disposal system. On the one hand, quality control measures during construction based on clearly defined conformity criteria/quality requirements, periodic testing and inspections, and on the other hand, maintaining the performance of system components when subjected to construction errors (e.g., through provision of safety margins in the design, diversity and redundancy, multi-barrier system, etc. (see for instance IAEA, 2006; U.S. NRC, 2016)).

Regular updates and the implementation of a RD&D programme in accordance with the timetable for the disposal programme (namely for DGR) are important means of managing these uncertainties. The RD&D programme should also include demonstration tests aimed at substantiating the feasibility of the repository construction, e.g., the project "*Full-scale Demonstration of Plugs and Seals*" (DOPAS) (see DOPAS, 2016). Such tests should allow demonstrating that it is possible to build the disposal facility in such a way to meet the required or expected level of performance.

Changes of personnel along the long-term disposal programme make documentation and knowledge management highly important. Therefore, it is necessary to have an adequate knowledge and safety culture management already in place at a very early programme stage. This will help to improve safety of the repository.

Other measures for reduction of this uncertainty and mitigation of consequences that could be applied are:

- good governance,
- networking and collaboration with external experts, researchers and university' lectures, and
- supporting the systematic training and education of specialists in related fields of RWM (e.g., specialists in mining engineering; in Germany may become rare because coal mining has phased out),
- periodic safety reviews along the disposal programme.

The choice of an appropriate set of actions may depend on the nature of the uncertainty, i.e., ignored/unknown knowns (available information which is not (properly) considered or known) vs. known unknowns (e.g., the percentage of defects that cannot be detected).

(4) Representation in safety assessments

Possible constructions errors can be represented explicitly in the safety assessment either by using specific parameter values or through consideration in scenarios. This might be done in the framework of the expected repository system evolution or reference scenarios or dedicated altered evolution scenarios, depending on the probability of occurrence of these deviations. Common are choices of conservative assumptions/parameter values or the inclusion of a “poor quality construction” FEPs-category in the FEPs database. This allows for dealing with the fact that data on the probability of these errors occurring are relatively rare.

The safety case needs to demonstrate not only “a good system” but also “good processes”, namely a “good construction process” and a “good safety analysis and evaluation”, i.e., it needs to prove that these uncertainties have been dealt with adequately (e.g., QA system, clear roles, etc.).

Furthermore, an update of the safety case/assessment considering the as-built repository and properties is also required. The use of the concepts of Safety Envelope (SE), Design Target (DT) and As Built State, developed in framework of the IAEA project GEOSAF (IAEA 2019), might be helpful to achieve this.

(5) Specific additional comments on uncertainties related to construction

From phase 3 onwards, it should be demonstrated that remaining uncertainties related to construction cannot jeopardise safety. However, this does not apply entirely in the case of a gradual construction of the repository (i.e., in more phases), when the construction will take place simultaneously with the operation of the repository.

One of the potential pitfalls associated with managing these uncertainties may be an assumption on an earlier than expected degradation of some components that can lead to non-conservative assessments of the radiological impact due to the radionuclide release in time. Furthermore, in safety assessments, the relevance of the engineered barriers may seem to be low if the focus is on dose rates in the biosphere. However, a proper DiD approach requires additional safety and performance indicators that show the proper functioning of an engineered barrier system.

5.4 Uncertainties in the evolution of the disposal system and environment

5.4.1 “New” knowledge

(1) Identification and assessing the safety relevance

These uncertainties include any new knowledge becoming available during a RWM programme that would be generated through RD&D activities, technology development, monitoring, etc. The term “new” may have different meanings. It means either:

- that unexpected new knowledge or findings have emerged by research, characterisation, or monitoring (i.e., unknown unknowns), or
- that the knowledge is available but is new for certain actors that were not aware of this knowledge (i.e., unknown knowns), or
- that the knowledge is available but is voluntarily discarded by certain actors without proper justification (i.e., ignored knowns).

The aspect of the transition from general or superficial to in-depth and/or professional knowledge can also be interpreted as an acquisition of "new" knowledge.

Unknown unknowns also relate to the completeness of the FEPs considered in the safety case as discussed in Chapter 2 in general and in Section 4.4.2 in the context of evolution of disposal system and its environment.

Unknown unknowns, by definition, cannot be identified, while ignored knowns can be identified e.g., through audits and independent reviews. Unknown knowns can be identified through:

- steady monitoring of the research landscape and research developments (new knowledge/technologies, scientific findings, etc.),
- international/national exchange with experts from the field of radioactive waste management,
- interdisciplinary exchange of knowledge and experiences,
- consideration of pitfalls and lessons learnt,
- audits (including FEP audits) and independent reviews,

while known unknowns can be identified through, for example:

- exploration activities,
- operation of a monitoring system.

The identification of unknown knowns leads automatically to their elimination.

International or broad exchange also helps to identify and rank/assess “new” knowledge.

In case of a DGR, a prominent “unknown known” is the close connection between repository safety and mining safety (at least in the operational phase). The death risk associated with mining activities is much higher than the radiological risk. This leads to different risk perception and acceptance as well as different safety cultures among different groups of staff.

The safety significance of unknown and ignored knowns is considered as high since the return on experience shows that past accidents/incidents were often associated with these uncertainties. An example of that would be the Fukushima Nuclear Power Plant (NPP) accident due to the earthquake and subsequent tsunami and ignorance of possible magnitudes of these disturbing events. The NPP was located in a tsunami hazard zone for which tsunami hazard and risk was taken into account, but although the mechanism of tsunami generation was well understood and had been predicted in advance, the height of the tsunami was underestimated because simulations assumed a considerably smaller earthquake than the one that actually struck on March 11, 2011. The underestimation of the seismic hazard provides evidence of systemic problems in disaster prediction and management. However, with appropriate foresight and tsunami risk management by Japan’s authorities and industry, it appears that the accident could have been avoided or prevented (Acton and Hibbs, 2012).

The safety significance of unknown and ignored knowns will remain potentially high during the different programme phases (i.e., the consequences could only appear much later).

Moreover, it is clear that the safety significance (risk) cannot simply be estimated a priori for new knowledge, and it is difficult to assess it for unknown unknowns due to their “unknown” nature. It can only be assumed/expected that the scope and quality of knowledge about the disposal facility and its behaviour increase with time, which will lead to at least partial clarification of certain unknowns and possibly to a reduction of these uncertainties. But this assumption/expectation is not enough. The uncertainty management strategy should ensure that, at the end of the decision-making process, no remaining uncertainty can potentially jeopardise repository safety.

Safety significance from WMOs perspective is rather low in all programme phases because of the stepwise approach and robustness by design. However, given the reversibility of decisions, retrievability and/or recoverability of the waste, “new” knowledge in terms of new materials/technologies can play a role in phases 3 to 5. For example, currently three types of host rock (rock salt, clay stone, and crystalline rocks) are considered in the German site selection process. Experience and knowledge on waste disposal are generally available for the rock salt, however “new” knowledge from RD&D activities and exploration works has to be gained for the other types of the host rock in phases 0 and 1. Further, because the current law (StandAG, 2017) envisages reversibility of the decisions, radioactive waste retrievability and recoverability, “new knowledge” in terms of available new technology and materials could play an important role also in phases 3 to 5.

Gained “new” knowledge, particularly with respect to the long-term evolution of the disposal system, could potentially lead to a revision of the safety assessment and/or to necessary adaptations, modifications, or optimisation of the repository design as well as to revisions of operational safety provisions. On the one hand, this helps to consolidate the existing knowledge and thus contributes to the reduction of uncertainties, including better quantification of safety margins; on the other hand, this could impact the overall work schedule including licensing.

This type of uncertainty relates to how new results, emerging in the course of the implementation of a disposal programme (e.g., from monitoring), can be taken into account in the programme including the safety case and the safety assessment.

One mean of assessing the safety relevance of this uncertainty during siting could be systematic analyses of its potential influences.

(2) Characterisation

Characterisation of these uncertainties can be realised via a stepwise approach, with intense communication with the stakeholders and interdisciplinary cooperation at each step as well as draft planning of the successive major decisions to be updated and shared.

The categorisation into known unknowns, unknown/ignored knowns, and unknown unknowns as explained in Chapter 2 constitutes a way to characterise these uncertainties.

(3) Classification and associated actions

Any uncertainty about the occurrence of unexpected new findings or knowledge is a persistent uncertainty that is very difficult or impossible to be reduced. Nevertheless, safety-relevant unknown unknowns need to be avoided or reduced as much as possible. This can be done by carrying out the following actions:

- well planned RD&D programme in the area of RWM,
- data acquisition and site characterisation, monitoring (it goes beyond the individual objectives of operational safety and compliance with the set values and is also aimed at gaining knowledge), etc.,
- refined modelling: 3D modelling can also raise some new issues/new knowledge e.g., thermo-hydro-mechanical (THM) processes in Cigéo, France,
- determination of site selection criteria to properly characterise the site and the host rock,
- appropriate design and construction of a disposal facility (e.g., use of proven methods and materials) complying with good practice and quality requirements,
- establishment of limits and conditions (e.g., waste acceptance criteria),
- interactions with stakeholders,
- exchange with international experts.

From the above, it may appear that the "new" knowledge is considered here only as a factor negatively impacting the implementation of the programme or safety, whereas, in fact, most knowledge can be considered as potentially beneficial (i.e., increasing the safety). Of course, new knowledge may show that a system initially considered as safe enough is no longer safe (e.g., due to variability of the geological environment). However, in such case, it is not safety itself that would be negatively impacted by new knowledge but only the hypotheses about safety made before this new knowledge became available.

Safety-relevant unknown knowns and ignored knowns (e.g., deliberately ignoring the possible magnitudes of disturbing events) need to be reduced an even "minimised". This can be done by carrying out the following actions:

- implementation of a sound management system ensuring the proper execution of the actions in the following bullet-points and notably an adequate performance of the uncertainty management process (e.g., supported by a uncertainties roadmap),
- knowledge and record management (including training and qualification of the staff involved in safety-relevant activities); development and application of standardised approaches for managing information, data, and knowledge regarding all aspects of RWM management is a common challenge for all countries (see e.g., NEA/OECD, 2012),
- systematic FEPs management – derivation of national and international FEPs lists and database (e.g., NEA FEPs Database, NEA/OECD, 2020b) and their regular review/updating,
- peer review of scientific developments also plays an important role in the advancement and dissemination of scientific research,
- implementation of an experience feedback programme allowing to take benefit of the experience gained from the management of other facilities,
- self-questioning and learning,
- safety culture: implementation e.g., of a Safety Culture Development Programme in connection with the improvement of the responsibility (and in particular of the safety leadership), professional competence and credibility of the responsible decision-makers, experts and employees,
- periodic safety reviews,
- interactions with stakeholders.

Several measures can also be implemented to mitigate consequences of remaining and emerging (safety-relevant) uncertainties:

- implementation of a flexible programme that allows to manage e.g., unexpected deviation in the safety function of the disposal system or some of its components during an unexpected event, A programme that keeps the options open (including repository loading options) and leaves room for optimisation of the repository design (design flexibility and flexibility in design steps) can mitigate potential effects of new knowledge,
- interactions with stakeholders to manage e.g., "programme uncertainties",
- implementation of the defence in depth principle (i.e., one of the fundamental safety principles identified by IAEA, see e.g., IAEA, 2006) that includes the provision of independent levels of protections and different types of measures, such as protective measures against disturbing events and processes, controls and corrective measures, safety margins (values of the parameters taken into account in the design are set in order to cover uncertainties related to known unknowns and possibly to unknown unknowns or ignored knowns) and last but not least a multi-barrier system.

The stepwise nature of the decision-making process (and the associated iterative approach to managing uncertainties related to the performance of a disposal facility as the programme progresses) facilitates the management of these uncertainties. This includes an iterative approach to research and data acquisition activities aiming at the reduction of uncertainties or the mitigation of consequences. At each stage of such a process, results from a safety assessment can be used to understand the parameters to which performance measures are most sensitive and therefore guide subsequent data acquisition activities and thus reduce associated uncertainty in a meaningful way.

The reversible character of the disposal programme also helps to manage and mitigate these uncertainties. In fact, decisions must be reversible or at least modifiable in view of new information, to the extent that this is feasible. Therefore, reversibility refers to the possibility of reconsideration of one or a series of steps at various stages of a programme. This involves a review of earlier decisions with the appropriate stakeholders and requires that the necessary means to reverse a step be available (NEA/OECD, 2015). The reversibility within a planned process should probably be discussed ahead of time (e.g., reversible character of the DGR site selection procedure in Germany (see §1 (2, 5) in StandAG, 2017).

Furthermore, the safety case should be established in several successive steps, prior to the license for construction, each of them being reviewed in detail by the regulator or its TSO, which may identify unknown or ignored knowns. The safety assessment needs to be updated along the stages of the lifetime of the facility or activity, so as to take into account possible changes in circumstances (such as the application of new standards or new scientific and technological developments), changes in site characteristics, and modifications of the design or operation, and also the effects of ageing (IAEA, 2016). The regulator will only allow operations that will be properly demonstrated as being safe. The licensee should regularly update the safety case to reflect as a minimum:

- changes to regulatory requirements and standards,
- results from surveillance programmes,
- changes in the radioactive waste inventory to be disposed of,
- results from analysis of operational occurrences and accidents, and
- results of the periodic safety reviews.

Updates shall be made as soon as reasonably practicable and in accordance with the safety importance of the improved knowledge (see e.g., WENRA WGWD, 2014).

(4) Representation in safety assessments

The safety case as a basic methodology to assure the consistency of all safety-related issues can be challenged when new evidence, knowledge, or techniques are developed. New knowledge is incorporated in the successive versions of the safety assessments and the safety case.

Available options for the representation of “new” knowledge related uncertainties in the safety assessment include conservatism, fuzzy sets, deterministic approaches, scenario analysis, etc.

The safety assessment can be used to demonstrate the robustness of the disposal system with respect to uncertainties like the occurrence of (unexpected) disturbing events using dedicated scenarios. What-if scenarios/analyses can be used when the cause of the degradation or failure of the disposal system or any of its components is not known, see e.g., IAEA (2012): “*Robustness of the disposal system is evaluated through comparison of the results of analyses of the base case with those of a range of scenarios illustrating specific perturbations or uncertainties. Among the different types of perturbation, the most generally considered are those where one component or one of its characteristics is considered to have failed (‘what if’ scenarios). Scenarios involving such strong perturbations applied to the disposal system are distinguished from scenarios describing degraded behaviour of the disposal system*”. Such analyses contribute to the assessment of the level of defence in depth provided by the disposal system.

New knowledge should be included/referred in the safety assessment also through the systematic FEPs management.

(5) Specific additional comments on uncertainties related to new knowledge

The degree of ignorance or acceptance of new knowledge and willingness to take it into account afterwards in practice is also related to: (i) the degree of responsibility, professional competence, and credibility of individual responsible staff or organisations/institutions; (ii) their cooperation regarding knowledge exchanges and, last but not least, (iii) to the safety culture as such.

The possible impact of “new” knowledge on safety assessments is expected to decrease over programme phases due to the fact that “new” knowledge will be taken into account systematically in the periodic safety reviews.

All methods and technologies selected and used in a RWM programme (disposal programme) have to be defensible with respect to good practice and quality requirements.

Implementation of already known knowledge or of a “new” knowledge that has not yet been applied but that could lead to a more effective solution, in other words proven solutions versus potential better solutions, is a dilemma that may be encountered.

Another question also arises: How to measure the "immediate benefits" of a given solution when facing intergenerational equity?

5.5 Uncertainties associated with data, tools, and methods used in the safety case

Management options and strategies regarding uncertainties associated with data, tools, and methods were not addressed in the context of human aspects related uncertainties.

5.6 Uncertainties associated with the completeness of FEPs considered in the safety case

Management options and strategies regarding uncertainties associated with the completeness of FEPs were addressed using the specific examples in previous sections.

6. Management options for uncertainties related to spent fuel

6.1 Selection of topical uncertainties and general comments

Subtask 3.5 analysed views of the different actors (WMOs, TSOs and REs) on the identification, characterisation, and potential significance of uncertainties associated with spent fuel (Herm, 2023). A preliminary list of uncertainties from Subtask 3.5 together with a preliminary evaluation of the responses to the 1st and 2nd UMAN Questionnaires served as starting point for uncertainties management options identification. Of particular value were the responses to the 2nd UMAN Questionnaire, where information on relevance, actors' preferences, evolution, and chosen approaches to handle specific uncertainties was collected. Further sources of information were the state-of-the-art report of the EURAD WP "*Spent fuel characterisation and evolution until disposal*" (SFC) (Caruso et al., 2020), the state of knowledge report on spent nuclear fuel (Spahiu, 2021), other available literature as well as discussions within UMAN subtasks.

Combining the input to assess safety relevance (see Appendix C for details) and considering the uncertainty classification schemes presented in Chapter 2 to assure good coverage of uncertainty types, the following specific topical uncertainties were selected for further discussions:

1. **Fuel history data** (e.g., composition of fresh fuel/cladding, especially on impurity level), reactor operation and irradiation conditions (e.g., burn-up history, cooling time) as an example of uncertainty related to the **initial characteristics** of the fuel and its **evolution**,
2. **Nuclear data** (e.g., cross-sections, fission product yields, decay data…) as an example of uncertainty related to **data, tools, and methods**,
3. **Performance of SNF during (dry) interim storage** (e.g., degradation mechanisms and their impact on handling of SNF for conditioning for final disposal) as an example of uncertainties related to **evolution** and to some extent also **data, tools, and methods**,
4. **Performance of SNF during final disposal** (e.g., radionuclides critical in safety assessments, radionuclides contributing to fast/instant release) as an example of uncertainties related to the **evolution** and to some extent to **initial characteristics** of the fuel as well as **data, tools, and methods**.

Neither programme uncertainties related to SNF nor uncertainties associated with the completeness of the FEPs in the safety case are considered in the present chapter.

For the selected uncertainties, further input was gathered via the UMAN Subtask 4.2 template (see Appendix A) and discussed by the partners involved in the Subtask 4.2 spent-fuel core-group. The discussions during the 3rd UMAN Workshop, organised by Subtask 4.3, have been considered during the finalisation of this chapter. As a result, general management strategies and options (Chapter 3) that can be used to handle the specific uncertainties are presented and discussed. While this is done in a structured way along the elements of the management scheme (*Figure 5* in Chapter 3) in the subsequent sections of this chapter, the following general comments resulted from the work:

- uncertainties related to the management of SNF are linked to the initial characteristics of the fuel and its evolution (irradiation in reactor, interim storage, and final disposal),
- data, tools, and methods are often used for predicting radionuclide contents in SNF, mechanical behaviour during interim storage or decay heat as an issue for final disposal of SNF. Thus, uncertainties are connected to input parameters used in these codes. These parameters are often related to the initial characteristics of the fuel and will therefore be discussed in the context of such specific topical uncertainties,
- uncertainties required in safety analyses involving SNF range from very high accuracy (few percent uncertainty) to fairly low accuracy (order of several 10% uncertainty) (Sjöland, 2021). A quite high accuracy is needed e.g., to determine decay heat or demonstrate sub-criticality in case of use of burn-up credit based on some key radionuclides, determining the reactivity of the

SNF over time, especially for MOX fuel. Moreover, fuel history and nuclear data must be sufficiently known.

6.2 Programme uncertainties

Programme uncertainties were not addressed in the context of the SNF related uncertainties.

6.3 Uncertainties associated with initial characteristics

6.3.1 Fuel history data

Identification and assessment of the impact on safety

Radionuclide inventory of SNF is crucial to accurately determine the source term in safety assessments. Moreover, the radionuclide content in SNF determines parameters such as decay heat and nuclear reactivity. These parameters are critical in order to evaluate how and how much spent fuel assemblies can be safely loaded into a disposal canister and how closely these containers can be emplaced in a deep geological repository for high-level waste. Also, a criticality safety assessment based on burn-up credit (BUC), requires an extended set of calculated radionuclide inventories, especially those affecting the reactivity of SNF[5] (Caruso et al., 2020). The radionuclide content in SNF is also important to assess the performance (quantification of dissolution and release rates) of SNF in a deep geological repository in the absence of air and hydrogen overpressure. In addition, the activation of cladding and other structural materials must be considered, since the radionuclide release from such materials could be faster than the SNF dissolution upon contact with groundwater (Caruso, 2016).

In order to calculate the content of radionuclides in SNF or cladding and structural materials, so called fuel history data, besides nuclear data (see Section 4.4.1), are key input parameters. Fuel history data comprises fuel properties e.g., composition of the fresh fuel or the cladding and structural materials as well as the operational history e.g., burn-up and cooling time. Especially the impurities present in these materials are of utmost importance to accurately determine the activation products[6] relevant for long-term safety analyses (Kurse et al., 2015; Caruso et al., 2020; Caruso, 2021; Spahiu, 2021).

The following aspects induce uncertainties that must be considered:

- fuel, cladding, and structural materials are commercial materials and their exact material composition (including impurities or additives used during fuel fabrication) after fabrication are possibly confidential and therefore not communicated by the fuel vendor,
- incomplete/lost documentation of experimentally obtained material composition data of fresh fuel, fuel rods/assemblies from fuel vendor possibly fabricated decades ago,
- incomplete measurements of impurities present in fresh fuel, cladding, and structural materials fabricated and analysed decades ago due to limitations of analytical devices at that time (higher detection limits),
- detailed operational history of a fuel rod/assembly (including burn-up, linear heat generation rate, effective full power days, cycles, date of discharge etc.) is possibly confidential and hence not communicated by the vendor/utilities,
- incomplete/lost documentation of detailed irradiation history of fuel rods/assemblies e.g., if the nuclear power plant is already under decommissioning.

(2) Characterisation

In activation calculations, often normative material specification data is used as input. Usually, these data indicate a range of composition for main constituents or maximum values for impurities. The use of those maximum values can lead to an overprediction of the radionuclide inventory, especially in cladding and structural materials (Spahiu, 2021). It has been also shown that the more complete the

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[5] e.g., $^{235,236,238}\text{U}$, $^{239,240,241}\text{Pu}$, ^{95}Mo, ^{99}Tc, ^{101}Ru, ^{103}Rh, ^{109}Ag, ^{133}Cs, $^{147,149,150,151,152}\text{Sm}$

[6] e.g., ^{14}C, ^{36}Cl, ^{41}Ca, ^{59}Ni, ^{63}Ni, ^{93}Mo or ^{94}Nb

irradiation history used in calculations is, the smaller is the gap between calculated and experimental values (Caruso, 2021).

(3) Classification and associated actions

The uncertainties associated with with initial characteristics are classified as to be adequately reduced, e.g., by data acquisition and management. In order to determine the source term accurately, detailed knowledge of the fuel history data is important in activation calculations, e.g., use of nominal data and maximum values possibly leads to an overprediction of the radionuclide content in fuel, cladding and structural materials.

As complete as possible fuel history data should be used in calculations and the calculated values should be validated against experimentally obtained radionuclide inventory of SNF, cladding, and structural materials.

It is therefore recommended to obtain data from fuel vendors and utilities on available impurity analysis data of fresh fuel, cladding, and structural materials as well as the complete irradiation history of fuel rods (e.g., fuel loading pattern, core operating parameters, etc.) (Spahiu, 2021).

The development of a strategy for data and records management as early as possible in the RWM programme is necessary. A clear definition of all necessary information/data is required and collection, transfer, and storage of all required data must be ensured.

(4) Representation in safety assessments

In safety assessments, a reliable determination of the SNF source term is mandatory. However, it is difficult or even impossible to measure the characteristics of all the SNF discharged from reactors (Ebiwonjumi et al., 2021). Hence, the SNF source term depends mainly on predicted values derived from dedicated codes and models. These codes and models rely on input parameter such as fuel history data. If no detailed material composition (e.g., precursor content of activation products) or burn-up history is available, conservative data must be used in safety assessments, potentially overpredicting the content of radionuclides present in SNF.

(5) Specific additional comments on uncertainties associated with initial characteristics

It appears that uncertainties related to the initial characteristics of SNF are estimated to have different importance - from low to high level – depending on the stage of the RWM programme, the particularities of the nuclear programme (different NPP and fuel types) and also the repository concept. Nevertheless, it is clear that these uncertainties must be adequately reduced.

6.4 Uncertainties in the evolution of the disposal system and its environment

6.4.1 Performance of SNF during (dry) interim storage

(1) Identification and assessment of the impact on safety

After discharge from a nuclear reactor, SNF is stored in spent fuel pools, usually close to the reactor, for several years and then possibly sent to a dry interim storage. When spent fuel pools are filled to their operational capacity, the older fuel is often transferred from the pools into dry storage facility (Bonano et al., 2018; Ebiwonjumi et al., 2021) until a repository for final disposal will be available. Integrity of the irradiated cladding and degradation of SNF after a (prolonged) dry interim storage is essential for transport and subsequent conditioning of the SNF for final disposal e.g., loading of SNF into final disposal canisters. The handling of the SNF after a (prolonged) dry interim storage is a safety relevant operation.

(2) Characterisation

Degradation effects possibly important during prolonged dry storage comprise, among others, cladding embrittlement processes because of reorientation of hydrides, increasing hoop stress due to pellet swelling, chemical interaction of the fuel with the cladding, the impact of irradiation, as well as the impact of annealing effects on mechanical properties of the cladding, such as ductility and creep (Spykman, 2018). Moreover, oxidation of the UO_2 matrix could occur in case the cladding fails and the fuel is exposed to air. The UO_2 oxidation could lead to swelling of pellets and cladding defects can propagate (Caruso et al., 2020).

Fuel-performance codes are used to simulate phenomena affecting the mechanical state of nuclear fuel and cladding during irradiation, focusing mainly on the thermo-mechanical properties of the fuel/cladding. These codes are now gradually extended to interim storage, transport, and handling to gain a better phenomenological understanding of the SNF rod mechanical behaviour under these conditions (Caruso et al., 2020). Yet, validation against experimental data of SNF experiencing interim storage is very limited, especially for high burn-up UO_2 and MOX fuels as well as novel types of fuels.

(3) Classification and associated actions

Uncertainties associated with the performance of SNF during (dry) interim storage are classified to be reduced and bound through data acquisition.

The performance of SNF and cladding must be investigated experimentally under dry storage conditions to assess the impact on the handling of SNF after dry storage and for conditioning for final disposal. Especially high burn-up UO_2 and MOX fuels have been identified as fuels with highest loads and therefore with highest potential for systematic cladding failure (Spykman; IAEA, 2012). Topics of particular interest involve, among others, hydrogen embrittlement (process understanding) and impact of the drying process on the cladding.

However, most studies performed so far on SNF and/or cladding degradation mechanisms (e.g., the ones mentioned above) were performed on (very) low burn-up fuel rods (Kimball and Billone, 2001) or non-irradiated cladding materials, completely disregarding the impact of irradiation on mechanical properties of claddings (e.g., ductility) or (chemical) interactions of fuel with the cladding (which happens at higher burn-ups when the gap between fuel and cladding closes).

(4) Representation in safety assessments

A safe handling of SNF after (prolonged) dry interim storage must be assured. Furthermore, post-closure safety assessments of final disposal facilities must use pessimistic assumptions if SNF properties such as cladding integrity cannot be warranted. However, cladding and SNF are affected by various degradation processes, especially involving high burn-up UO_2 and MOX fuels. Experimental results can be used to validate fuel-performance codes for further prediction of the SNF behaviour under interim storage, transport, and handling conditions.

(5) Specific additional comments on uncertainties related to the performance of SNF during (dry) interim storage

Assessment of safety relevance of uncertainties related to performance of SNF during (dry) interim storage varied from low to high and it was considered particularly relevant for prolonged storage (more than 50 years). Cladding integrity was deemed particularly important because it is of concern for transport from an interim storage to the encapsulation plant and when repackaging in a disposal container. However, there was agreement that it has in general low relevance for post-closure safety because usually no credit is taken from cladding in safety assessments.

6.4.2 Performance of SNF during disposal

(1) Identification and assessment of the impact on safety

Direct disposal of SNF in a DGR is the preferred management strategy in many countries operating nuclear power plants. With the aim to safely isolate the SNF from the biosphere and contain their radiological content in the long-term, various types of host rocks are being considered for a repository on an international level. These host rocks have their strengths and weaknesses. However, common to all DGR concepts is the access of groundwater and the eventual contact of the respective pore water solutions with the emplaced wastes. Thus, in safety analyses of such facilities, the failure of canisters and the loss of the cladding integrity, finally leading to a release of radionuclides from the SNF into the aqueous and gaseous phases must be considered.

(2) Characterisation

Evaluation of the performance of SNF in the near-field of a deep geological disposal systems requires the understanding of SNF dissolution process and its rates as well as the quantification of radionuclides release from SNF under reducing conditions of a breached container. With the aim of deriving a radionuclide source term, the SNF dissolution and alteration processes can be assigned to two steps: (i) instantaneous/fast release of radionuclides (IRF) upon cladding failure from gap and grain boundaries and (ii) a long-term release that results from dissolution of the fuel grains/matrix itself (Ewing, 2015).

In safety analysis of a deep geological repository, the fast release of mobile fission and activation products[7] from SNF is critical for the long-term dose rates in the environment. However, reliable data on inventory and release rates as well as chemical form after release are limited.

Most radionuclides produced during irradiation are trapped in the SNF matrix (Pastina and LaVerne, 2021). Dissolution of the SNF matrix and hence release of radionuclides is controlled by radiolytic oxidants and complexing species on one side and inhibitors on the other side (Metz et al., 2012). Thorough understanding of effects e.g., hydrogen effect and mechanisms that control the dissolution of the matrix and release rates of radionuclides is crucial.

(3) Classification and associated actions

Uncertainties associated with the performance of SNF during disposal are classified to be reduced and bound through data acquisition.

The performance of SNF and cladding must be investigated experimentally under geochemical conditions (e.g., pH, redox potential and ionic strength) representative for the near field conditions of various repository concepts. Hence, the interaction of SNF with the backfill materials, the influence of iron corrosion products, and the consequence of radiolytic surface reactions on the SNF dissolution has to be examined.

Especially the behaviour of high burn-up UO_2 and MOX fuels, but also of novel types of fuels such as Cr-doped fuels or other accident tolerant fuels (ATF) should be investigated. Moreover, segregation of fission and activation products during reactor operations to water accessible sites of the SNF often depends on fuel history data such as burn-up or linear heat generation rate (temperature) (Lemmens et al., 2017). The influence of the operational history of the fuel rod on the radionuclide segregation in SNF is not yet fully understood.

(4) Representation in safety assessments

In safety assessments of disposal facilities contact of groundwater with the emplaced SNF must be considered in the long-term leading to a release of radionuclides to the aqueous and gaseous phases. To derive a realistic source term, it is advised to explicitly address remaining uncertainty related to key radionuclides relevant to IRF, processes affecting the matrix dissolution and hence the release of radionuclides as well as the behaviour of novel fuel types.

(5) Specific additional comments on uncertainties related to the performance of SNF during disposal

It is important to underline that only few radionuclides are considered relevant for post-closure safety, namely because most radionuclides readily decay within the repository system. Management of uncertainties shall thus focus on these radionuclides, namely most likely Cl-36, C-14, Se-79, I-129, Ni-59, tc-99 Ra-226.

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[7] e.g., ^{14}C, ^{129}I, ^{135}Cs, ^{36}Cl, ^{59}Ni, ^{107}Pd, ^{79}Se, ^{147}Sn or ^{99}Tc

6.5 Uncertainties associated with data, tools, and methods used in the safety case

Some management options and strategies regarding uncertainties associated with data, tools, and methods were addressed in the context of the specific examples in previous sections. As another example, nuclear data is discussed below.

6.5.1 Nuclear data

(1) Identification and assessment of the impact on safety

As already discussed in Section 6.3.1, the radionuclide inventory of SNF is crucial to accurately determine the source term in safety assessments. Moreover, the radionuclide content in SNF determines parameters such as the reactivity and the decay heat. Consequently, the radionuclide content is crucial to assess how and how many spent fuel assemblies can be loaded into a disposal canister and how closely these containers can be emplaced in a DGR.

The radionuclide inventory determination of the SNF source term requires, besides fuel history data, nuclear data, such as cross-sections, fission product yields, decay data as well as neutron and γ-ray properties as input (Caruso et al., 2020). These data can be found in general-purpose libraries e.g., ENDF/B, JEFF and JENDL in which the uncertainties of the data are included and should be employed.

(2) Characterisation

The aforementioned libraries mainly contain data from evaluation processes based on nuclear reaction formalisms and/or theories that involve model parameters, which are then adjusted according to available experimental data (Caruso et al., 2020). In addition, the determination of nuclear data and their related uncertainties is an on-going dynamic process, which obviously leads to differences among the libraries or their own updated versions (Caruso et al., 2020).

(3) Classification and associated actions

Uncertainties associated with nuclear data are classified to be reduced and bound through data acquisition.

For an accurate determination of the SNF source term and hence e.g., radionuclide inventory and in particular the decay heat, calorimetric measurements or experiments are needed to improve the cross-section data, especially in the resolved resonance region for key radionuclides (Fröhner, 2000; Schillebeeck et al., 2012; Caruso et al., 2020).

(4) Representation in safety assessments

Sensitivity analyses can help to determine dominant uncertainty and the impact of remaining uncertainty. On the one hand, such studies can be used to represent the remaining uncertainty and its impact in safety assessments. On the other hand, sensitivity studies also help to design targeted experiments with the aim of improving the nuclear data for the most relevant parameters (Caruso et al., 2020).

(5) Specific additional comments on uncertainties related to nuclear data

There was agreement that nuclear data is very important but the level of significance of this uncertainty is between low or medium. Since the nuclear data libraries are continuously tested by benchmarks, revised and updated by providing more accurate values, the uncertainties are well documented and tend to reduce over time. Nuclear data libraries consider also the completeness of the data on presence of activation products and other radionuclides that are important in the long-term safety analysis of the repository

6.6 Uncertainties associated with the completeness of FEPs considered in the safety case

Uncertainties associated with the completeness of FEPs considered in the safety case were not addressed in the context of SNF related uncertainties.

7. Management options for uncertainties related to waste inventory

7.1 Selection of topical uncertainties and general comments

Subtask 3.2 analysed views of the different actors (WMOs, TSOs and REs) on the identification, characterisation, and potential significance of uncertainties on waste inventory and on the impact of predisposal steps (Bielen et al., 2023b). A preliminary list of uncertainties from Subtask 3.2 together with a preliminary evaluation of the responses to the 1st and 2nd UMAN Questionnaires served as basis for the present chapter. Because of partially sparse information, a short survey to identify the uncertainties that are of highest safety relevance was sent to organisations involved in Subtask 4.2 and to members of the EU project "*Pre-disposal management of radioactive waste*" (PREDIS). Based on above information, uncertainties were selected as discussed in the following paragraphs.

The respondents to the survey were asked to assess the importance respectively priority of the uncertainties identified by Subtask 3.2 in their national programme (see *Table 3*). The importance/priority was defined as "High", "Medium" and "Low".

Table 3 – Survey on importance respectively priority of uncertainties related to waste inventory, prepared by Subtask 4.2, shown for an example of uncertainty related to behaviour of cementitious waste forms.

Topical area	**Associated uncertainties on:**	**Description of the uncertainty**	**Safety relevance of the uncertainty**	**Importance/priority**		
				High	**Medium**	**Low**
Physico-chemical properties	Behaviour of cementitious waste forms	*Uncertainty in the occurrence of ASR & DEF in cementitious waste forms:* chemical reactions within the waste matrix can cause the hardened concrete to expand, the production of gel and induce tensile cracking.	ASR & DEF could have an impact on the stability of the waste package and surrounding barriers and may result in a higher dissolution rate and release of radionuclides.	X		

The results are presented below in two ways. The first way is that a weighted average was determined, where "High importance" for a response was given 3 points, "Medium importance" 2 points and "Low importance" 1 point. The points from the different respondents were summed and divided by the number of the responses. The score gives thus an indication of the importance attributed to the uncertainty. A score of 3 would mean that all respondents identified the uncertainty as of "High importance", while a score of 1 would mean all respondents identified the uncertainty as of "Low importance" (*Figure 7*). It can be seen that the following four uncertainties were assessed as most important: "**Chemical composition"**, **"Radionuclide activity"**, "**Scaling factor"** and "**Physicochemical conditions in the storage or disposal facility"**. Besides these, also important were the uncertainties regarding "Waste form behaviour (ageing) in storage and disposal facilities", "Waste acceptance criteria (WAC)" and "List of critical radionuclides". Seen as of low importance were uncertainties regarding "Voids" and "Treatment techniques". These results show a very good consistency with the output from Subtask 3.2 (Bielen et al., 2023).

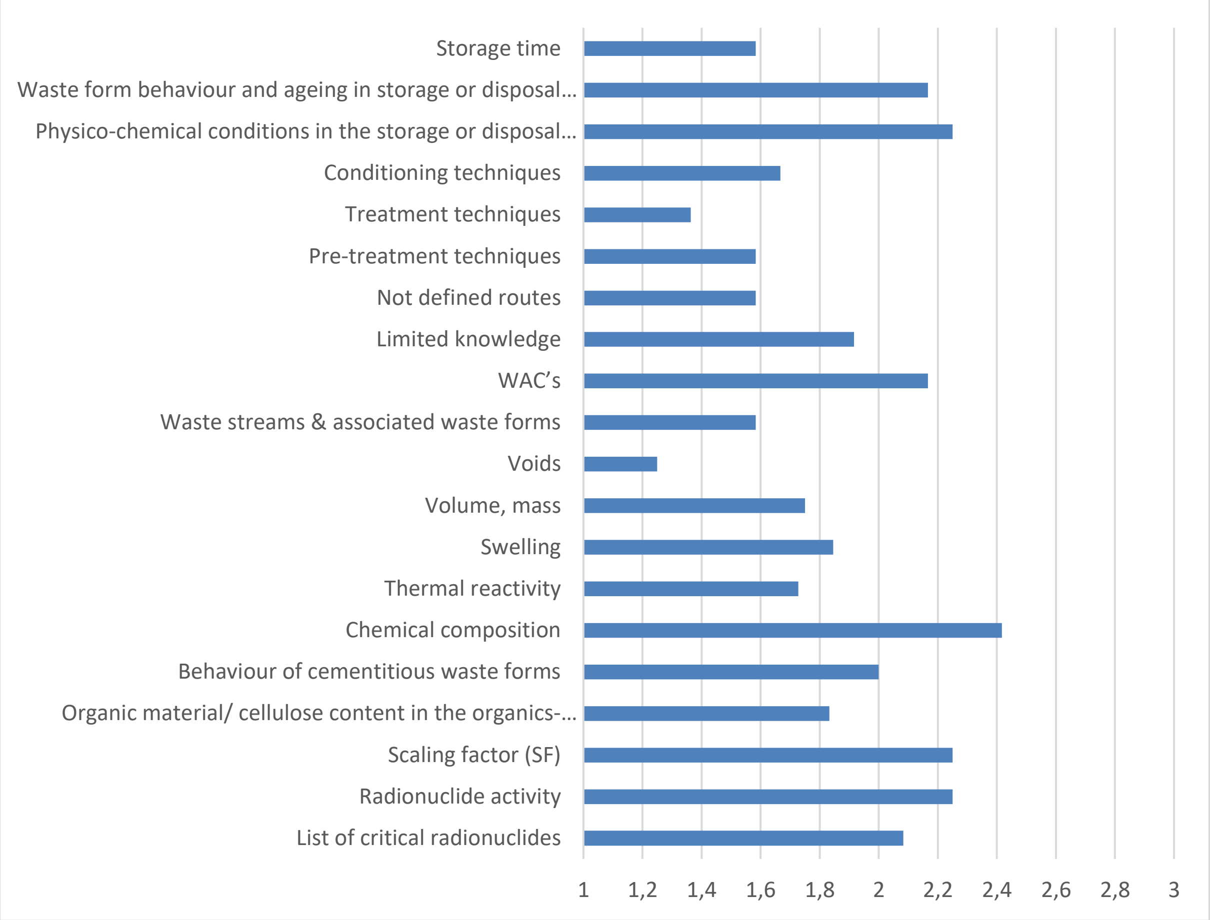

Figure 7 – Weighted average score of the safety-related importance of the uncertainties associated with waste inventory resulting from the survey of Subtask 4.2. Regarding the scale, a score of 1 would mean that all organisations assessed the safety importance as "Low", whilst a score of 3 would mean that all organisations rated the safety importance as "High".

Another way of representing the results are bars showing the number of replies with "High", "Medium" and "Low" importance/priority (*Figure 8*). It has to be remarked that the total number of responses received is not always 12, as sometimes for some uncertainties, respondents indicated that these uncertainties were not applicable, or one respondent indicated two choices for an uncertainty that appears in two different programme situations. Similar conclusions to the case of using the weighted average approach can be drawn. Looking at the number of answers with "High" importance ratings, the same uncertainties arise ("Chemical composition", "Radionuclide activity", "Scaling factor" and on the "Physicochemical conditions in the storage or disposal facility"), and the "List of critical radionuclides" also received a high number of "High" importance choices. Uncertainties related to "Treatment techniques" and "Voids" were seen by none of the participants as of "High" importance. Uncertainties associated with "re-treatment techniques" and "Not defined routes" also received few "High" choices.

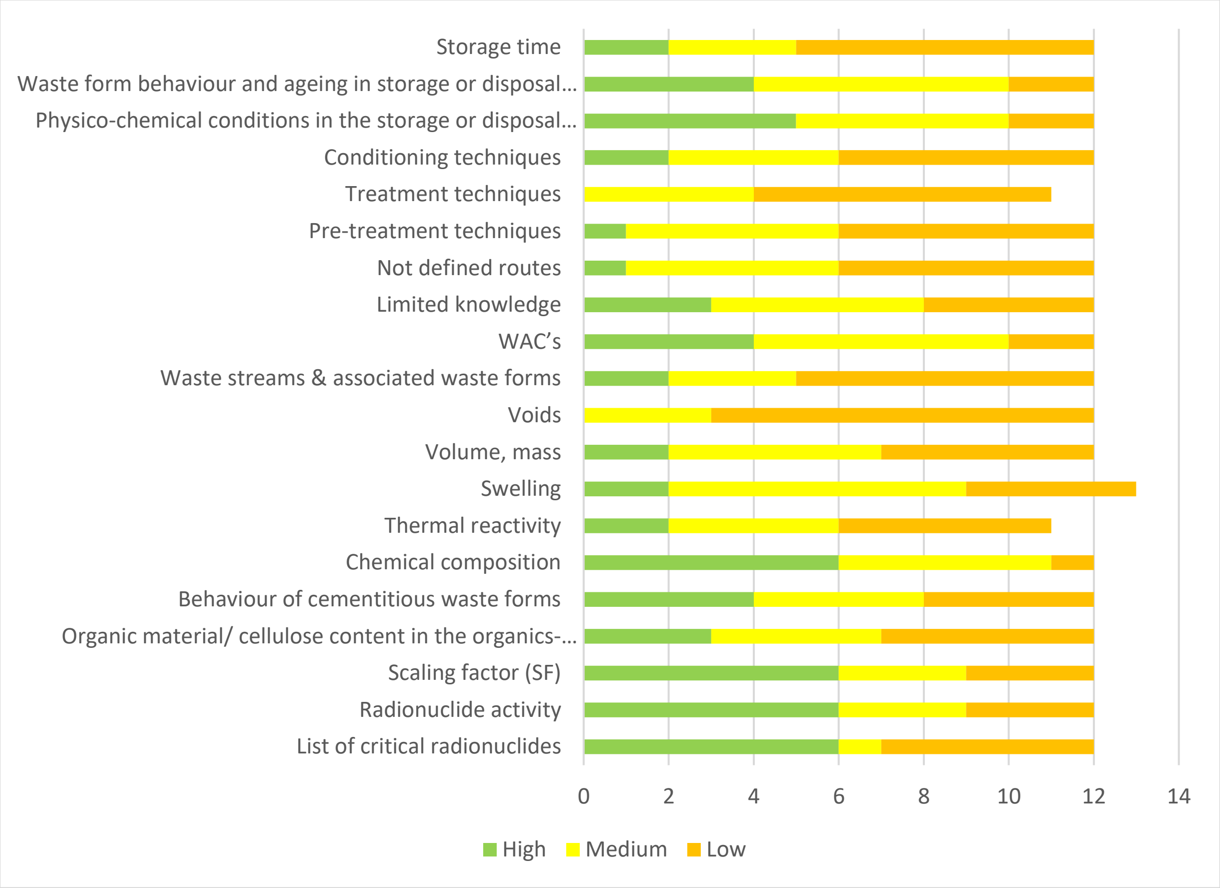

Figure 8 – Results of the survey of Subtask 4.2 indicating the number of responses with "Low", "Medium" and "High" ratings regarding the safety related importance of the uncertainties associated with waste inventory.

Thus, the waste inventory core-group from Subtask 4.2 selected three uncertainties, for which the management options were studied and discussed. It was decided to combine five uncertainties from the list into three topical uncertainties, being:

1. **Physico-chemical conditions** in the **storage or disposal facility** as an example for uncertainties in the **evolution** of the disposal system,
2. **Radionuclide activity** (including the scaling factor) as an example for uncertainties associated with **initial characteristics**,
3. **Chemical composition** (with a special attention to organic content) as an example for uncertainties associated with **initial characteristics**.

Information related to above uncertainties was collected from the 2nd UMAN Questionnaire regarding waste inventory and from six responses to a specific survey distributed amongst the Subtask 4.2 participants (survey template in Appendix A). The discussions during the 4th UMAN Workshop, organised by Subtask 4.3, have been considered during the finalisation of this chapter. As a result, general management strategies and options (Chapter 3) that can be used to handle the specific uncertainties are presented and discussed. While this is done in a structured way along the elements of the management scheme (*Figure 5* in Chapter 3) in the subsequent sections of this chapter, a few general trends were observed:

- uncertainties in waste inventory are usually strived to be identified and reduced in early programme phases, in particular during the waste inventory evaluation process or while developing waste acceptance criteria (WAC),
- safety significance of these uncertainties is expected to decrease throughout the programme phases and to be acceptably low at the operational license application stage at the latest,

- uncertainties depend on the characteristics of chemical elements or radionuclides; those of higher safety significance can often be linked to a reduced set of chemical elements or radionuclides, e.g., radionuclides with potentially high contribution to dose rates. Accordingly, efforts to reduce uncertainties can focus on specific chemical elements or a selection of waste packages,
- differences in safety relevance were noticed between different repository types (surface, near-surface, deep geological repositories), with a trend of higher safety significance for surface disposal facilities,
- in cases where the uncertainties are difficult to be reduced, a conservative approach is usually used in safety assessments,
- during the 4th UMAN Workshop of Subtask 4.3, the importance of joint RD&D activities that help to reduce the uncertainties, e.g., EURAD WP "*Cement-Organic-Radionuclide interactions*" (CORI) and WP "*Mechanistic understanding of gas transport in clay materials*" (GAS) was highlighted.

7.2 Programme uncertainties

No programme uncertainties were amongst the three topical uncertainties selected.

7.3 Uncertainties associated with initial characteristics

7.3.1 Uncertainties related to radionuclide activity (including the scaling factor)

(1) Identification and assessment of the impact on safety

It was identified in preceding UMAN work (Bielen et al., 2023) that a variety of methods can be applied to estimate the activity levels of radionuclides enclosed in a waste package, including direct measurements (e.g., gamma spectrometry) and calculations (e.g., activation calculations). The determination of the gamma emitters activity is usually achieved by a measurement, while activities of the difficult to measure (DTM) alpha and beta emitters areare calculated using scaling factors (SF). Each of these methods is subject to uncertainties.

Uncertainties related to radionuclide activity are linked to representativeness of samples, measurement accuracy, and model uncertainty. It is indicated in IAEA (2007) that the most relevant uncertainty sources, when performing activity measurements, are: incomplete definition of the sample, deviation in the reading of an instrument, instrument resolution, value assigned to the reference data or parameters used in the calculations, representativeness of the sample and environmental conditions.The development of scaling factors, used for determination of activity of DTM radionuclides, is accomplished through several stages, which include sampling, radiochemical analysis, determination of SF and application of SF (IAEA, 2009). Each of these stages introduces some uncertainties. At sampling stage, the uncertainties are related to inhomogeneity of the waste, number of samples, decay of short-lived radionuclides, etc. During the radiochemical analysis stage, it is important which methods of radiochemical analysis are used and how the measurements of radionuclides with activities below the minimum detectable activity are treated. In the SF determination stage, it is important to consider factors as the number of radiochemical analysis data points, the dispersion or variance of data and the SF determination method. Uncertainties related to the application of SF are linked to the definition of the physical parameters of the waste package and to the measurement of the gamma spectrum or radiation level to determine the key nuclide concentration (IAEA, 2009).

Another source of radionuclide activity uncertainties, as pointed out in Bielen et al. (2023), is associated with the limited knowledge about the historical waste. Also, for future waste, sometimes only best and reasonable estimations about the radiological content are available.

Uncertainties related to the waste inventory can be identified by performing different activities in the repository development programme: in the conceptual phase by processing the waste inventory, performing radiological characterisation, regularly updating the inventory, or by demonstrating the compliance of the waste with the WAC.

Uncertainty related to radionuclide activity can have an impact on conceptual planning, siting, construction, waste emplacement, operational and post-closure safety, WAC derivation, the waste acceptance process, and instructions for safe waste management. Throughout these steps, the diversity of the types of radionuclides in the waste should be taken into account.

It was highlighted by WMOs in the 4th UMAN Workshop of Subtask 4.3 that it is necessary to know the characteristics of each kind of waste packages and their radioactive content already for the early stages of repository design because this is the key information with regard to the radionuclide source term, the exothermicity (e.g., in order to optimise the spacing of the micro-tunnel cells in the HLW repository zone) and the gas production, among others. The amount of radioactive material that could be dispersed in case of an accident and associated dose rates are especially important for assessing the operational safety. The post-closure safety requires the knowledge of the maximum radiological inventory and the proof of the absence of criticality risk.

It is indicated in Bielen et al. (2023) that the determination of radioactivity is one of the waste characterisation activities that contributes to defining an appropriate waste management route. If the uncertainties are large, it might happen that the optimal waste management route is not selected. It is also pointed out in this document that uncertainties in the activity may lead to an underestimation of the inventory and consequently to an underestimation of the doses to workers, as well as potential releases and impact on humans and the environment. During the 4th UMAN Workshop of Subtask 4.3 it was pointed out that especially scaling factor uncertainty may lead to an inventory underestimation or overestimation, with consequences on environmental impact and/or costs. Other safety relevant aspects include waste form selection, leaching rate, volume of waste (e.g., double drums have to be used in the case of higher activity which increases waste package volume), the stability of the waste form and release processes.

The safety relevance of radionuclide activity uncertainty is usually determined by safety assessments. It should be pointed out that although the safety assessment with deterministic (bounding) cases demonstrates low significance of the remaining uncertainty, for specific radionuclides with considerable dose-rate contribution, safety relevance might be medium to high (e.g., C-14) and specific measures to reduce the uncertainty might be required. On the other hand, while using the scaling factors, the uncertainty may be relatively large for a specific DTM radionuclide in a specific waste package, but the aggregated inventory of a repository is generally more certain due to averaging effects of large numbers of packages (activity in some packages will be overestimated and, in some packages, will be underestimated) (IAEA, 2009).

Another way to study safety relevance is the comparison of the upper bound activity (which is a sum of declared activity and uncertainties) with WAC (concentration limits per nuclide or the total activity in a waste drum/package for human intrusion scenarios). In the case when this upper bound activity complies with the WAC, very few additional tests regarding the nuclide activity have to be undertaken. If, however, the upper bound activity does not meet the WAC, then the uncertainty is important and needs to be reduced through additional tests regarding the radionuclide activity.

The importance of radionuclide activity uncertainties can be demonstrated when preparing the plan for facility loading. If the uncertainty of the nuclide activities could give rise to a significant effect on the total activity in the facility (in the case of systematic bias), then additional measures regarding waste package loading or additional tests for uncertainty reduction are required.

However, it should be pointed out that during the 4th UMAN Workshop of Subtask 4.3 there was no general agreement between the actors about the relevance of the uncertainty affecting radionuclide activity. It was considered certainly relevant, but according to some actors, these uncertainties are very predictable or not very significant for post-closure safety.

(2) Characterisation

Two types of uncertainties related to the determination of radionuclide activity that need to be characterised can be distinguished: uncertainties related to measurements and uncertainties related to models. Uncertainty in the radionuclide activity is generally an aggregation of the uncertainty on the measurement, the uncertainty on the conversion towards activity, and, for the DTM radionuclides, of the uncertainty on the SF.

Measurement uncertainties can be characterised by applying statistical methods on data, considering the accuracy of measurements and conducting multiple measurements per waste type, which allows to obtain average, maximal, and minimal activity values.

Model uncertainties arising during radionuclide activity calculations can be quantitatively described using probabilistic modelling (e.g., Monte-Carlo modelling techniques), through validation of calculations with sampling campaigns, considering the location of samples (e.g., near the core/ far from the core) or making appropriate assumptions to calculate average or maximal values (e.g., assuming accordingly material impurities).

Other aspects that should be considered when characterising radionuclide activity uncertainty include:

- comprehensiveness of the radionuclide list,
- waste flows estimation and their impact on post-closure assessment,
- radionuclide composition in radioactive waste and institutional waste composition,
- waste stored by waste producers for historical reasons,
- waste production process, waste producer declaration,
- quantification by expert judgement in connection with prediction of future waste inventory.

Uncertainties related to radionuclide activity can be estimated for each waste stream/family, for each waste drum/package and for each radionuclide. For example, activity can be declared in each waste drum/package and each radionuclide with indication of uncertainty expressed as a factor of declared activity. The multiplication of the declared activity with the uncertainty factor will give the upper bound activity for a specific radionuclide in a specific waste drum/package. Applying this procedure for all waste drums/packages allows demonstrating the compliance with WAC.

(3) Classification and associated actions

Significant uncertainties related to radionuclide activity have to be reduced or their consequences mitigated (the latter considers mainly historical waste). For this purpose, the amount of waste and radionuclide inventory are regularly checked and updated. Uncertainties related to radionuclide activity can be reduced by performing additional measurements, including analysis of raw waste and conditioned waste samples, more accurate determination of activities (e.g., daughter radionuclides) and more accurate knowledge of impurity concentrations (e.g., N as a source for C-14). The focus here could be on more accurate evaluation of activities for specific key radionuclides with highest contributions to dose rates. The most significant radionuclides identified by REs include C-14, Cl-36, Ni-63, Tc-99 and I-129. During the 4th UMAN Workshop of Subtask 4.3, a special attention was given to radionuclide C-14, since it is not only important to know the C-14 inventory, but also the fraction of organic and inorganic C-14 as well as the potentially gaseous fraction. It was pointed out that there is a need for investigations in Cl-36 and the organic/gaseous C-14 source term in spent fuel, gaseous C-14 source term evolution over time for metallic waste, activity of radionuclides I-129, Cl-36 and C-14 in HLW glass (no measured data available).

Uncertainties arising in the determination of scaling factors can be handled regularly by performing measurements and redefining/updating scaling factors, if needed. Activation calculations (Monte Carlo based) and verification of the calculations by measurements can help to bound activation related uncertainty.

An example of management of the radionuclide activity uncertainty can be taken from the Belgian case for the radioactive waste disposal in a near-surface repository. If the radionuclide activity uncertainty needs to be reduced, a special additional test programme will be elaborated to determine the activity of the different nuclides. For this purpose, a combination of non-destructive testing (e.g., gamma spectroscopy) and destructive testing (sampling and lab analysis for difficult to measure radionuclides) will be used. This programme will focus on a selection of drums of the waste family under consideration, containing the highest activity, and on the radionuclides posing the greatest threat to compliance with the waste acceptance criteria. Depending on the testing results, the waste drums can either be declared in compliance with the WAC or could be excluded from surface disposal. In both cases, the uncertainty on the activity of (some of) the radionuclides will be reduced through these additional tests. The results of the investigations can also be used to assess if other drums of the same family should be tested or not.

It is recognised that close cooperation between WMOs and waste producers is of great importance in reducing uncertainties on the waste inventory. Regular exchange of information about deviations from normal operation or expected changes in the batches, plausibility checks, and refinements (e.g., in the waste specification) can help to reduce these uncertainties. Control of waste production processes and appropriate quality control according to the type of waste and the method of conditioning (including control carried out by the waste producer and independent control performed by relevant institutions) are also important.

In cases where uncertainty is difficult to reduce, a conservative approach in inventory definition should be applied and regular review and update of the safety assessment should be performed. It was also pointed out during the 4th UMAN Workshop of Subtask 4.3 that early identification of radionuclide activity uncertainty is important, even if it is not very accurate – it can be later improved with more detailed and accurate measurements.

Other aspects and actions related to management of radionuclide activity related uncertainties include:

- legal and regulatory requirements,
- improvement of waste management for pre-sorting,
- minimisation of the inventory,
- development of robust engineered barrier system providing safety functions for repository post-closure period,
- operational and post-closure monitoring,
- verification of scaling method,
- uncertainty oriented research,
- development of novel waste characterisation methods and methods for prediction of the future radioactive waste inventory (especially in the case of DGR),
- verification and validation of computing tools used for radionuclides content assessment.

In the 4th UMAN Workshop of Subtask 4.3 some more strategies for radionuclide activity uncertainties management were identified, such as:

- better understanding of the irradiation conditions effect on isotopic composition in order to use better approaches for calculations, reducing the level of detail needed from the nuclear power plants irradiation records,
- development of models for the temperature evolution during the interim storage to reduce/remove temperature requirements for disposal,
- reliability and traceability of the radionuclide activity per waste package.

It was also remarked that the completion of boiling water reactor (BWR) experimental data could allow to develop a methodology for burnup credit for BWR spent fuel during interim storage and transport. Albeit it concerns radionuclide activity, this topic belongs more to the discussions on uncertainties related to spent nuclear fuel (see Chapter 6) and is not pursued further in this chapter.

(4) Representation in safety assessments

Uncertainties related to radionuclide activity can be represented in safety assessments in different ways. One of the options is to use reference activity values and upper bound values in combination with conservative values and approaches where needed. It should be noted that the upper bound value sometimes must be determined by expert judgement since upper bounds given by waste producers might be very conservative.

An example for management of radionuclide activity uncertainties in the post-closure safety assessment was presented during the 4th UMAN Workshop of Subtask 4.3. For the Cigéo project in France, four possible levels of knowledge were identified, and according to the selected level the radiological inventory of the waste types was increased by a factor ranging from 1.5 to 10. This increased radiological inventory can be used for post-closure safety assessments because these margins make the results more robust. However, it was pointed out that this approach could lead, for some poorly known waste types, to exaggeratedly increased radionuclide contents leading to inconsistencies. In this case, some specific scenarios, such as human intrusion, require a specific method to avoid focusing on results that would not have any physical meaning.

Safety assessment usually includes a part dedicated to uncertainty analysis. This analysis has to cover uncertainties on input data, which includes uncertainties related to radionuclide activity.

Other aspects of the representation and the evaluation of radionuclide activity uncertainties in the safety assessment, that were identified during the 4th UMAN Workshop of Subtask 4.3, include:

- regular review of safety assessment,
- development of a burnup credit methodology for disposal criticality evaluation,
- regarding the impact of irradiation conditions on the activity (and thus the heat load), development of methodologies reducing conservatisms for the loading of disposal canisters.

In the case where radionuclide activity uncertainty is dealt with on the level of testing the compliance with the WAC, there is no need for special representation in the safety assessment (e.g., no special scenarios with higher source term).

(5) Specific additional comments on uncertainties related to radionuclide activity

Significance of uncertainties related to radionuclide activity depends on the phase of a disposal programme, the waste inventory and repository type and varies from country to country. For example in Switzerland remaining radionuclide activity uncertainties are of low safety significance (i.e., well enough bound) at the site selection stage (phase 1) of the DGR disposal programme with the exception only for a few specific radionuclides with considerable dose-rate contribution (e.g., C-14), for which safety relevance might be medium to high and specific measures to reduce uncertainty might be warranted.

Limited significance of uncertainties related to radionuclide activity was mentioned also during the 4th UMAN Workshop of Subtask 4.3 by some TSOs regarding spent fuel from research reactors, vitrified waste from NPPs, ILW-H and ILW-L, LLW and VLLW (mainly depleted uranium). It was recognised that reprocessing can affect uncertainties evaluation, especially in case of technology change over time, and inventory depends on future NPPs design. However, uncertainties related to radionuclide activity for fission products is assumed to be small since they are considered as well predictable. It was also pointed out that there could be a large uncertainty concerning activation products but given the low radiotoxicity and short half-life of most of those nuclides, significance is also considered limited. Some REs indicated that the safety significance of this uncertainty is quite high though only for few radionuclide inventories uncertainties are safety relevant (e.g., I-129 content of glasses, for which no measured values are available).

For the DGR planned in Czech Republic, which is currently also in the phase of site identification and selection, the uncertainties on waste inventory are of high importance/priority. This is mainly due to a lack of information on waste and spent fuel that could arise from any potential new nuclear facility, as well as information on any high-level waste that would be generated if any decisions were made to reprocess spent nuclear fuel. These uncertainties can have a serious impact on the repository volume and site capacity.

It is expected that uncertainties related to radionuclide activity would decrease gradually as waste characterisation improves, disposal programme progresses, and WAC become clearer. In any case, these uncertainties must be reduced to such extent that it could not affect repository safety. In general, it is expected that starting from phase 3, remaining uncertainties related to radionuclide activity are sufficiently reduced and the uncertainty is therefore of low significance. However, these uncertainties can be of high importance for demonstrating the conformity of the different waste families with the waste acceptance criteria.

7.3.2 Chemical composition (with a special attention to organic content)

(1) Identification and assessment of the impact on safety

Chemical composition of radioactive waste packages must be considered when designing storage or disposal facilities as it must conform with the system. Certain chemicals might also impact the stability of the waste and waste packages themselves. Furthermore, chemical interaction with radionuclides might alter transport properties. Finally, hazardous materials such as asbestos might impact waste handling and operational safety.

Examples of relevant chemical elements that may impact safety are chlorides, sulphates, and nitrates. Furthermore, of particular interest is the organic content of the waste, which might, for instance, influence radionuclide retention respectively release through e.g., the formation of complexing agents.

The safety impact of uncertainties on chemical composition concerns thus several aspects:

- damaging barriers and reducing or preventing their proper functioning (impact on safety functions of certain barriers) as e.g.,
    - steel corrosion,
    - sulphate attack of cementitious materials,
- impacting radionuclide retention and release through chemical interaction through e.g., forming complexing agents,
- hazardous materials that impact waste handling and operational safety.

Uncertainty related to chemical composition is usually identified early in the development of the waste disposal programme, in particular during the waste inventory evaluation process or while developing WAC and measures to enforce and demonstrate compliance. For example, plausibility checks on data entered to waste specification sheets can help to identify the uncertainty (Nagra, 2010). References can be found in safety reports, licensing conditions, QA/QC documents, or specifications done in the course of waste production (NPPs operational experience). Specific references from the Czech programme can be found in Havlová et al. (2020) and Decree No. 377/2016 (2016).

Uncertainty may also simply appear through the absence of a detailed declaration of chemical components, especially if these do not contribute much to the total weight of the waste. This is e.g., observed with regard to organic content that is not always specified or when being confronted with limited knowledge of non-radiological features of certain components as e.g., for waste simply specified as "electronic waste”.

Uncertainty may also be linked to laboratory measurements (i.e., data uncertainty) as for example when determining organic and inorganic C-14 content in spent ion exchange resins (Vaitevičiene, 2013).

More formally, with respect to identifying safety relevant uncertainty, uncertainty related to chemical composition is identified through systematic FEPs-analysis done during safety assessments, e.g., linked to the license application (see for example NIRAS, 2019a). While safety relevance depends on the chemicals in question and the disposal system, uncertainty linked e.g., to chlorides, sulphates, nitrates, celluloses, and other complexing agents, was identified as having potentially high safety impact.

Qualitatively, safety relevance can be assessed through phenomenological descriptions of the repository performance. This can be done by providing descriptions of how engineered barriers might be degraded and their associated safety functions impaired. For example, linked to the most recent Belgian safety case (NIRAS, 2019b), it was assessed that the presence of sulphate and chloride could degrade concrete barriers and that the presence of chloride, celluloses, and other complexing agents could have a negative effect on radionuclide sorption in the barriers.

Quantitatively, the safety relevance of the uncertainties is usually assessed through phenomenological assessments of the barrier performance (“performance assessments” as part of “safety assessments”). Specific sensitivity and uncertainty analysis is used to determine the most relevant parameters and assess the safety impact of (remaining) uncertainty. References can e.g., be found in safety reports, licence conditions, or the programme of operational controls.

Sometimes, also literature surveys are used to assess the safety relevance.

There is good agreement across the community that uncertainty with respect to the following topics has the highest relevance for post-closure safety of the disposal facility:

- chemicals that lead to the degradation of barriers as e.g.:
    - sulphate attack of cementitious materials,
    - Alkali-Silica-Reaction (ASR) and carbonation (Kosakowski et al., 2014; Wieland et al., 2018),
    - chloride attack of steel waste drums and reinforcement in concrete,
- complexing agents that enhance radionuclide mobility respectively reduce radionuclide retention by e.g., reduced sorption or increased solubility,
- chemical components that enhance radionuclide release, e.g., through enhanced corrosion,
- chemical components that may influence the speciation of radionuclide release, e.g., the form of C-14 compounds (organic/inorganic) affects its release rate and migration through engineered and natural barriers.

During the discussions in the 4th UMAN Workshop of Subtask 4.3, the following specific examples were given by WMOs to illustrate the above statements:

- organic matter contained in some waste packages will degrade into complexing substances, such as isosaccharinic acid (ISA); ISA can mobilise even poorly mobile radionuclides and facilitate their migration in clay rock,
- certain ILW waste packages may produce heat due to exothermal chemical reactions for several centuries; this heat can impact the viscosity in some waste packages and the transport properties of radionuclides.

Other examples with limited safety relevance were:

- waste packages may contain high quantities of salts, including sodium, potassium, nitrates and sulphates, which can worsen some properties of clay rock; however, the available knowledge shows that this influence is not significant for safety,
- some bacteria can consume the organic matter and thus influence the geochemical environment in some disposal cells; while this uncertainty is rather large, its potential effect would reduce the influence of the organic matter and preserve or even improve the performance of the system (e.g., of clay rock),
- the chemical composition of vitrified waste has in general few uncertainties; boron content in the glass matrix might have larger uncertainty, however it is known to have no impact on the properties of clay host rock; thus, for disposal systems in clay, low safety relevance remains,
- also the chemical composition of SNF is deemed to have, in general, few uncertainties which are of limited safety relevance.

In general, safety relevance of these uncertainties is estimated higher for surface disposal facilities, at least for some waste types (e.g., containing cellulose, water soluble chlorides & sulphates, and for

ASR/DEF in concrete). For geological disposal, overall safety relevance was estimated lower (medium or less) and concentrated to the topics mentioned beforehand.

(2) Characterisation

Ideally, the chemical composition of the waste should be well known, thus related uncertainty should be quantitatively well characterised. However, several issues lead to a more complex situation in reality:

- often, only limited information respectively data is available and e.g., the mass of overall materials and additives is uncertain or even unknown (e.g., complexing agents not specified); quantitative estimates using e.g., expert judgement may then be used to characterise and quantify content and uncertainty,
- waste acceptance criteria define e.g., upper bounds for certain chemicals or materials; it is thus only assured that the waste respects those upper bounds, which may lead to overestimated uncertainty; the chemical content of the waste and related uncertainty may further be characterised based on available data, but uncertainty remains,
- limited accuracy of measurements, subsample analysis, or the application of statistical methods on data induces uncertainty,
- waste generation history may have varied or may vary; thus, this will increase uncertainty,
- there may be evolution of the waste during (intermediate) storage or in the disposal facility so that uncertainty regarding the influence of the conditions in the facility on the behaviour of the chemicals and of the status of the waste and their packages must be accounted for.

Nevertheless, usually it is strived to characterise the uncertainty in chemical composition quantitatively, possibly with some additional safety margin.

There was agreement in the 4th UMAN Workshop of Subtask 4.3 that focussing characterisation efforts on safety relevant properties will help reducing uncertainty where it is most relevant. An example mentioned by WMOs was to perform analysis of specific waste streams related to dose-contributing radionuclides (e.g., C-14) in order to gather more detailed information about specific safety relevant materials.

In more detail, contributors from Belgium describe their approach exemplarily as follows. The chemical content of the waste is characterised based on available data from the waste families and concerns the sulphate content, chloride content, celluloses, and other complexing agents. Those contents need to respect the WAC for the future near-surface disposal (NIRAS, 2019b). The available data is analysed, and an estimation of the content is undertaken by the WMO and documented in the so called “waste conformity files”. The characterisation for chloride and sulphate is at this moment mostly done through calculations using bounding hypothesis. For celluloses, the available data is analysed, and the content determined; this is mostly a more realistic estimation, based on a classification into different celluloses mass categories. For celluloses, a strategy for the determination of the uncertainty is still under development. For the other complexing agents, there are no a priori limits but their presence should be avoided, so there is a verification that these agents are not present in the waste. This is done through analysis of the data and is also based on knowledge about the history of the waste (whether it could have been in contact with complexing agents or not). For the complexing agents other than celluloses, there is no specific characterisation of the uncertainties. If they should be present, a specific assessment will be undertaken, for which also the uncertainty on the content will have to be characterised.

(3) Classification and associated actions

It is recognised that most uncertainty related to chemical composition must be avoided or adequately reduced before licensing steps and in particular before the operational license. Nevertheless, some uncertainty will remain and needs to be represented adequately in safety assessments (see Point 4).

There is consensus that appropriate WAC together with strategies for verification and thus enforcement must be put in place to achieve adequate uncertainty reduction.

Furthermore, the following strategies can be applied to reduce the uncertainty:

- analysis of specific waste streams or specific waste samples to gather more detailed information about specific safety relevant materials. Examples are:
    - materials that impact the release of dose-contributing radionuclides as e.g., C-14,
    - the content of cellulose in a waste family can, for certain families, be verified by examining some of the drums using a high energy X-ray imaging, or by destructive methods,
    - for chloride and sulphate, reduction of uncertainties may (only) be possible by sampling waste and performing chemical analysis (like XRF).
- assure best possible description of used materials as soon as possible and *before* conditioning and store the information accordingly. An example from the Czech Republic was provided as follows. The national inventory of radioactive waste (RAW) and spent nuclear fuel SNF can be found in the National Reports under Joint Convention and in the National Reports under Directive 2011/70/Euratom (Czech Republic National Reports, 2011) and in the Policy for Radioactive Waste Management and Spent Fuel Management in the Czech Republic and its updates are approved by Czech government resolutions (Policy for Radioactive Waste Management and Spent Fuel Management in the Czech Republic, 2019). The detailed inventory of all disposed RAW is internally available in the electronic database of the Czech WMO SÚRAO.
- optimise waste conditioning and packaging where possible and appropriate. In some countries (e.g., Czech Republic), the WMO has specifically the possibility to control the waste conditioning process guaranteed by waste producer and approved by the regulatory body. An example from the Czech Republic was provided as follows. In Decree No 377/2016 Coll. (Decree No. 377/2016, 2016), guidance is given by two paragraphs: § 3 *Radioactive waste or mixtures thereof with other substances shall be collected and segregated according to physical and chemical properties and according to its expected processing and treatment;* § *5 Prior to the conditioning of radioactive waste, a technical procedure shall be stipulated for every conditioning method used. This procedure shall include conditions for effective and safe conditioning of radioactive waste, for example mixing ratio or specific consumption of bracing, and conditions for solidification, restriction, or rejection of some types of waste or permitted substitution of individual waste components for the given treatment method. Acceptance conditions for hardeners and the way these conditions are checked to ensure their required quality shall also be stipulated.*
- assure that information on waste amounts, radionuclide inventory, and chemical composition is updated regularly and appropriately.
- improve process understanding e.g., by laboratory measurements on (site specific) sorption of organic and inorganic (C-14) compounds.
- influence conditioning where possible and appropriate.
- perform more accurate dose rate measurements, gamma spectrometry, improve waste acceptance processes, and increase knowledge of physical-chemical properties like leaching rates, release rates.
- improve experimental techniques to measure isotopes that might overall contribute to dose rates, as e.g., as C-14 or Cl-36, but might have locally very low concentration which arise from impurities in the nuclear fuel materials. As an example, Laser Ablation allows the measurements of low concentration radionuclides.

Similar to the above, there are also strategies to avoid chemical composition related uncertainty altogether by enforcing waste acceptance criteria that prohibit certain chemicals or components within the waste to be disposed of. One example is Bulgaria’s WAC that prohibit hazardous materials such as asbestos to be disposed of in radioactive waste disposal facilities. In practice, this is imposed as a technical requirement in the treatment process of the decommissioning waste. Partially related to this matter, mixing of radioactive and non-radioactive wastes is not allowed, as specified in Regulation for Safe Management of Radioactive Waste (BRNA, 2013).

For historical waste on which little is known, one might have to mitigate consequences of the uncertainty e.g., by proper re-packaging of already disposed waste in adapted or reconstructed waste packages.

Furthermore, making the waste producers aware of potential issues will help to ensure that relevant elements/compositions are given as precisely as possible in specification sheets, and are not omitted.

During the 4th UMAN Workshop of Subtask 4.3, the importance of joint RD&D activities that help to reduce the uncertainty has been highlighted, e.g., EURAD WP CORI and EURAD WP GAS.

(4) Representation in safety assessments

Predominantly, remaining uncertainty is treated by conservative assumptions in safety assessments. Sometimes, specific assumptions are made, or altered evolution scenarios defined, to explore the impact of remaining uncertainty in safety assessments. This may include scenarios with faster waste form degradation and radionuclide release rates, with degraded barriers, etc. The following examples illustrate strategies for representing remaining uncertainty in safety assessments:

- Example from Switzerland (Nagra, 2008): For low and intermediate level waste in a cementitious near field, a splitting into two waste groups was postulated, where for one waste group we can assume better sorption behaviour; for the second group, pessimistic sorption is assumed in a conservative way to account for complexing agents.
- Example from Lithuania: Remaining uncertainties in the programme phase 2 were addressed in safety assessment using a number of conservative assumptions associated with presence of organic C-14 compounds (e.g., scenarios with faster degradation of the waste package, fraction of released organic C-14 compounds, etc.).
- Example from Belgium (NIRAS, 2019a): As there are several ways in which chemical species might degrade barriers or form complexing agents bypassing the retention barriers, special consideration is given to this in the safety assessment.. The assessment considers a specific Altered Evolution Scenario, in which it is supposed that 1% of the waste drums fails and contains complexing agents that had not been detected during verification of waste conformity. This results in a scenario where for 1% of the waste, all retention properties of the engineered barriers are reduced to 0. The results are then compared to the risk criterion to be applied to these scenarios.

(5) Specific additional comments on uncertainties related to chemical composition

Post-closure safety relevance is estimated rather high in early programme phases and is expected to decrease over time. At the latest for the operational license, the remaining uncertainty is not expected to compromise safety. Some differences of safety relevance have been noticed between different repository types (surface, near-surface, deep geological repositories). The evolution of the safety relevance and differences are illustrated by the following examples:

- The uncertainty is very relevant at the current stage of the Belgian surface disposal programme. Currently, the WMO is in the phase of preparing the ‘conformity files’ for the different waste families, demonstrating the conformity with the waste acceptance criteria. In these files, which are reviewed and approved by the regulator and its TSO, the treatment of uncertainties is an important axis. In the coming years, the additional test programme for all these families must be established and executed to be ready to start waste encapsulation and disposal as from the mid-twenties on.
- In Switzerland, during the last stage of site selection and for the preparation of a general license application for a DGR, safety relevance is estimated as medium.
- In Bulgaria, there is an accordance of the status of the RWM with the national legislation, waste management strategy and programme (Act on the safe use of nuclear energy /ASUNE, 2023; Strategy for the management of spent nuclear fuel (SNF) and radioactive waste (RAW), Council of Ministers of Republic of Bulgaria, 2015; Regulation on Safe Management of Radioactive Waste, BRNA, 2013), and the uncertainties are low and in practice are mastered by operational actions.

- In Germany, safety significance is estimated very relevant for getting the Konrad disposal facility operational.
- For existing disposal facilities in the Czech Republic (NRS – Richard, Bratrství and Dukovany) safety relevance and priority is deemed low for this uncertainty at the present stage of the RWM programme.

Besides radiological post-closure safety aspects, it has been remarked that chemical composition and related uncertainty may also have to be considered with respect to “classical” environmental protection laws and regulations (i.e., non-radiological impact), as e.g., licensing according to the water protection law (see WVG, 1991; NWG, 2010; TrinkwV, 2016; AwSV, 2017, respectively). However, it is estimated that – while politically sensitive – such aspects should hardly present any safety issue for disposal facilities of radioactive waste.

Chemical composition and uncertainty therein should also be considered in the context of operational safety, where it is presenting no particular challenges.

For chemical composition related uncertainty management, the following specific examples were provided for the Czech Republic:

- Only relevant permission holders are eligible to manage RAW and SNF; permissions are issued by the regulator provided that requirements specified in the Atomic Act (ACT, 2016) and related implementing regulations have been met. RAW and SNF management in the Czech Republic must be conducted in compliance with national strategic aims and internationally recognised principles (IAEA and OECD/NEA recommendations, and EC requirements).
- Waste producers apply for a special type of waste management to the regulator. Waste producers submit documents describing the way of waste characterisation, including used methods, their quality and system of control. Documentation must include the waste origin, and subsequently all changes of waste owners and contain information on waste processing, conditioning and other situations that could lead to the change of waste characteristics.
- In NPP Dukovany and in NPP Temelín the procedures for characterisation and sorting of RAW are described in the internal documents inspected by the regulator. The documents comply with the requirements of the Decree No. 377/2016 Coll. (Decree No. 377/2016, 2016), as amended.

A similar example was provided for the Republic of Bulgaria: In Kozloduy NPP the procedures for characterisation and sorting of RAW are described in internal documents and these are inspected and approved by the BNRA in accordance with the Regulation on Safe Management of Radioactive Waste, adopted by CM Decree № 185/23.08.2013, promulgated, SG, No. 76/30.08.2013, amended, SG No. 4/9.01.2018; 37/4.05.2018.

7.4 Uncertainties in the evolution of the disposal system and environment

7.4.1 Physico-chemical conditions in the storage or disposal facility

(1) Identification and assessment of the impact on safety

Physico-chemical conditions in the storage or disposal facility impact the long-term behaviour of the waste package and waste matrix in the surface facility or under disposal conditions. Uncertainties to be considered are linked to e.g., the evolution of the pH, the presence and the migration of aggressive species (e.g., chlorides, sulphates), mechanical stresses, etc. The specific conditions could produce reactions with the waste form, or result in corrosion, swelling of the matrix, etc. This can have an influence on the properties of the waste form in disposal conditions, and on the degradation rate and aging.

The uncertainties cover a quite large domain. First of all, at the basis can be uncertainty around many parameters regarding the physico-chemical conditions in storage and disposal facilities; and secondly, the resulting uncertainty in the behaviour of the waste form can also be different in view of different waste types that exist, for example cementitious waste forms or bituminous waste forms. Therefore, the identification of this uncertainty might be a complex process.

The presence of aggressive species and water could have an impact on the stability of waste and waste package. This impact can also be indirectly affected by the external conditions, for example when a storage site is located in an area with extreme weather conditions (heavy rains, storms, tornadoes, and heat waves) or severe winter conditions. Therefore, identification of these factors, including determination of statistical parameters, is recommended.

The identification of the uncertainty can be done in diverse ways, e.g., through literature survey, through the development of the system understanding (understanding the phenomenology that will give rise to the uncertainty, such as complex analysis of internal and external conditions) or by using FEPs-screening, or a combination thereof. Most of the countries see the identification of the uncertainty within the safety assessment process of a disposal facility.

It was found important for the identification to perform an exhaustive analysis of the physico-chemical conditions that could arise in and around waste storage and disposal facilities. For storage facilities, one could for example think about uncertainty in temperature (extremely hot or cold conditions) and (relative) humidity as two of the parameters that could influence the behaviour/ageing/evolution of the waste form. Regarding disposal, specifically the uncertainties regarding pH and the presence of aggressive species such as chlorine or sulphate or nitrates in the internal environment of the facilities are to be mentioned as well as the presence of water, which might be an issue for hygroscopic materials such as some types of bituminous waste.

The uncertainty was found safety relevant for both surface disposal facilities and deep geological repositories. In fact, it will impact the parameters related to the long-term waste package behaviour, and it can result in (faster than foreseen) leaching out of the radionuclides, chemicals, by-products, etc. into the environment with subsequent potential risk to human health and the environment.

The uncertainty was considered safety relevant within the phases 0 - 4, i.e., in all phases the respondents are active in.

The way in which the relevance of the uncertainty is assessed is again diverse:

- literature survey,
- expert judgement,
- and, mostly cited by the respondents, safety assessment, including sensitivity and uncertainty analysis. Specifically, (probabilistic) performance assessment should be mentioned, which is used, for example, to assess gas generation, dissipation, and gas pressure build-up.

Physico-chemical conditions in the storage or disposal facility and thus the uncertainty associated with it may have the following relevance for disposal:

- impact on the physico-chemical properties important for safety, such as mechanical stability or permeability of the waste form,
- impact on the estimation of radionuclide release from the waste form, as it can result in increased leaching and/or degradation of the waste form, with earlier and or larger release of radionuclides as a result,
- impact on the mobility of safety relevant radionuclides when interacting with engineered barrier materials, its alteration products and the repository rock,
- impact on the safety functions of the components surrounding the waste due to e.g., faster degradation processes of the waste. The latter could damage or degrade engineered barriers, resulting in the loss of their containment functions (e.g., increase in permeability or other transport parameters). We can think for example about the swelling of waste as a result of matrix degradation or corrosion of the package, mechanically damaging engineered barriers.

Uncertainties regarding the physico-chemical conditions, which might affect the waste properties, can thus result in uncertainties regarding safety related properties and their evolution.

It might be that the importance of the uncertainty also depends on specific (types of) nuclides, for example, the uncertainty might have a more important effect on the retention of nuclides present under the form of anions than under the form of cations.

When it comes to the safety significance, WMOs consider the importance somewhere between medium and high, explained by the lack of knowledge at the early stages of the development of the disposal facility. WMOs expect it to decrease to low significance once the disposal facility will be constructed.

REs have a slightly distinct view on the safety significance. They see the conditions itself as very important, but the uncertainties around them as of lower importance, at least in the later stages of the disposal programme. In any case, with the increase of knowledge and experience, it is expected that the safety significance of the associated uncertainties will decrease over time. However, the safety significance can also increase in the course of time, due to e.g., ageing of equipment and facilities, non-implementation of programmes, etc.

Divergent views on the importance of this uncertainty were noted amongst TSOs. Especially on the importance at the later stages of the disposal facility. It might be that antagonising factors are here at play. The physical-chemical conditions themselves (and thus the uncertainties also) come at play at the later stages of the disposal facility (typically after closure the physico-chemical conditions will evolve). However, the more evolved the facility implementation is with time; the more data there will be available regarding these physico-chemical conditions and thus reducing the uncertainty.

(2) Characterisation

The storage conditions inside the building are the first thing to look at when characterising this uncertainty. During storage, the microclimate of the indoor environment (temperature, humidity, etc.) and content of chemicals from a certain type of waste that could be released into the storage environment are important. In addition, the information regarding the conditions outside the building might also be of relevance for the uncertainty characterisation, when it can be combined with knowledge on the building isolation and air tightness and ventilation parameters. Thus, the influence of the external conditions outside the storage building could be characterised depending on the type, parameters, characteristics, and stability of the storage building, isolating ability, and, in some cases, even the hermeticity of the construction.

On top of that, it might also be relevant to look at accidents/incidents that happened and might have changed the waste (for example fire accidents, exposure to extreme meteorological conditions outside or specific environments that were induced through mitigation actions during accidents like fire extinguishing chemicals, etc.). Those might give rise to uncertainties in the conditions the waste experienced prior to disposal.

The characterisation of the uncertainty regarding the disposal conditions will depend on the type of disposal facility (whether it is surface or deep geological) and the specific conditions that reign in there (regarding water, pH, and aggressive species). It might have to be beard in mind that the aggressive species could not only come from the surroundings of the facility (EBS, host rock), but also could originate from waste containing aggressive species that degraded and liberated these species, which could provoke unfavourable physico-chemical conditions for the surrounding waste.

The uncertainty in disposal conditions was found to be characterised in different ways as highlighted by the input received from the survey:

- laboratory and demonstration experiments can deliver data from which the uncertainty can be characterised, e.g., by applying statistical models,
- modelling (scenario development, sensitivity analysis) and FEPs analysis,
- quantification by expert judgement.

(3) Classification and associated actions

The uncertainty was by the majority chosen as “to be reduced”. This is likely in relation to the importance it can have on various properties and safety functions of the disposal facility. However, not every organisation sees this uncertainty to be reducible, which is connected to the attribution of a lower safety significance of it in some programmes.

There are different ways in which the uncertainty can be reduced. When it concerns the physico-chemical conditions in the storage facility:

- A first way of coping with the uncertainty is assuring stable and favourable physico-chemical conditions in the storage facility, which will avoid the potential for waste package degradation. The uncertainty on these conditions will then as such become minor and not of importance. This could be done by e.g., climatic control of the air in the storage facilities. Keeping stable low moisture conditions and constant temperatures at all times will assure that the waste packages will not corrode or degrade from the outside on. In order to assure stable conditions at all times, mitigation measures might be put in place in case of accidents (type of fire extinguishing, back-up climate regulation, etc.). References regarding this matter are exemplarily the Bulgarian Regulation for Safe Management of Radioactive Waste (BNRA, 2013 and amended, SG No. 4/9.01.2018; 37/4.05.2018), Ordinance on the Terms and Conditions for the Transfer of Radioactive Waste to SE RAW (2015), and Guide for Safe Transport of Radioactive Materials (BNRA, 2016) (see also ARTEMIS, 2018).
- When a storage facility is in operation, the uncertainties associated with the physico-chemical conditions in storage can be reduced by periodic or continuous monitoring of the physico-chemical parameters in the facility. It could be done through measurement of relative humidity and temperature or other measurements, maybe related to specific chemicals that could be present. Additionally, such measurements can also be used as an input for assuring the stable conditions in the facility as discussed in the previous bullet. In case no direct measurements are available, the conditions might be estimated by using knowledge on the building (isolation and other building parameters, construction plans, and ventilation systems) and information regarding outside climatic conditions, in order to increase knowledge on the conditions the waste is or was stored in.
- In case the information regarding conditions of storage have not been recorded or if waste has been displaced towards another facility and the original physico-chemical conditions are not known, it might seem that the uncertainty cannot be reduced. However, the physical conditions of the waste packages itself will give indications of the past storage conditions, and indirectly might reduce this uncertainty. The effect of the previous storage conditions on the waste can be assessed through inspection programmes on the waste packages. For example, the absence of (external) corrosion and degradation of waste drums indicates that the previous physico-chemical storage conditions were unfavourable for corrosion, while waste drums showing signs of (external) corrosion were stored in humid conditions which allowed corrosion to progress. This reduces the uncertainty on the physico-chemical storage conditions.

An alternative strategy to manage the uncertainty is to perform frequent inspections and follow-up of the conditions of the waste package (so a focus on the potential effects, rather than on the physico-chemical conditions and the uncertainty of it), see e.g., the Bulgarian Regulation for Safe Management of Radioactive Waste (BNRA, 2013 and amended, SG No. 4/9.01.2018; 37/4.05.2018)), Ordinance on the Terms and Conditions for the Transfer of Radioactive Waste to SE RAW (2015), Regulation on the Conditions and Procedure for Delivery of Radioactive Waste to the Radioactive Waste State-Owned Company (BNRA 2015) and Guide for Safe Transport of Radioactive Materials (BNRA, 2016) (see also ARTEMIS, 2018).

When it concerns the physico-chemical conditions in the disposal facility:

- First of all, experimental research regarding the physico-chemical conditions in the facility can be undertaken. This could be for a DGR in-situ experiments, at depth, for example instrumentation of a mock-up of the facility in the host rock, determining all kinds of physico-chemical parameters such as e.g., the pH. Additionally, experiments to determine the corrosion potential of metals in in-situ conditions can also be performed, in order to determine directly the impact of the physico-chemical conditions on the waste package. For a surface disposal facility, the mock-ups can be constructed as well, for example a mock-up of the cover-design, instrumented with a drainage system to collect the percolated water, in order to determine its pH and the presence of aggressive species such as sulphates. This reduces the uncertainty on the physico-chemical properties of the water that will in the end be in contact with the waste package and might give rise to waste package degradation. Besides in-situ or mock-up experiments, laboratory experiments can also be envisaged, which could especially be useful to simulate the evolution of the physico-chemical conditions in an accelerated way and reduce the uncertainty on the long-term evolution of the conditions.

- Besides the experimental research, the uncertainty regarding the physico-chemical conditions in the disposal facility could be reduced through phenomenological assessments using modelling techniques. These aim to estimate physico-chemical conditions and together with sensitivity studies might better delimitate and reduce the uncertainty.

Although not a way to reduce uncertainty, several respondents noted that, upstream in the programme, ensuring a robust waste package (e.g., by using appropriate storage containers and a waste form that is stable under all unfavourable physico-chemical conditions that they might come into contact with) is a way of coping with this uncertainty.

In fact, it does not reduce the uncertainty on the physico-chemical conditions, but it reduces the uncertainty on the disposal package reaction to it and so the safety relevance of the uncertainty. This could be done by assuring for example a package that is corrosion resistant towards all kinds of aggressions such as wet-dry cycles, chlorine, etc. In the same view, conditioning techniques can be strived for that will provide the most stable and robust waste form relative to potentially aggressive physico-chemical conditions, for example, by using matrices that are not susceptible to swelling. An example from Belgium is the rejection by the regulator of thermally compacted spent ion exchange resins, as a treatment and conditioning technique. High humidity conditions or contact with water might make the resins swell which might degrade the package and even the surrounding EBS. The assurance of a robust waste package/waste form is something WAC could take into account, and that the processes throughout the waste management route can oversee. An example of this was provided for the Richard, Bratrství and Dukovany facilities in operation in the Czech Republic, where:

- *"The producer must prove in a verifiable manner that the storage/disposal packing set with radioactive waste meets the condition of long-term stability pronounced in WAC. E.g., providing an evaluation of the influence of the presence of corrosive substances on RAW, i.e., the influence of expansion, gas evolution, heat release, and evaluation of the effect of external effects.*
- *The WMO verifies the conformity of waste packages with the WAC by checking records of testing, assessment, waste package manufacturing control, and inspections conducted by the waste producers […]. In acceptance process, limited number of waste packages is controlled."* Waste packages are controlled with focus on surface contamination, weight, surface dose rate, and integrity. This control is performed in the acceptance process.
- Further, the WMOs emphasised the importance of a good cooperation between the waste producers and the WMO in order to assure good knowledge transfer of all relevant data towards the WMO.

WMOs and REs also stated that a proper siting and design strategy of the disposal facility can also limit the presence of the uncertainty regarding the physico-chemical conditions in the disposal facility. This would consist in limiting disturbances of the host rock. Measures could be taken such as low void fraction and use of material that limits chemical disturbances.

After repository closure, the physico-chemical conditions can be monitored, in the facility or, if that is not possible, in a pilot or mock-up facility. This might further reduce the uncertainty on the physico-chemical conditions, although safety cannot rely on this reduction, as the safety demonstration at that moment was already completed.

Finally, it was noted by WMO's that for a proper management of uncertainties related to physico-chemical conditions a close cooperation among waste producers and the WMO is important.

(4) Representation in the safety assessments

The uncertainty can be represented in the safety assessments in different ways:

- Via a set of scenarios, including a normal or expected evolution scenario, and altered evolution scenarios, which suppose a faster degradation of the waste and/or the engineered barriers. The set of scenarios then covers the range of uncertainties regarding the physico-chemical conditions in the facility. It could, for example, be supposed in an altered evolution scenario that a part of the facility degrades faster than expected, which could cover certain uncertainties in the physico-chemical conditions in the facility.
- Via carefully chosen pessimistic (conservative) assessments of the reference scenario, that will select the parameters to be an envelope of the uncertainty on the physico-chemical conditions. For example, for the surface disposal facility in Belgium, it was chosen to suppose oxidised conditions within the facility, as this would foster degradation and radionuclide migration. Moreover, the hypothesis of instantaneous release at the moment of degradation was also selected. This covers the uncertainties regarding the physico-chemical conditions that might degrade the waste form. In order to deal with coupled processes, it might be necessary to introduce quite large conservatism for this method. An example can be taken from Nagra (2008): "*Often, coupled processes occur which make proper uncertainty propagation a challenge. e.g., corrosion impacts gas generation and radionuclide (e.g., 14C) release, and depends on saturation, chemical environment, and waste form*".
- Via probabilistic scenario assessments where the uncertainty is introduced in a probabilistic manner (probability density functions of parameters).

7.5 Uncertainties associated with data, tools, and methods used in the safety case

Management options and strategies regarding uncertainties associated with data, tools, and methods were addressed to some extent in the context of the specific examples in previous sections.

7.6 Uncertainties associated with the completeness of FEPs considered in the safety case

Uncertainties associated with the completeness of FEPs considered in the safety case were not addressed in the context of waste inventory related uncertainties.

8. Summary and concluding remarks

In the context of RWM programmes for near-surface and geological disposal of radioactive waste, a comprehensive overview about the different approaches and uncertainty management options to assess and, where relevant, to reduce risks and optimise safety, was developed and presented in this report.

The work focused on four topical sources of uncertainties, namely on uncertainties related to site and geosphere, human aspects, spent nuclear fuel, and waste inventory. For each of these topics, specific topical uncertainties were selected according to highest safety significance as estimated by the WMOs, TSOs, and REs participating in WP UMAN, while assuring coverage of the full spectrum of types of uncertainties according to the classification schemes developed in WP UMAN.

For each specific topical uncertainty, management strategies and options were then assessed. The overviews on generic strategies in uncertainty management and possible management options developed in WP UMAN served as common basis for the assessments. The experiences of organisations participating in UMAN and topically related EURAD WPs were gathered from the responses to the 1st and 2nd UMAN questionnaires and from additional input collected with a specifically designed template. Of particular interest were references to existing documentation (e.g., regulations, guidelines, handbooks, national reports) and examples from literature or experiences of the WP UMAN participants that illustrate good practice and hint at potential pitfalls. Where applicable, the evolution of uncertainty management strategies and options along the RWM programme phases was also captured.

The available information was extensively discussed and compiled by the UMAN Subtask 4.2 participants (WMOs, TSOs and REs). The compilation, topic by topic, formed the basis for broader discussions in the UMAN workshops organised by Subtask 4.3 and as input to the interaction with different types of actors including Civil Society in UMAN seminars organised by Task 5. Additional information gained during the workshops was then integrated and the topical compilations synthesised into the present comprehensive overview.

The input gathered, and thus to some extent the present overview, reflects the available experience and knowledge in the participating organisations at the time when this work was performed. This links to the current phases of national programmes, some of which advance rapidly. This overview does thus not strive to be a complete overview of all the possible or existing management strategies and options. However, we perceived the approach for developing this overview very positively, in particular because of the extensive discussions among different stakeholders. Moreover, the results as synthesised in this report may still serve as a valuable reference for the actors in any RWM programme.

While we refer to Chapters 4 - 7 for in-depth information related to the topical uncertainties, the following general concluding remarks are made:

- A common understanding of what safety relevance means for any given uncertainty is fundamental for adequate uncertainty management. Moreover, safety relevance almost certainly evolves along the disposal programme, respectively along the repository life-cycle phases. Thus, this common understanding must be maintained as the safety relevance evolves over time. At any given milestone, the relevant questions to be asked and answered are: Is an uncertainty safety relevant for the given decision at hand? Must and can it be reduced, avoided, or consequences mitigated, thus, can it be dealt with accordingly in the safety case that accompanies the decision at hand? An outlook to further steps in the programme is also warranted e.g., in the sense of “this accuracy is sufficient at the current step and we can reduce the uncertainty during the next steps using a given approach or strategy”. The importance of this last aspect, also expressed as “when to stop; when is it enough?”, was discussed extensively with respect to communication aspects and regular stakeholder dialogue.
- In early stages of a disposal programme, many uncertainties are potentially safety relevant. However, as the programme progresses, uncertainties that relate to the disposal system itself are often rather quickly under control and even preliminary safety cases for geological disposal

facilities are very robust with respect to such remaining uncertainties. Site selection is significant for this to happen, together with preliminary designs of the engineered barrier system. For example, safety significance may be assessed differently depending on the host rock, safety concept, and type of disposal system. Furthermore, over the last decades, the scientific understanding of the phenomenology related to the processes happening over time in a geological disposal system as e.g., radionuclide release, transport, and retention or thermo-hydro-mechanical evolution has reached such a level that remaining uncertainties usually cannot endanger the safety case. It has however been remarked that this does not imply that future research is obsolete/unnecessary; it merely means that further reduction of certain uncertainties is not needed for a robust safety case; it may still be very useful to further improve systems understanding and reduce uncertainties, e.g., in the context of optimisation.

- It has been recognized that decisions and comportment in early programme phases – or even before a disposal programme starts – can impact uncertainty management strategies and options in later stages. For example, information on waste inventory respectively the lack thereof impacts the assumptions that can or need to be made for a safety case; it may also lead to the need of significant efforts to reduce uncertainties at later stages, e.g., with measurement campaigns. Another example are administrative measures taken during programme establishment; these can be very efficient in preventing uncertainties to appear at later programme stages, prominently for uncertainties related to human factors.
- Throughout the iterative development of a RWM programme, regular broad stakeholder dialog is seen as an important strategy for uncertainty management. Not only does it lead to a common understanding of the (safety) relevance of remaining uncertainties and thus prevent misunderstanding and create trust. Also does it help to keep the awareness for appropriate uncertainty management and a safety culture alive.
- Uncertainties associated with initial characteristics of the system (e.g., waste, site, engineered components, …) or associated with data, tools, and methods can often be well characterised and it is strived to reduce such uncertainty until it is not safety relevant anymore. In contrast, uncertainties in the evolution of a disposal system include uncertainties on very long-term processes, where reduction becomes challenging. Such uncertainties are better avoided, if possible, e.g., through site selection, or need to be tackled using bounding or pessimistic scenarios. In some cases, e.g., related to human intrusion, it might be possible to mitigate consequences.
- In general, it is preferred to reduce or avoid uncertainties as early as possible, so that they are not safety relevant anymore. However, care must be taken that decisions do not prevent adequate uncertainty management in the future. This is particularly true for so-called unknown unknowns that link to the completeness of knowledge and assessment. Keeping options open to deal with such uncertainties in the future might contradict rapid reduction of other uncertainties.
- When remaining uncertainty can be quantified, probabilistic uncertainty analyses are often used to study the impact of remaining uncertainties in safety assessments. If extensive computations shall be avoided, assessments using bounding or pessimistic values can be used to gain some insight.
- The robustness of a disposal system is often illustrated using so-called what-if cases or scenarios. This can be seen as a technique to represent respectively avoid explicit treatment of uncertainty in safety assessments. What-if cases or scenarios are also a tool to handle uncertainties associated with completeness of FEPs and so-called unknown unknowns.

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Appendix A. Template to gather input on uncertainty management strategies and options

Input on uncertainty management has been gathered from the Subtask 4.2 participants and selected other UMAN or EURAD contributors using below template.

Contributor	**Name:** **Actor:**		**Actual phase:** 1 **Repository type:**
Source (pick Subtask 3.3 list, 2nd Questionnaire, or explain other source)			
Uncertainty... (refer to classification scheme)	**...category**	**...type**	**Specific uncertainty** (if applicable); **Description, comments**
Safety relevance (explain e.g., with respect to safety functions)	**Post-closure**		
	Operational		
Management options and strategies (specify your preferred options referring to list of options and strategies; if available, provide references, examples, etc.)	**Identification**		
	Characterisation		
	Assess safety relevance		
	Classification (choose between “to be reduced”, “to be mitigated”, “to be avoided”)		
	Actions (according to classification above)		
	Representation in safety assessments		
Evolution over phases (refer to programme phases)	**Relevance at your current phase**		
	General comments		

Appendix B. Generic strategies and uncertainty management options

Table of uncertainty management techniques that has been generated by grouping the techniques according to overarching principles and strategies (see Chapter 3).

Management option / generic strategy	means or tools	sub-strategy (if applicable)	goal / comments on strategy
general management principles / strategies			
stepwise, iterative approach			
	maintain register of key uncertainties		To inform future phases of disposal system development (e.g. site characterisation activities and design modifications) and future research needs, with the aim of seeking to reduce or mitigate the key uncertainties
		track uncertainties along time	
	stepwise, flexible decision-making process		
		keep options open	keep flexible; be able to manage new (emerging) uncertainties
		roadmap when to address which uncertainty	identification of key milestones
		roadmap when to make which decision	identification of key milestones
		stakeholders contribution to the decisions wherever it is possible	identification of a mode of governance that allows the widest possible consideration of points of view while regulating contradictory positions
	continuous improvement (experience feedback) programme		
		incl. international experience	
regular stakeholder dialog			transparency increase social trust
	network of citizen experts		
	good dialog with media		
management of uncertainties in the safety assessment			
Identification of uncertainties to be managed			
	Preparatory safety assessments		
	FEP analysis		
	Thorough identification of externalities	stakeholder dialogue	
	experience feedback program		identify new, emerging uncertainties
Characterization			
	quantitative description when possible		
	Expert judgment		
Assess impact: Analysis of safety relevance of uncertainties			Assessment of impact on safety assessment results; if possible quantitatively
	systematic uncertainty analysis		
	sensitivity analysis		
	(preparatory) safety assessments		
		evaluate impact on safety indicators	
Classification in "to be reduced", "to be mitigated", "to be avoided"			it needs to be considered: (1) if an uncertainty can be reduced (for a given stage of the process) (2) if there is benefit (for a given stage of the process) in reducing the uncertainty
	To be reduced: uncertainties for which present level leads to safety issues or which reduction allows reduced costs for the same safety performance		
	To be mitigated: uncertainties for which present level can be accepted at present stage of the process, provided mitigation provisions, and for which waiting for the result of reduction efforts, if possible, would delay the process beyond what is considered acceptable		
	To be avoided: uncertainties for which reduction or mitigation is not acceptable or feasible at the present stage of the process		includes uncertainties in terms of Yes/No where only one answer is acceptable

Management option / generic strategy	means or tools	sub-strategy (if applicable)	goal / comments on strategy
Representation of safety-relevant uncertainties **in safety assessment**			
	Address explicitly	e.g., probabilistic techniques	Show that residual uncertainties do not undermine the goals of the present stage Demonstrate uncertainty irrelevance or of low consequences to the safety case Show that residual uncertainties can be dealt with at the relevant (next) stage
	Rule out uncertain FEP (e.g. low probability)		
	Use of different scenarios of disposal system evolution		
	Use of alternative models		
	stylised approach		
	bounding cases		
	conservative approaches		
	Use of complementary approaches to specify safety in SA (e.g. confinement vs. release)		
	Multiple lines of evidence		e.g. natural analogues
Action according to "reduce", "mitigate", "avoid"			
Reduce			
	RD&D		
		Experimental program	
		Demonstration tests	
		RD&D roadmap	
		Combination of field surveys, experiments and numerical modelling	
	site selection and characterization		
	continuous improvement (experience feedback) programme		
Mitigate			
	safety by design		
		on the level of the whole system	e.g., multi-barrier system
		on the level of the component	robustness of individual components
		use safety margins	maintain performance also with disturbances
	controle measures and procedures		
		prevent deviations	prevent deviations from normal operation, prevent unwanted events or developments
		detect deviations	
		prevent progress of resp. mitigate consequences	
	reversibility of decisions		e.g., contributes to mitigation of programme uncertainties
Avoid			
	use of proven methods and material		
	promote strong safey culture		
	demonstrate very low probability		risk mitiation
	systematic QA / QMS		detect deviations
		Independent technical reviews	

Appendix C. Analysis of input related to spent nuclear fuel

The score in each cell corresponds to the sum of the scores from the different institutions. **Color code**: green - lowest values, red - highest values. **Safety significance**: High - 3, Medium - 2, Low - 3, not known or assessed yet - 0	**Impact on source term assessment for SNF disposal and dose assessment**	**Impact on transport safety**	**Impact on operational safety during storage**	**Impact on operational safety during disposal**	**Impact on postclosure safety**	**Impact on safety function(s)**	**Other**	**Total score**
A.1 Fabrication process (e.g. annealing) additives, impurities and tolerances of the NF components	13	2	7	5	10	2	2	**41**
A.2 Composition (physicochemical) of the cladding materials	7	8	7	6	7	8	6	**49**
A.3 Composition (radio- and physicochemical) end enrichment of the fuel	21	10	13	13	4	7	4	**72**
A.4 Thermo-mechanical and chemical behaviours of the NF components	5	5	7	6	5	3	3	**34**
A.5 Irradiation conditions (dose rate, cumulated doses, types of radiations…)	20	14	12	15	10	10	4	**85**
A.6 Burnup and respective isotopic composition, in case of use of "burnup credit"	18	9	9	9	8	5	2	**60**
A.7 Uncertainties on the instrumental control of SNF burnup, that is applied in case of use of "burnup credit"	6	4	6	6	4	4	4	**34**
A.8 Methodology and nuclear data for SNF inventory calculations: cross-sections, decay properties of the isotopic inventory, dose conversion factors	21	4	11	13	9	6	4	**68**
A.9 Residual heat generation	12	8	8	8	13	11	9	**69**
A.10 Isotope transport properties within the SNF components	9	4	4	4	12	4	4	**41**
A.11 Radiation characteristics, residual heat generation and residual neutron absorption properties of irradiated non-fuel elements (absorbind rods, shim rods…)	9	5	7	5	10	5	5	**46**
B.1 Hydrogen embrittlement and hydride reorientations	3	5	8	5	3	3	3	**30**
B.2 Delayed hydride cracking: crack growth due to precipitation of hydrides at the cracks	2	4	6	4	2	2	2	**22**
B.3 Cladding creep: deformation of the cladding material due to stress	2	5	3	2	2	2	2	**18**
B.4 Deformation of cladding material during crying	2	2	2	2	2	2	2	**14**
B.5 Stress and deformation of cladding material during SNF unloading from the dry-type storage	3	3	6	6	3	3	3	**27**
B.6 Cladding and pellet oxidation mechanisms	2	6	7	6	5	4	1	**31**
B.7 Stress corrosion cracking	3	3	3	3	3	3	3	**21**
B.8 Mechanisms for degradation of damaged fuel	5	5	5	4	2	2	2	**25**
B.9 Safety of SNF handling operations in course of its preparation for long-term storage	4	7	7	4	4	4	4	**34**
B.10 Management of damaged and non-tight spent fuel assemblies	4	10	10	6	6	4	4	**44**
C.1 Failures of the material used in the fabrication	10	7	7	7	7	7	4	**49**
C.2 Quality of the welds	7	7	7	7	7	4	4	**43**
C.3 Stress level of welds	4	4	4	4	4	4	4	**28**
C.4 Characteristics of the neutron absorbers used for ensuring subcriticality	5	5	7	5	5	5	5	**37**
C.5 SNF loading into canister. Deviations from criteria	5	5	5	5	5	4	4	**33**
C.6 SNF drying inside the container	4	4	4	4	4	4	4	**28**
C.7 Uncertainty in the He filling of the container	4	8	8	4	4	4	4	**36**
C.8 Release of inert gases by the fuel element inside the container	6	6	6	8	8	5	5	**44**
C.9 Radiolysis, hydrogen generation	4	4	6	4	8	4	4	**34**
C.10 Corrosion of external elements due to salt	3	3	3	3	3	3	3	**21**
C.11 Changes in the humidity	7	5	5	5	7	7	5	**41**
C.12 Temperature profiles and thermal modelling applicable in different countries	6	6	6	4	8	6	6	**42**
C.13 Canister degradation due to radiation	7	5	5	5	7	7	5	**41**
C.14 Comprehensive monitoring of parameters for indirect assessment of tightness of canister, condition of fuel, heat removal, gamma and neutron radiation	4	4	4	4	4	4	4	**28**
C.15 Measurement of the medium in dry airtight or transport canisters, in case of gas leakage	3	3	3	3	3	3	3	**21**
D.1 Atmospheric and aqueous corrosion	6	6	6	6	6	6	6	**42**
D.2 Time evolution of the sealing performance and gas leakage	4	5	7	5	4	4	4	**33**
D.3 Radiological ageing	4	6	6	6	4	4	4	**34**
D.4 Time and temperature effects. Corrosion and creep of metals	3	3	5	3	3	3	3	**23**
E.1 Concrete shrinkage and creep caused by long term dry out	2	2	2	2	2	2	2	**14**
E.2 Carbonation caused by reaction with CO2 in the atmosphere	4	4	4	4	4	4	4	**28**
E.3 Ingress of chlorides in disposal conditions	8	3	3	3	5	6	3	**31**
E.4 Freeze-thaw due to use of concrete in cold environments	3	3	3	3	3	3	3	**21**
E.5 Alkali-silica reaction (ASR) within the concrete	3	1	1	1	3	1	1	**11**
E.6 Sulphate attack on the concrete	4	2	2	2	4	2	2	**18**
E.7 Neutron induced radiation damage in the concrete	3	3	3	3	3	3	3	**21**
E.8 Thermal degradation of concrete	7	2	2	2	4	5	2	**24**
E.9 Leaching and efflorescence	3	1	1	1	5	1	1	**13**
E.10 Concrete swelling due to the sub-microcrystals crystallization	2	2	2	2	2	2	2	**14**
E.11 Degradation of concrete due to ettringite and thaumasite crystallization	3	1	1	1	3	1	1	**11**
E.12 Degradation of concrete due to metal corrosion	1	1	1	1	1	1	1	**7**
E.13 Degradation of concrete induced by mechanical stresses	3	1	1	1	3	1	1	**11**
F.1 Knowledge on the source term and dose evaluation	12	10	12	12	10	5	5	**66**
F.2 Thermal and thermal oxidative degradation	6	6	6	6	6	6	6	**42**
F.3 Degradation due to irradiation	7	7	7	7	7	7	7	**49**
F.4 Hydrogen quantity	5	5	5	5	5	5	5	**35**